# METAMORPHISM, STRUCTURAL EVOLUTION AND EXPERIMENTAL PETROLOGY OF LAMBERT GLACIER GRANULITES, ANTARCTICA

BY

# **GEOFFREY TERENCE NICHOLS**

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This thesis contains no material which has been accepted for the award of any other higher degree or graduate diploma in any other tertiary institution, and that to the best of my knowledge and belief, this thesis contains no material previously published or written by another person, except when due reference is made in the text of the thesis.

L. Jahola:

Geoffrey Terence Nichols August, 1992

### "Utram bibis? Aquam an undam?"

Which are you drinking? The water or the wave?, The Magus, J. Fowles, 1966

to my Parents, Grandparents and Don Millard, who have given me hope

### Abstract

The preserved peak, and post-peak metamorphic evolution culminating around 1000 Ma ago, which affected granulite-facies rocks from adjacent East Antarctic regions, the Reinbolt Hills and the Prince Charles Mountains, is described and quantified here for the first time. The derived pressure-temperature paths from these regions display a continuum in both the maximum preserved conditions and in the gradients of their trajectories, passing from higher pressures ( $\approx$ 8 kbar) along the eastern margin of the Lambert Glacier, to low pressures ( $\approx$ 4.5 kbar) in the north-west Prince Charles Mountains. The maximum preserved temperatures are slightly higher in the east than the west, however retrograde temperatures along the east Lambert Glacier ( $\approx$ 700°C) differ by a maximum of 250°C from those in the west ( $\approx$ 450°C). This retrograde temperature differential is best explained by waning deformation promoting re-equilibration during retrogression in the Prince Charles Mountains, whereas, deformation preceded peak metamorphic conditions in the Reinbolt Hills.

The early episodes of deformation in both the eastern and western regions are characterized by high strain rotational deformation, transposing earlier structures. Intrafolial, frequently rootless, isoclinal and sheath geometry  $F_1$  and  $F_2$  folds have axes sub-parallel to the orientation of strong mineral stretching lineations defined by high-grade assemblages of minerals such as pyroxenes, garnet aggregates, sillimanite, recrystallized quartz and feldspars. High-strain progressive and rotational deformation, was localized as early (MY<sub>1</sub>) layer-parallel mylonitic thrusts at Mt Lanyon and Mt Meredith. The primary thrust movement-sense at Mt Lanyon indicates transport towards the south and southeast, with a later right-lateral shear-sense, determined from drag fold asymmetry adjacent to highly strained carbonate bodies which were remobilized early in the D<sub>3</sub> deformational episode. Porphyroclast asymmetry, and mineral stretching lineations at Mt Meredith indicate an easterly MY<sub>1</sub> transport direction.

The third recognizable deformation produced folds which are characteristically of tight to open styles, with moderately dipping fold limbs and axes. They deform the MY<sub>1</sub> thrusts although they were themselves produced in a similar stress regime, where the principal shortening was predominantly north-south. Significant volumes of charnockites which preserve an alignment of K-feldspar phenocrysts sub-paralleling S<sub>2</sub>, were emplaced in both the Reinbolt Hills and Prince Charles Mountains, and appear to be chronological equivalents of the Mawson Charnockite. Open folds produced during D<sub>4</sub>, refold lineations about axial planes which trend north-south, but the effects of this deformation are not preserved in the Reinbolt Hills. Later, sub-vertically dipping mylonites, were formed during low-granulite to high-amphibolite facies conditions, and this fourth deformational event appears correlatable throughout much of East Antarctica.

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Hercynite-gahnite spinels are an important accessory phase in many metapelitic rocks from East Antarctica, and other granulite-facies terranes. In order to determine their formation conditions and to further constrain the retrograde history of the Prince Charles Mountain rocks, piston-cylinder apparatus was employed to calibrate the equilibrium

### garnet + sillimanite / kyanite = spinel + quartz

between 11 and 30 kbar, and over the temperature range of 950 to 1200°C, at low oxygen fugacities and under anhydrous conditions. A ternary Fe-Mg-Zn symmetric mixing model for aluminous spinels in equilibrium with garnet was derived, and quantifies the increase in gahnitic end-member of spinel with increasing pressure and decreasing temperature. Further experiments in the spinel-cordierite-quartz-sillimanite stability field were combined with garnet-cordierite data from the literature to produce an internally consistent set of equations describing useful thermobarometric exchange reactions, relevant to quartz-sillimanite bearing assemblages at granulite-facies conditions.

The metamorphic and deformational features of this region of East Antarctica, are interpreted as a mid-Proterozoic aged continent-continent collision. The resultant significant increase in crustal thicknesses are directly responsible for the high grade metamorphic conditions. Crustal collision along an approximately east-west striking convergence zone, is suggested by the southerly to southeasterly interpreted tectonic transport direction indicated by  $MY_1$  mylonites, and the orientation of early  $F_2$  and  $F_3$  folds. An anticlockwise rotation of the stress regime, suggested to be related to an impediment placed on convergence by continued crustal-thickening, is indicated by the orientation of near-metamorphic peak second-generation mylonites, that may record the initiation of crustal exhumation in the Lambert Glacier region.

A consistent right-lateral shear geometry portrayed by shallowly dipping third generation mylonitic structures over the entire Lambert Glacier region, is interpreted to have resulted from an easterly directed transport  $\approx$ 500 Ma ago and is unrelated to the early history of the region.

An elegant although conjectural model, based on the co-linearity of stress orientations reported from central Australian granulites, with those described here, amalgamates an interpreted convergence zone through the Albany-Fraser region, with a possible westward extension passing from the Lambert Glacier region around the southern margin of Enderby Land, to Sri Lanka. Available chronological constraints indicate that either compressional reworking was active over the entire belt for a protracted period (possibly from  $\approx 1500$  to 1000 Ma), or that the convergent Himalayan-style regime was diachronous, commencing in the east, and followed a gradual westward translation with time.

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### Abbreviations and terminology

Symbols (from Kretz 1983, where practicable)				
Ab	albite	NaAlSi <sub>3</sub> O <sub>8</sub>		
Adr	andradite	$Ca_3(Fe^{3+})_2Si_3O_{12}$		
Alm	almandine	Fe <sub>3</sub> Al <sub>2</sub> Si <sub>3</sub> O <sub>12</sub>		
Amp	amphibole	$(Na,K)_{0-1}Ca_2(Mg,Fe,Al)_5(Si_{6-7}Al_{2-1}O_{22})(OH,F)_2$		
An	anorthite	CaAl <sub>2</sub> Si <sub>2</sub> O <sub>8</sub>		
And	andalusite	AloSiOs		
Ann	annite	$K_2Fe_6(Si_6Al_2O_{20})(OH)_4$		
An	apatite	$Cas(PO_A)_3(OH.F.Cl)$		
Bt	biotite	$K_2(Mg, Fe)_6 \sqrt{(Fe, Al, Ti)_0} 2Si_6 sAl_2 2O_20(OH, F)_4$		
Cal	calcite	CaCO2		
Chl	chlorite	$(Mg Al Fe)_{12}((Si Al) \otimes O_{20})(OH)_{16}$		
Crd	cordierite	$(Mg Fe)$ $Al_4SisO_{12}$		
Cor	conundum	$Al_2 \Omega_2$		
Cum	cummingtonite	$(M_{4} \text{ Fe})_{7}(\text{Sig}(\Omega_{22}))(\Omega H)_{2}$		
Di	dionside	CaMuSioOc		
En	anetotita	Mussio		
Ea	forrogilite (ortho)	FeeSiaO		
Fo	forutorite	Massio		
FU	noi sienne gebrite	$N_{12} > 0.4$		
Gan	gamme			
Grs	grossular	$(E_3 M_2) = A_1 S_2 O_2$		
	gamet	$(Fe, Mg)_{3A12}S1_{3}O_{12}$ $(Ne K)_{2} = (Oe (Ma Ee A))_{2}(Se A)_{2} = (A e A)_{2}(OH E)_{2}$		
	homolence	$(Na, K)_{0-1}Ca_2(Mg, Fe, AI)_5(S16_7AI_{2-1}O_{22})(OH, F)_2$		
HC	hercynte	FeAl204		
Hem	haemante	Mar(OHE) 1 dMar SiO		
HU	humite	$Mg(OH,F)_{2.1-4}Mg_{23}O_{4}$		
Hy	nypersinene	(Mg,Fe)SIO3		
lin Kr	ilmenite	Fe1103		
KIS	K-feidspar	KAISi3O8		
Ку	kyante	A12S105		
Mag	magnetite	Fe3O4		
Mei	meionite	$Ca_4(Al_6Sl_6O_{24})CO_3$		
Ms	muscovite	$K_2Al_4(S_{16}Al_2O_{20})(OH,F)_4$		
OI	olivine	$(Mg,Fe)_2SiO_4$		
Opx	orthopyroxene	(Mg,Fe)SiO <sub>3</sub>		
PhI	phlogopite	$K_2Mg_6(Si_6Al_2O_{20})(OH,F)_4$		
Pl	plagioclase	$NaAlSi_3O_8 - CaAl_2Si_2O_8$		
Ро	pyrrhotite	Fe <sub>7</sub> S <sub>8</sub> to FeS		
Prp	pyrope	Mg <sub>3</sub> Al <sub>2</sub> Si <sub>3</sub> O <sub>12</sub>		
Prv	perovskite	CaTiO <sub>3</sub>		
Ру	pyrite	FeS <sub>2</sub>		
Qtz	quartz	SiO <sub>2</sub>		
βqtz	beta-quartz	SiO <sub>2</sub>		
Rt	rutile	TiO <sub>2</sub>		
Sa	sapphirine	$(Mg, Fe)_2Al_4SiO_{10}$		
Sch	scheelite	CaWO <sub>4</sub>		
Scp	scapolite	$(Ca,Na,K)_4(Al_6Si_6O_{24})CO_3$		
Sil	sillimanite	Al <sub>2</sub> SiO <sub>5</sub>		
Sp	spessartine	Mn <sub>3</sub> Al <sub>2</sub> Si <sub>3</sub> O <sub>12</sub>		
Spl	spinel	$(Mg,Fe)Al_2O_4$		
Spn	sphene	CaTiSiO4		
Spr	sapphirine	$(Mg,Fe)_2Al_4O_6(SiO_4)$		
Sps	spessartine	Mn <sub>3</sub> Al <sub>2</sub> Si <sub>3</sub> O <sub>12</sub>		
Tr	tremolite	Ca <sub>2</sub> (Mg,Fe) <sub>5</sub> (Si <sub>8</sub> O <sub>22</sub> )(OH,F) <sub>2</sub>		
Wo	wollastonite	Ca(SiO <sub>3</sub> )		
Zm	zircon	$Zr(SiO_4)$		

Nomenclature of chemical systems is based on a combination of the following abbreviations

Α	Al <sub>2</sub> O <sub>3</sub>
С	CaO
Cr	Cr <sub>2</sub> O <sub>3</sub>
F	FeO, & or, $Fe_2O_3$ in oxidized systems where Fe has <sup>3+</sup> valency
Н	H <sub>2</sub> O
К	K <sub>2</sub> O
М	MgO
N	Na <sub>2</sub> O
0	O <sub>2</sub>
S	SiO <sub>2</sub>
Т	TiO <sub>2</sub>
V	$CO_2 \pm H_2O$
Zn	ZnO

Thermodynamic symbols

$a_{\rm A}^{\rm i}$	activity of component i in phase A
ΔG	Change in Gibbs free energy for a reaction, J
γi	activity coefficient for component i
ΔH	Change in enthalpy for a reaction, J
R	gas constant, 8.3143, J $K^{-1}$ mol <sup>-1</sup>
ΔS	Change in entropy for a reaction, J K <sup>-1</sup>
ΔV	Change in volume for a reaction, J kbar <sup>-1</sup>
$W_{ij}^{A}$	Margules interaction parameter for mixing between components i and j in the phase A, J
$x^{i}_{A}$	mole fraction of component i, in phase A

### Structural symbols

С	cisaillement	(French), or shear

- Di
- Fi
- signifies the i<sup>th</sup> deformation signifies the i<sup>th</sup> folding phase signifies the i<sup>th</sup> mineral-stretching lineation Li
- the i<sup>th</sup> metamorphic episode Mi
- the i<sup>th</sup> mylonite generation denotes the i<sup>th</sup> foliation MYi
- Si

### Miscellaneous symbols

- pressure, in kbar (1000 bars), equivalent to  $10^8$  Pascals, or  $\approx 1000$  atmospheres Р Т
- t
- temperature, in °C time, in Ma, millions of years

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### Chapter 3 The deformational history of the Lambert Glacier Region, East Antarctica

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### Chapter 1

### 1.1 Introduction

1.1.1 Aims

The aims of the research presented in this thesis were to determine, and further the understanding of, the deformational episodes and metamorphic conditions of Lambert Glacier granulite facies rocks, from East Antarctica.

### 1.1.2 Methodology

Three austral-summer field trips supported by the Australian National Antarctic Research Expeditions, were conducted to the Antarctic continent, from 1987-1988, 1988-1989 and 1989-1990, to collect rock-specimens, record structural data, and to observe, photograph and sketch geological field relationships, of granulite facies rock-types.

During the first field-season, nunataks along the eastern margin of the Lambert Glacier were examined, including the McKaskle Hills, Jennings Promontory, whilst the larger of the areas, the Reinbolt Hills, was mapped in detail. As aerial photography only existed for the northern margin of the Reinbolt Hills, subvertical and oblique black and white photographs were taken with a hand-held 35 mm SLR camera from a helicopter, flying at an altitude of 10,000 feet. A base-map was drafted from the photographs which were later corrected for optical-aberrations by triangulation, using compass bearings of land-mark features, measured in the field.

The northern Prince Charles Mountains (nPCM), visited during the second and third field-seasons, consist of a series of large peneplanar massifs and steep-sided nunataks, which crop out on the western side of the Lambert Glacier and, at approximately the same latitude as the Reinbolt Hills. Surficial elevations of the glacial tributaries which flow north-eastward, past the nunataks of the nPCM and into the Lambert Glacier, vary between 200 metres in the east, about the same as the Reinbolt Hills area, to 1700 metres in the west of the nPCM. Height above sea-level has a strong influence on wind-ferocity, turbulence and temperature, so that day-time conditions in the west were commonly < -10°C (and as low as -20°C), with winds between 0 to 60 knots, effectively producing difficult working conditions.

Geological maps of the larger massifs, Mt Lanyon, and a photographic interpretation of the better exposures of Manning Massif are presented in Appendix 1, however, the majority of maps depict structural interpretations, as the steep-sided topography of many nunataks makes plan mapping difficult. An excellent southward facing cliff exposure at Mt Lanyon, is one important locality where geological relationships are well exposed, and these were mapped as a cliff section with the aid of enlarged photographs.

Particular emphasis was placed on collecting lithologies best suited to geothermobarometry, such as metapelites, garnet-orthopyroxene bearing felsic gneisses and calc-silicates rocks from the nPCM. Thin-sections were studied optically for reaction textures before analysis with a WDS Cameca SX50 microprobe (analyses are tabulated in Appendix 4). The microprobe was calibrated using international mineral standards considered to have equivalent absorption and matrix characteristics to the minerals being analysed, and silicate-minerals' calibrations were compared with a Delegate clinopyroxene mineral standard. Individual oxide weight percents, within one calculated standard deviation of the averaged Delegate Cpx values, were considered satisfactory for analysis.

Structural data (and reference bearings) were measured with a Japanese Brunton-style compass, which was corrected for a magnetic declination of 75° to the west of true north in the Reinbolt Hills, and a declination of 67°W of true north in the nPCM. Lower hemisphere, equal area, stereographic projections of poles to gneissic layering, were contoured by computer utilizing the Kamb technique.

### 1.2 Structure of the thesis

The research sections of this dissertation begin with an experimental investigation and quantification of the effect of the zincian-spinel end-member, gahnite, on the stability relationships of hercynitic-spinel in equilibrium with garnet, cordierite, quartz and sillimanite. Thermodynamic modelling of the experimental data permitted the derivation of new internally consistent geothermobarometers in the FMASHZn system, presented in Chapter 2, which are applicable to aluminous granulite facies rocks. This chapter follows the format of the manuscript, "Internally consistent gahnitic spinel-cordierite-garnet equilibria in the FMASHZn system: geothermometry and applications" by G.T. Nichols, R.F. Berry & D.H. Green, which has been accepted for publication in Contributions to Mineralogy and Petrology.

Interest in gahnitic spinels, which ultimately resulted in this experimental investigation, was initiated by studying metapelites from the Reinbolt Hills. In particular, quantifying a decompressional P-T trajectory experienced by these rocks, which is indicated by the post-kinematic development of delicate symplectitic intergrowths of bottle-green hercynitic spinel and cordierite, between the reactants, garnet and sillimanite, suggested that zinc may influence the stability-field of spinel, and hence the interpreted P-T path. The

metamorphic evolution of the Reinbolt Hills which is presented in Chapter 4, is based on the published work of Nichols & Berry (1991).

A comparable P-T trajectory, is present in Chapter 5, for another although more northerly East Lambert Glacier nunatak, the McKaskle Hills, and was derived from thermobarometry of spectacular symplectites of orthopyroxene, plagioclase and magnetitespinel solid solution, reacting from grossular-andraditic garnet and quartz. An experimentally derived magnetite-hercynite solvus was used to estimate a minimum temperature of spinel exsolution, from the magnetite-reactant phase, which was important in establishing a minimum retrograde temperature, and thus a steep P-T path for this region.

The peak and retrograde pressures and temperatures conditions of rocks from the nPCM are derived and discussed in Chapter 6. Well established paths are documented for six separate domains, and display gradations, both in gradients, and in the maximum preserved conditions, from flatter lower pressures in the west, to steeper and high pressures in the east. The nPCM paths are also compared with P-T-t paths reported in the literature for terranes which may have formed in regions adjacent to this area of East Antarctica. The structural evolution of this portion of East Antarctica, subdivided into the structure of the Reinbolt Hills and that of the nPCM, is discussed in Chapter 3, and compared with the structural evolutions reported in the literature, of adjacent Archaean and Late Proterozoic terranes.

The regional significance of the gradual P-T path changes are unified with the structural evolution of the East Antarctic region, and possible tectonic models are discussed in Chapter 7.

Finally the results and interpretations, reported in this thesis, are summarized in Chapter 8.

### 1.3 Granulite facies rocks

The gneissic Late Proterozoic (Sheraton *et al.* 1980) lithologies, which crop out as the greater proportion of the East Antarctic region, are composed of granulite facies rocks, whose mineralogy, mineral-reaction textures, and macro- microstructures, are the centre of this study. Many similar petrological features of granulite facies rocks are reported in an extensive literature referred to in this thesis, and also summarized by Harley (1989).

The term 'granulite', according to Vielzeuf (1988), was first used to describe garnet, quartz, feldspar, bearing rocks, with or without kyanite, of the Saxon Granulitgebirge, Germany. In 1952 Eskola broadened the granulite definition to include any rock which was of the granulite facies. This definition is considered satisfactory here, and is now generally accepted throughout the literature. Although the definition is independent of lithological composition, granulite facies rocks are considered to contain predominantly orthopyroxene, in preference to amphibole in felsic compositions (Vernon 1976 & Winkler 1979), whilst in more aluminous or metapelitic rocks, almandine to pyrope garnet, with K-feldspar (Vernon 1976, Vielzeuf 1988) are diagnostic of granulite facies metamorphism.

The pressure-temperature conditions responsible for the generation of granulite facies rocks vary significantly, indicated by Bohlen's (1987) estimate that only 50% of granulite terranes lie within the calculated averaged conditions of  $7.5\pm1$  kbar and  $800\pm50^{\circ}$ C. The variability is displayed in both pressure and temperature, with pressures ranging from less than 4 kbar to 12 kbar. Maximum preserved metamorphic temperatures as high as 1000°C, with minimum temperatures of less than 700°C have been reported (Harley 1989). Temperatures of less than 700°C are unusual for the peak of granulite facies metamorphism. However, they may be understood in the context of long-duration thermal perturbations, metamorphosing previously dehydrated terranes.

Early dehydration of lithologies is postulated as a prerequisite to the formation and preservation of granulite facies rocks. It is suggested to occur via one, or a combination of, four mechanisms (modified from Vielzeuf, 1988), (a) removal of H<sub>2</sub>O by mantle-CO<sub>2</sub> (or CH<sub>4</sub>) degassing, (b) localized buffering by CO<sub>2</sub> generated during the metamorphism of carbonate and/or calc-silicate lithologies, (c) metamorphism of previously dehydrated rocks, & (d) the removal of H<sub>2</sub>O and therefore the effective reduction in the  $a_{H_2O}$ , as it preferentially partitions into crustal-melts, that may then be removed from the region of equilibrium.

Granulites occur in many tectonic regions; although they are predominantly preserved in extensive Precambrian crustal, cratonic areas, from mid-Archaean to Proterozoic ages (e.g. East Antarctica, Central Australia, southern India, Sri Lanka, Greenland), granulites also crop out in younger orogenic regions as tectonically exposed fragments (e.g. Serre Massif southern Italy, Pyrenes), or as young granulitic terranes (e.g. Gruf Complex,  $\approx$ 38 Ma).

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### Chapter 2

### INTERNALLY CONSISTENT GAHNITIC SPINEL–CORDIERITE GARNET EQUILIBRIA IN THE FMASHZn SYSTEM: GEOTHERMOBAROMETRY AND APPLICATIONS

### 2.1 Introduction

pinel minerals are an important phase participating in metamorphic reactions in rocks, particularly those of pelitic compositions, which have been modelled in the FeO-MgO-Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub> (FMAS) system (e.g. Seifert & Schumacher 1986, Hensen 1987, Bertrand *et al.* 1989).

Granulite facies pelitic rocks (e.g. East Antarctica, Central Australia, the Adirondacks and the Coast Mountains) often contain hercynitic spinels with variable amounts of ZnO. The aim of this study was to delineate the effect that ZnO has on the stability field of spinel and to quantify the shift in pressure of equilibria involving spinel.

The alteration of the stability field of spinel can be visualized in a simplified FMAS system, where the equilibria

$$grt + 2 sil = 3 spl + 5 \beta qtz$$
 ...(2.1)

defines a narrow divariant field in P-T space. With the additional component Zn, the four phase assemblage is stable over a very large field in P-T space; zinc effectively stabilizes spinel to higher pressure in the garnet field and to lower pressures in the cordierite field. The spinel garnet equilibria in this 5 component system has strongly pressure dependent reactions which are useful geobarometers at crustal conditions.

In order to constrain temperature effects on these equilibria the experimental data were combined with spinel-cordierite experiments reported here and in Bertrand *et al.* (1991), and with garnet-cordierite data of Hensen & Green (1971), Hensen (1977), Aranovich & Podlesskii (1983) and Bertrand *et al.* (1991). The water effect on cordierite was included using the water solubility model of McPhail *et al.* (1990). These data are combined to produce a consistent set of equations describing the sliding reactions in the system and these formulations are useful as geobarometers and geothermometers.

### 2.2 Experimental methods

### 2.2.1 Materials

The experimental charges were prepared with a combination of natural and synthetic starting minerals. Natural, low Fe-sillimanite from Broken Hill (University of Tasmania, specimen N<sup>o</sup> 19545), quartz from a natural clear crystal, were combined with synthetic cordierite prepared from analytical reagents (AR) of 99.9% purity MgO,  $Al_2O_3 \& SiO_2$ , heated at 1550°C for 4 hrs and quenched into distiled water (after Putnis, 1980). The glass was then crushed under acetone in an agate mortar and pestle and heated at 1275°C to ensure the formation of the orthorhombic form. Almandine garnet was prepared in three experimental runs using AR Fe<sub>2</sub>SiO<sub>4</sub>, SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub> & Al(OH)<sub>3</sub> at 20 kbar and 900°C for 24 hrs. Pyrope garnet was prepared from the AR MgO, SiO<sub>2</sub> and Al(OH)<sub>3</sub> reacted at 25 kbar and 1100°C for 10.75 hours.

Gahnite was prepared using AR ZnO (fired for 12 hrs at 800°C to remove volatiles) and Al<sub>2</sub>O<sub>3</sub> (prepared from the ignition of AR Al(OH)<sub>3</sub>, fired for 12 hrs at 900°C) which were ground under acetone with an agate mortar and pestle, dried at 120°C, pelletized and suspended in a Pt crucible inside an air furnace at 900°C for 12 hrs, then for 120 hrs at 1200°C. Hercynite was prepared from AR FeO, Fe<sub>2</sub>O<sub>3</sub> and Al<sub>2</sub>O<sub>3</sub>, which were ground, pelletized and then heated in an evacuated silica tube at 1050°C for 72 hrs. The hercynite was subsequently annealed under iron-wüstite buffering conditions in an evacuated silica tube for 72 hrs at 1000°C, to ensure that all iron was in its ferrous state.

Gahnite and hercynite were mixed under acetone with an agate mortar and pestle in the required stoichiometric proportions, dried for 3 hrs at 120°C, pelletized, and annealed at 1100°C in an evacuated silica tube for 120 hrs under iron-wüstite conditions.

The starting phases were mixed in an agate mortar and pestle under acetone and dried at 120°C for 4 hours.

### 2.2.2 Experimental apparatus and procedure

Approximately 22 mg of the experimental mixes were packed in graphite capsules with fitting graphite lids, and enclosed in 3.5 mm diameter  $Ag_{50}Pd_{50}$  or Pt tubing. The tubing was crimped, arc-welded and seals were checked by weighing before and after the capsules were immersed in acetone. The experimental mix was deliberately separated from the metal capsules, to ensure that no dissolution of zinc occurred into the capsule as reported by Shulters & Bohlen (1989), and to minimize potential iron loss from the mix.

The experimental assemblies consisted of 7mm bore Pyrex sleeves surrounded by NaCl tubes, and were run in a 2.54 cm bore piston-cylinder apparatus utilizing the piston-in technique. Runs at 850°C and 1000°C used either pure NaCl assemblies or NaCl with pyrex

sleeves. The temperature was measured using Pt/Pt90Rh10 thermocouples connected to a Eurotherm 818P programmable controller which provided an estimated accuracy of  $\pm 2^{\circ}$ C and is periodically verified separately by measurements made with an Analogic Digi-Cal II meter. The effect of pressure on emf was considered to be negligible. Experimental samples are placed within the uniform temperature regime of the graphite-heater elements, while the maximum temperature range over the entire assembly is  $\pm 10^{\circ}$ C at 1000°C. The estimated precision of the pressure is considered to be better than  $\pm 0.5$  kbar, based on the cumulative experimental work conducted at the University of Tasmania and on the work of Mirwald *et al.* (1975).

As all experiments were run under essentially vapour absent conditions and in graphite capsules, the oxygen fugacity was not buffered intensively, however the upper limit was constrained by the graphite equilibria,  $C + O_2 = CO_2$ , considered to be more reducing than the fayalite-magnetite-quartz buffer at experimental conditions (Hensen & Green, 1971). The stoichiometry of spinel, garnet and cordierite shows iron to be almost exclusively in the ferrous rather than ferric state, which confirms the estimate of relatively low experimental  $f_{O2}s$ .

Three compositionally different mixes were made, each with  $Al_2O_3 / (Al_2O_3+MgO+FeO)$  close to 0.6, and ZnO / (ZnO+MgO+FeO) = 0.1. Mix A was produced with a bulk mix Mg N° (100\* MgO / (MgO+FeO) of 40; Mix B had a Mg N° of 60 and Mix C has a Mg N° of 47 (Table 2.1).

	Mix A	Mix B	Mix C
Weight % SiO <sub>2</sub> Al <sub>2</sub> O <sub>3</sub> FeO MgO ZnO	28.34 49.29 13.70 5.26 3.40	35.12 45.87 8.50 7.32 3.18	38.28 41.21 11.76 5.84 2.92
Mg/(Mg+Fe) Al/(Al+Fe+Mg) Zn/(Zn+Mg+Fe)	40.6 60.1 11.5	60.6 60.0 11.5	47.0 56.7 10.4
Mineral mix (%) almandine pyrope cordierite Fe <sub>0.9</sub> Gah <sub>0.1</sub> Al <sub>2</sub> O <sub>4</sub> gahnite sillimanite quartz	1.20 15.60 46.20 5.80 31.20	0.88 25.05 33.00 7.77 32.30 1.00	13.70 7.80 6.50 9.00 58.00 5.00

Table 2.1 Experimental mix compositions.

#### 2.3 Experimental results

#### 2.3.1 Experimental products

Experimental run products were analyzed using WDS techniques on a Cameca SX50 electron microprobe with PAP corrections. Analytical conditions were 20 kV, 20 nA, 1  $\mu$ m beam diameter and counting times (in seconds): Al and Si 10 peak, 5 background, Mg 15 & 7, Zn and Fe 20 & 10. Al was calibrated on synthetic corundum (International standard N<sup>o</sup> USNM 657S), Si on natural quartz from Hot Springs (N<sup>o</sup> USNM R17701), Mg on a forsteritic San Carlos olivine (N<sup>o</sup> 111312), Fe on fayalite from Rockport, MA (N<sup>o</sup> USNM 85276), and Zn on a Brazilian gahnite (N<sup>o</sup> USNM 145883). A complete tabulation of experimental products is presented in Appendix 3.

Grain size of the experimental minerals is quite variable depending largely on run temperature (Fig. 2.1). Garnets often reach 10-25  $\mu$ m and are usually weakly poikioblastic at the lower experimental temperatures (Fig. 2.1b), and contain inclusions of quartz and spinel. Spinels are characteristically idioblastic and usually in runs witn garnet, are <10  $\mu$ m in diameter; spinels, in garnet absent runs, have grain sizes up to 15  $\mu$ m. Alumino-silicates (sillimanite and kyanite) are easily identifiable by their idioblastic laths of up to 30  $\mu$ m (Fig. 2.1a & b), however there are no chemical or visual distinctions between these alumino-silicates. Orthopyroxene (Table 2.2) was present in two runs using mix B (Fig. 2.1c); it is characterised by an acicular form and has a similar SE contrast to garnet. Cordierite occurs in two of the lower pressure runs, (mix C) and it forms homogeneous sub-idioblastic crystals (Fig. 2.1d & Table 2.2).

Individual spinels are essentially homogeneous, with variations in Mg cations typically less than 0.025 cations (per 4 oxygens), with the variation increasing to 0.09 cations in the excluded disequilibrium experiments. Analyses with Si less than 0.03 cations and a stoichiometry of 2.995  $\pm 0.011$  were accepted for barometric calculations.

Unlike spinels, garnets in the low temperature experiments are compositionally zoned, around cores of the seeds added to the mixes. The effect that the zoned garnet may have had on reducing the effective bulk-mix Mg, is considered negligible, as almandine seeds in mixes A and B, are at a maximum of only 1.2 % of the starting reactants. Mix C was made with almandine and pyrope seeds (21.5 % of the starting reactants), permitting a qualitative determination of the approach to equilibrium, from both the iron and magnesium end-members. Experimental run T-3310 contains garnets that appear to have attained equilibrium and Fe-Mg-Zn values are consistent with other runs. However, two analyses of garnets in this run have Mg N<sup>o</sup> of 48. These values are 6 units above those of all other garnets; this disparity can be explained by the rapid over-stepping of the equilibrium

 $3 \text{ crd} = 4 \text{ sil} + 5 \beta \text{qtz} + 2 \text{ prp}$  ...(2.2)

so that cordierite persisted meta-stably for a short period in the run, became isolated by sillimanite, and reacted to a garnet with an unusually high Mg N<sup>o</sup>. This phenomena was only observed in one run, probably because at 1050°C the temperature was not great enough to homogenize Mg-Fe over the entire capsule (as occurred in T-3335 at 1200°C), and at these *P-T* conditions, the equilibria defining the formation of garnet is over-stepped by  $\approx 10$  kbar.



Figure 2.1 Backscattered electron images of experimental products. (a). Run T-3442 mix C, 25 kbar & 1150°C, two coarse grained idioblastic spinels (Spl) surrounded by coarse grained idioblastic garnet (labelled Gnt) with very fine grained spinel and quartz inclusions (Qtz), with a groundmass of sillimanite (Sil) and fine grained quartz (black grains), (b). T-3277 mix A, 11 kbar & 850°C, Non-equilibrium texture of idioblastic almandine seeds (labelled Gnt) surrounded by sub-idioblastic garnet with fine inclusions of spinel, in a groundmass of sillimanite & fine grained quartz. Note the slightly brighter almandine rich rims, (c). T-3190 mix B, 12 kbar & 1050°C, idioblastic spinel & sillimanite, with sub-idioblastic garnet and acicular orthopyroxene (Opx), and (d). T-3303 mix B, 9 kbar & 1050°C, idioblastic spinel & sillimanite, sub-idioblastic cordierite (Crd) and fine grained quartz. Note the increasing grain size from runs at 850°C to those at 1050-1150°C and the decrease in the volumetric abundance of spinel from runs at 11 to those at 25 kbar. Scale bars are 10 μm.

Garnets in run T-3422 (30 kbar, 1150°C) contain 2.62 - 3.18 wt% ZnO (0.142-0.182 cations per twelve oxygens), while retaining the correct Si to Al stoichiometry. Zn is thus forced to occupy the octahedral site normally filled with either Mg or Fe<sup>2+</sup>. Such a site occupancy is to be expected as the effective ionic radius of Zn<sup>2+</sup> (0.90 Å) has an intermediate value between Fe<sup>2+</sup> (0.92 Å) and Mg (0.89 Å), calculated for eight fold coordination (Shannon 1976). The increasingly high Zn solubility in garnet at about 30 kbar places an upper limit, in qtz-sil assemblages, on the stability of aluminous spinel for realistic Zn contents of pelitic assemblages.

Run	T-3190	T-3270/2	T-3258	T-3303	T-3320	T-3335	T-3442
	Орх	Opx	Cordierite	Cordierite	Sillimanite	Sillimanite	Sillimanite
Mg №	71.2	71.3	77.3	83.6	-	-	•
SiO <sub>2</sub>	46.755	46.435	49.109	50.750	37.168	36.858	39.390
Al <sub>2</sub> O <sub>3</sub>	12.691	16.243	33.348	33.503	61.762	61.764	57.860
FeO	15.994	15.750	5.469	3.977	0.902	1.594	1.320
MgO	22.217	21.966	10.477	11.389	0.089	0.328	0.289
ZnO	0.829	0.739	0.621	0.220	0.261	0.290	0.621
Total	98.486	101.133	99.024	99.839	100.182	100.834	99.480
cations							
Si	1.720	1.658	4.971	5.041	1.007	0.994	1.076
Al	0.551	0.684	3.979	3.923	1.972	1.968	1.863
Fe	0.492	0.470	0.463	0.330	0.020	0.036	0.030
Mg	1.218	1.169	1.580	1.686	0.004	0.013	0.012
Zn	0.023	0.019	0.046	0.016	0.005	0.006	0.013
Total	4.004	4.000	11.039	10.996	3.008	3.017	2.994

Table 2.2 Representative microprobe analyses of sillimanite, orthopyroxene and cordierite. Cations calculated per three, six and eighteen oxygens respectively; total Fe calculated as Fe<sup>3+</sup> for sillimanite.

T-3310, mix A, run at 20 kbar and 1050°C, contains acicular grains of corundum (<1  $\mu$ m by 2  $\mu$ m), which are always associated with spinel. It is inferred that in this composition, and at these conditions, the mix had become undersaturated with silica allowing the localized formation of corundum via the reaction:

$$spl + sil = grt + cor$$
 ...(2.3)

The run T-3337 (850°C and 20 kbar), did not contain corundum, but was virtually quartz absent with only one grain of (metastable) quartz in contact with spinel detected. According

to the slope of the grt + cor reaction, corundum should have occurred in this experiment. Its absence can be explained by the slower reaction rates at 850°C and the apparent slow nucleation rate of corundum at these experimental conditions.

### 2.3.2 Attainment of equilibrium

Experimental run assemblages composed of natural and synthetic minerals, as used here, are usually slower to react than runs composed of oxide mixes or glasses, consequently metastable products are not as common, although metastable reactants may still persist. In addition, experiments conducted under essentially anhydrous conditions require one to two orders of magnitude more time to reach equilibrium, at the same P-T conditions, as those conducted with vapour.

To ensure equilibrium conditions were attained in the experiments, relatively long run times were used (Table 2.3), particularly at the lower temperatures (504 hours at 850-950°C). To fully assess mineralogical zoning and the establishment of equilibrium garnet compositions, Mix C (Mg N<sup>2</sup> 47) was prepared with both almandine and pyrope garnet seeds. Experiment T-3335 was then run at 20 kbar and 1200°C, with Mix C sandwiched between layers of Mix A, in a graphite capsule.

Run	Mix	Duration (hrs)	P (kbar)	$T(^{\circ}C)$	Products
T-3169	A	168	10	1050	Spl Sil Qtz
T-3176	А	163	12	1050	Gnt Spl Sil Qtz
T-3182	Α	168	13	1050	Gnt Spl Sil Qtz
T-3187	А	168	11	1050	Spl Sil Qtz
T-3190	В	168	12	1050	Gnt Spl Sil Qtz Opx
T-3191	В	168	10	1050	Spl Sil Qtz
T-3193	А	168	15	1050	Gnt Spl Sil Qtz
T-3196	В	168	11	1050	Spl Sil Qtz
T-3200	Α	170	10.5	1050	Spl Sil Qtz
T-3201	А	504	12	950	Gnt Spl Sil Qtz
T-3202	А	120	12	1100	Spl Sil Qtz
T-3204	В	120	12	1100	Spl Sil Qtz
T-3258	В	168	7	1050	Crd Spl Sil Qtz
T-3267	В	148.5	- 14	1100	Gnt Spl Sil Qtz
T-3270	B+T-3258	95	12	1050	[Gnt Spl Sil Qtz Opx]
T-3272	- 11 -	121	-*-	-"-	
T-3276	А	504	12	850	[Gnt Spl Ky Qtz]
T-3277	А	504	11	850	[Gnt Spl Sil Qtz]
T-3303	В	168	9	1050	Crd Spl Sil Qtz
T-3310	Α	168	20	1050	Gnt Spl Ky Cor
T-3320	С	168	17	1000	Gnt Spl Ky Qtz
T-3335	A+C	83.5	20	1200	Gnt Spl Ky Qtz
T-3337	А	504	20	850	[Gnt Spl Ky [Qtz]]
T-3422	С	72	30	1150	Gnt Ky Qtz
T-3442	С	72	25	1150	Gnt Spl Ky Qtz

Garnet products from T-3335 plotted in AFM, cluster around an equilibrium and mean (A+C) composition, but with scatters towards almandine and pyrope seeds. This clearly demonstrates that although compositional zoning in garnets is preserved (Fig. 2.2c & d), rim compositions represent an equilibrium assemblage with the homogeneous groundmass spinels (Fig. 2.2a & b). Significantly there are no detectable differences between the equilibrium composition attained for the layers of Mix C, with initial bulk Mg N<sup>o</sup> of 47 (that contains both almandine and pyrope seeds) and Mix A, Mg N<sup>o</sup> 40, (which contains only 1.2% almandine seeds), demonstrating equilibration and homogenization of the experimental products, over the entire capsule, and similarly seen in other runs (e.g. Fig. 2.2e & f).

The 850°C experiments failed to equilibrate (see Fig. 2.1b) even at these long run times and the results from these experiments were excluded from the modelling as were the results from experiments described above where a phase was completely consumed.

Experiments in the kyanite field were corrected for the alumino-silicate transition by calculating a sillimanite activity based on the thermodynamic data set of Berman (1988).

The accepted equilibrium compositions were either rim analyses of the zoned garnets or discrete fine grained garnets with similar Mg  $N^{\circ}$ , and adjacent spinels (Table 2.4).

### 2.4 Thermodynamic modelling

The experimental data were considered in the context of the Berman (1988) data base with the compatible pure phase hercynite values from Sack & Ghiorso (1989). In order to simplify the calculations it was assumed that the values of  $\Delta H$ ,  $\Delta S$  and  $\Delta V$  are constant over the applied range of these experiments and they were estimated from the Berman data base at 1000°C and 8 kbar.

For each experiment, the 3 relevant reactions were modelled with equal statistical weight. Each Gibbs free energy equation of the reactions were rewritten in the form,

$$-RT \ln K_{d \text{ ideal}} - nRT \ln \gamma_{\text{grt}} = \Delta H - T\Delta S + P\Delta V + nRT \ln \gamma_{\text{spl}} + nRT \ln \gamma_{\text{crd}}$$

where the left hand side was calculated for each equation. The resulting 138 equations were

Figure 2.2 X-ray emission images of run products from experiments T-3335, (Mix A+C, 20 kbar & 1200°C) (a)-(d), and T-3310, (Mix A, 20 kbar & 1050°C) (e)-(f). (a) and (b) images depicting the relative proportions of Fe and Zn, respectively. A homogeneous garnet, outlined in (b), contains idioblastic spinel inclusions, and is surrounded by acicular sillimanite, quartz and coarser grained spinels. In comparison, (c) depicts the equilibrium Fe-rich rim around a pyrope seed, shown in (d) with Mg X-ray emissions for the same frame. A fine grained almandine seed, with slightly more Mg-rich rims, is also indicated in (d). Homogeneity of sub-idioblastic garnets is shown in (e) and (f) with uniform Fe, and Mg X-ray emissions, respectively. Image dimensions vary between 30 to 40 µm square.
solved using least squares minimization methods with Singular Value Decomposition (SVD) using the subroutines of Press et al. (1986) and incorporating a tolerance level of 10<sup>-6</sup>. The quoted errors are two standard deviations (94% confidence) based upon the assumptions of normally distributed analytical errors, and do not include propagation of errors from the quoted pure phase data. As such they minimize error estimates. SVD was chosen because it is not sensitive to highly correlated errors that would deleteriously affect normal matrix inversion methods when applied to the narrow temperature range of the experimental data. In the final calculation  $\Delta V$  was fixed at the value calculated from Berman (1988). The 3 assemblages are linked so that there are only 4 independent values of  $\Delta H$  and  $\Delta S$ respectively. Of these, 2 values of  $\Delta S$  were fixed at the values calculated from Berman (1988). Thus in the final calculation, there were 11 variables of which the ternary term for spinel and the  $W_{\text{FeMg}}^{\text{crd}}$  are close to 0, so in the final formulation these values were set to 0 while  $W_{\text{FeMg}}^{\text{spl}}$  was set to 1960 J as described below, leaving a total of 8 unknowns. The equations were weighted on the basis of the total size of the system described; all garnetcordierite equations were given a  $\sigma$  of 2.5 because of the larger number of moles in the balanced reactions. The spinel-cordierite data from Bertrand et al. (1991) suffer from poor control on water activity as melt was present, thus the geobarometers were given a lower weighting of 2 but the Fe/Mg exchange reaction is not affected by this and so was weighted more highly, with a  $\sigma$  of 1. The best experiments from this study were given a weight of 0.5 to emphasize the fit to spinel-garnet equilibria.

While some very complex spinel models incorporating disordering-ordering effects in spinel are available (e.g. Sack & Ghiorso 1991, Nell & Wood 1991), it was felt that the additional complexity of these models was not required for the aluminous spinel system, where a simpler model fits the data adequately. Additionally, the uncertainties in estimating the thermodynamic parameters are of the same orders of magnitude as the total non-ideality in spinel. The simple model is more appropriate as it fits the data adequately, while retaining the advantage of easy applicability. Prior to selecting the favoured mixing-model presented below, both symmetric and asymmetric models with and without temperature dependence, were tested. No significant improvement in the statistical fit was obtained using asymmetric models or by including a temperature dependent term in the Margules parameter. The form of the ternary model applied was of the symmetrical three-suffix Margules equation, Wohl-type (Eq. 57 Wohl 1946). The garnet mixing model of Berman (1990), which minimizes  $W_{\text{FeMg}}^{\text{grt}}$ , and performs the most consistently in independent granulite facies geobarometric calibrations, was selected in the calculations of an activity model for spinel. The Fe-Mg

	<b>T-3</b>	76	Т-3	182	T-3	190	Т-3	193	T-3	201	Т-32	267	<b>T-3</b>	320	Т-3	335	T-34	442
	Spinel	Garnet	Spinel	Garnet	Spinel	Garnet	Spinel	Garnet	Spinel	Garnet	Spinel	Garnet	Spinel	Garnet	Spinel	Garnet	Spinel	Garnet
Mg Nº	40.1	43.6	39.4	40.8	57.7	60.9	38.8	41.9	40.3	45.0	59.4	60.9	45.1	50.4	45.1	48.4	44.4	46.4
SiÖz	0.139	39.303	0.965	39.145	0.200	40.045	0.164	39.479	0.244	40.140	0.289	40.387	0.286	39.917	0.113	39.592	0.789	39.148
AbÔn	61.567	23.117	59.655	23.155	62.231	23.564	59.985	22.817	60.654	23.202	62.281	23.638	58.586	23.545	60.393	22.632	57.549	23.353
FrÖ	23.305	25.914	22.136	28.366	16.367	19.166	19.690	27.529	19.059	26.185	14.733	19.340	11.896	24.164	17.424	24.723	8.568	23.680
MgO	8.762	11.264	8.083	10.948	12.529	16.757	6.998	11.135	7.215	12.006	12.111	16.910	5.468	13.799	8.037	13.026	3.836	11.516
ZnO	6.599	0.531	7.883	0.458	7.571	0.382	12.883	0.545	12.896	0.351	9.575	0.529	23.381	0.817	12.838	0.895	28.584	2.506
Total	100.372	100.129	98.722	102.072	98.898	99.914	99.720	101.505	100.068	101.884	98.989	100.804	99.617	102.242	98.805	100.868	99.326	100.203
cations																		
Si	0.004	2,979	0.027	2 943	0.005	2 947	0.005	2 973	0.007	2 985	0.008	2 949	0.008	2 941	0.003	2 970	0.023	2 966
AL	1 981	2 065	1 965	2 052	1 978	2 045	1 981	2 026	1 987	2 034	1 982	2 035	1 980	2 045	1 991	2 002	1 976	2 086
Fe	0 532	1 643	0.515	1 784	0.369	1 180	0.461	1 734	0 443	1 629	0 333	1 181	0.285	1 489	0 407	1 551	0.200	1 500
Mo	0.356	1 272	0.335	1 227	0.503	1 838	0.292	1 250	0.799	1 331	0.333	1 840	0.234	1 515	0.335	1 456	0.167	1 300
7.0	0 133	0.030	0.162	0.025	0.151	0.021	0.266	0.030	0.265	0.019	0.107	0.029	0.495	0.044	0.265	0.050	0.107	0 140
Total	3 006	7 080	2 995	8 031	3,006	8 031	3 005	8 013	3 001	7 008	3 001	8 034	3 002	8 034	3 001	8 0 2 0	2 000	7 002
	2.000		a. ) ) S	0.051	2.000	0.051	5.005	0.015	5.001	1.570	5.001	0.054	5.002	0.054	5.001	0.029	2.330	1.776
		1										2		1				

Table 2.4 Microprobe analyses of spinel-garnet pairs used in the barometric derivation. Cations calculated per four and twelve oxygens for spinel and garnet, respectively.

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binary has been modelled with a symmetric  $W_{\text{FeMg}}$  term by O'Neill & Wall (1987) and Sack & Ghiorso (1989). Shulters and Bohlen (1989) investigated the Fe-Zn binary for aluminous spinels, with the corundum-bearing, quartz-absent reaction

3 hc + 3 sil = alm + 5 cor ...(2.6)

They attempted to calculate the binary interaction parameter but found a very poor fit with  $W_{ZnFe}$  ranging from 6.31±17.00 (Hc<sub>70</sub>) to -10.29±27.75 (Hc<sub>86</sub>), at 900°C and -2.84±6.77 (Hc<sub>70</sub>) to -9.90±13.83 (Hc<sub>86</sub>), at 1050°C. A  $W_{ZnFe}$  of -2.6 kJ mol<sup>-1</sup> implied by these experiments lies within the large range of their values, and is most consistent with their higher temperature data.

Initial attempts to fit my data to the Berman data set indicated the values for the FAS reaction were compatible with this data set which also predicted reasonable pressures in natural rocks, but the predicted position of the MAS reaction was inconsistent with my data, at any reasonable value for the non-ideality terms in spinel, and was also inconsistent with natural compositions. In order to further constrain this reaction, the model was expanded to include the spinel-cordierite experiments (this chapter, Bertrand *et al.* 1991) and garnet-cordierite experiments (Aranovich & Podlesskii 1983, Bertrand *et al.* 1991, Hensen & Green 1971, Hensen 1977), all coexisting with quartz and sillimanite. In using this data base, the water activity must be included and so the hydrous cordierite model of McPhail *et al.* (1990) which assumes that Fe-cordierite has the same water solubility as Mg-cordierite, was selected. This activity model brings the reversed anhydrous experiment of Hensen (1977) and the water-saturated experiments of Aranovich & Podlesskii (1983) into close agreement.

The  $\Delta V$  of the reactions was calculated from Berman (1988) at 1000°C and 8 kbar. In addition  $\Delta S$  for the FAS spinel-garnet reaction and  $\Delta S$  for the MAS spinel-cordierite equilibria were calculated from Berman (1988), and were fixed as these were the only values available which closely matched the slopes of these reactions within my data, and which correctly projected experimental data to natural rock conditions. The modelling included a symmetric regular solution model for cordierite and the ternary model for aluminous spinel. The resulting values for the various thermodynamic parameters are shown in Table 2.5. The least squares solution by SVD has a  $\chi^2$  value of 2.3 x 10<sup>10</sup> J<sup>2</sup> which is an average mismatch of 4500 J. The statistics of fitting errors are shown in Table 2.6 and are generally within the range 0.6 to 1 kbar or 50-112°C. The formal calculation of precision of the

	$\Delta H$	$\Delta S$	$\Delta V$	interaction parameters
Reaction	J	J K-1	J kbar-1	J ·
$alm + 2 sil = 3 hc + 5 \beta qtz$	49360	57.48	2400	
$alm + 2 ky = 3 hc + 5 \beta qtz$	70000	78.88	3460	spinel W <sub>Fe-Mg</sub> 1960
$prp + 2 sil = 3 spl + 5 \beta qtz$	37464	46.49	2340	spinel W <sub>Fe-Zn</sub> -3800 °
$prp + 2 ky = 3 spl + 5 \beta qtz$	58104	67.89	3400	spinel W <sub>Mg-Zn</sub> -2600
prp + 3 hc = alm + 3 spl	-11896	-10.99	-60	
$crd = 2 spl + 5 \beta qtz$	12208	-19.50	-3330	cordierite W <sub>Fe-Mg</sub> 0
$Fe-crd = 2 hc + 5 \beta qtz$	-17566	-22.63	-3500	
crd + 2 hc = Fe-crd + 2 spl	29774	3.13	170	
$2 \operatorname{alm} + 4 \operatorname{sil} + 5 \beta \operatorname{qtz} = 3 \operatorname{Fe-crd}$	151416	182.85	15300	
$2 \text{ prp} + 4 \text{ sil} + 5 \beta \text{qtz} = 3 \text{ crd}$	38300	151.48	14670	
2  prp + 3  Fe-crd = 3  crd + 2  alm	-113116	-31.37	-630	

Table 2.5 Derived thermodynamic data used in the modelling of calibrations.

-	Joules	P & T equivalent
Grt-Spl		
MAS	2700	1.1 kbar
FAS	1850	0.8 kbar
FeMg K <sub>d</sub>	1870	_
Spl-Crd		
MAS	1870	0.6 kbar
FAS	2396	1.0 kbar
FeMg K <sub>d</sub>	2700	112 °C
Grt-Crd		
MAS	8380	0.6 kbar
FAS	8940	0.6 kbar
FeMg K <sub>d</sub>	10859	50 °C

Table 2.6 Fitting statistics on separated calibrations, quoted in Joules and equivalent pressures and temperatures.

parameters, at the 90% confidence level, from the SVD analysis assuming normally distributed errors in the data suggests extremely high precision on all parameters modelled. Approximate errors suggested are <15 J for  $\Delta$ H and ≈0.01 J K<sup>-1</sup> for  $\Delta$ S terms and ≈4 J for W terms. This is clearly an unrealistic estimate. Sensitivity analysis on parameters indicates a standard error for W terms, at 90% confidence, are ±2500 J (Fig. 2.3a) while for  $\Delta$ S spl-grt MAS is 7 J K<sup>-1</sup> and  $\Delta$ S spl-crd is 5 J K<sup>-1</sup> (Fig. 2.3b). Here an F test has been applied to the increase in  $\chi^2$  associated with fixing an additional parameter (e.g. Davis 1973).

Cordierite closely approximates an ideal solid solution with a calculated value  $W_{\text{FeMg}}^{\text{crd}}$  of -60 J, which was set equal to 0. The  $W_{\text{FeMg}}^{\text{spl}}$  was calculated as 1400 J, but the model is insensitive to this parameter and therefore the value of 1960 J recommended by O'Neill & Wall (1987), which is compatible with my data, was used in the final calculation. The much higher  $W_{\text{FeMg}}^{\text{spl}}$  of 8.2 kJ suggested by Sack & Ghiorso (1989) is not consistent with the derived spinel mixing-model, and this difference may in part be due to the selection of activity models for garnet, and in their case olivine (see Kohn & Spear 1991). The resulting model has a negative non-ideality for  $W_{\text{FeZn}}^{\text{spl}}$  and  $W_{\text{MgZn}}^{\text{spl}}$  which is consistent with the

observation that the zinc content of spinel in the experiments increases more slowly with increasing pressure



Figure 2.3 (a) Variation in  $\chi^2$  plotted against interaction parameters as a sensitivity analysis, with the 90% confidence level shown; open squares  $W_{MgZn}^{spl}$ , filled squares  $W_{FeZn}^{spl}$ , filled triangles  $W_{FeMg}^{crd}$  and

unadomed graph  $W_{\text{FeMg}}^{\text{spl}}$  (b) Variation in  $\chi^2$  plotted against the calculated  $\Delta S$  grt-spl MAS for the left hand curve and  $\Delta S$  spl-crd FAS, with the 90% confidence level indicated.

than predicted by an ideal ionic model for spinel. Attempts to force  $W_{\text{FeZn}}^{\text{spl}}$  and  $W_{\text{MgZn}}^{\text{spl}}$  to

positive values either substantially increases the fitting error or requires a very large ternary term to balance the resultant increase in calculated  $\gamma$  spinel. The estimated  $W_{\text{FeZn}}^{\text{spl}}$  lies within

the range calculated by Shulters & Bohlen (1989) from their binary data. Equivalent negative non-idealities in spinels are interpreted by O'Neill & Navrotsky (1984) as deriving from differences in cation distributions between end-members; the negative non-ideality associated with ordering is probably greater than any positive non-ideality due to size-mismatch, created by adding Zn.

Figure 2.4 depicts the slopes of the univariant reaction lines, modelled using my thermodynamic values for the garnet-spinel, spinel and spinel-cordierite fields. The garnet-spinel divariant field is contoured for  $X_{Zn}^{spl}$ ; four experiments within the garnet-spinel stability field are garnet absent (two at 1050°C and two at 1100°C) as the high  $X_{Zn}$  of the bulk composition puts the experiment outside the narrow two phase garnet-spinel field at these conditions. Similarly the run at 30 kbar is spinel absent because the  $X_{Zn}^{mix}$  was too low at these conditions to stabilize spinel.



Figure 2.4 Pressure-temperature diagram depicting the garnet-spinel, spinel and spinel-cordierite stability fields inferred from experimental runs, in the FMASZn system; spinel and sillimanite in excess, except where indicated. Contours of  $X_{spl}^{Zn}$  (drawn for Mg N<sup>o</sup> 50) depicted by dashed lines. Mix A squares, Mix B circles and Mix C hexagons, Cor corundum, -Spl spinel absent, R reversed run. Stable phases are represented by filled boxes: see key on figure. Note the size of boxes is much greater than the estimated errors in the *P* and *T* of the experiments. Metastable runs enclosed in parentheses were not used in barometric calculations.

Figure 2.5 depicts the chemographic relationships in Fe-Mg-Zn based upon my spinel model which incorporates the garnet activity model of Berman (1990), with the water activity formulation of McPhail *et al.* (1990). Garnet-spinel fields are stabilized with increasing pressure at constant temperature at the expense of the spinel, spinel-cordierite and the garnet-spinel-cordierite fields. While increasing temperature at constant pressure stabilizes the spinel field with respect to the garnet-spinel, spinel-cordierite and garnet-spinel-cordierite fields.



Figure 2.5 Chemographic Fe-Mg-Zn triangles calculated at three temperatures and at pressures from 6-11 kbar, display the inter-relationship of the divariant garnet-spinel field (dotted tie-lines sub-parallel to the FeZn axis represent equilibrium grt-spl pairs), with the divariant spinel-cordierite field (tie-lines sub-parallel to the FeMg axis represent equilibrium spl-crd pairs). Spinel-cordierite hydrous field shown in dashed lines. Numbered fields are I spinel, II garnet-spinel, III garnet-spinel-cordierite, and the un-numbered field spinel-cordierite. Quartz and sillimanite in excess: low  $f_{O2}$ .

## 2.5 Calibrations and applications

2.5.1 Temperature dependence of Garnet-spinel Fe-Mg-Zn exchange The small  $K_d \frac{\text{grt-spi}}{\text{FeMg}}$  restricts the use of this exchange reaction and it is unsuitable as a geothermometer. The reaction does however, place strong constraints on any mixing model between spinel end-members by ensuring the use of equilibrium garnet-spinel pairs. A fit to the experimental data by least squares minimization and SVD indicates a  $W_{MgZn}$  value of -2600 J mol<sup>-1</sup>. The  $\Delta$ H and  $\Delta$ S for this reaction are not consistent with the Berman (1988) values. This cation exchange reaction can be written to give an estimate of the Gibbs free energy:

$$alm + spl = prp + hc$$
 ...(2.7)

$$\Delta G_{err} = 11896 + 60P - 10.99 T + RT \ln \frac{a_{Grt}^{prp} (X_{spl}^{hc})^3}{a_{Grt}^{alm} (X_{spl}^{spl})^3} + 3RT \ln \gamma_{hc} - 3RT \ln \gamma_{spl} \dots (2.8)$$

where T is in K, P in kbar, RT ln  $\gamma_{hc}$  from Eq. (2.17),  $a_{Grt}^{prp}$  and  $a_{Grt}^{alm}$  from Berman (1990).

Where equilibrium between the mineral pairs is suggested by  $\Delta G_{err} \leq 3.7$  kJ (2 $\sigma$ ), and where the difference between the FASZn and MASZn barometers is small, the pressure of equilibration is well defined. If however,  $\Delta G_{err} \leq 5.6$  kJ (3 $\sigma$ ) approach to equilibrium is suggested and the calculated pressures will only be useful in bracketing the equilibration pressure.

The model closely reproduces the experimental pressures, except for the three disequilibrium runs which were excluded from the model, and all experiments lie within the  $2\sigma$  error range.

2.5.2 Garnet-spinel barometry, quartz sillimanite assemblages, FASZn  $alm + 2 sil = 3 hc + 5 \beta qtz$  ...(2.9)

where P is in kbar, T in K and  $a_{\text{Grt}}^{\text{alm}}$  from Berman (1990).

2.5.3 Garnet-spinel barometry, quartz kyanite assemblages, FASZn  $alm + 2 ky = 3 hc + 5 \beta qtz$  ...(2.11)

where P is in kbar, T in K and  $a \frac{\text{alm}}{\text{Grt}}$  from Berman (1990).

2.5.4 Garnet-spinel barometry, quartz sillimanite assemblages, MASZn  $prp + 2 sil = 3 spl + 5 \beta qtz$  ...(2.13)

where P is in kbar, T in K and  $a_{Grt}^{prp}$  from Berman (1990).

2.5.5 Garnet-spinel barometry, quartz kyanite assemblages, MASZn  $prp + 2 ky = 3 spl + 5 \beta qtz$  ...(2.15)

$$P = \frac{-58104 + 67.89T - RT \ln \frac{(X_{spl}^{spl})^3}{a_{Grt}^{prp}} - 3RT \ln \gamma_{spl}}{...(2.16)}$$

where P is in kbar, T in K and  $a_{Grt}^{prp}$  from Berman (1990).

$$RT \ln \gamma_{hc} = W_{MgFe} (X_{Mg}^2 + X_{Mg} X_{Zn}) + W_{FeZn} (X_{Zn}^2 + X_{Mg} X_{Zn}) + W_{MgZn} (- X_{Mg} X_{Zn}) ...(2.17)$$

$$RT\ln \gamma_{spl} = W_{MgFe} (X_{Fe}^{2} + X_{Fe} X_{Zn}) + W_{MgZn} (X_{Zn}^{2} + X_{Zn} X_{Fe}) + W_{FeZn} (- X_{Fe} X_{Zn}) ...(2.18)$$

where  $W_{MgFe} = 1960 \text{ J}$ ,  $W_{FeZn} = -3800 \text{ J}$  and  $W_{MgZn} = -2600 \text{ J}$ .

# 2.5.6 Application

The new garnet-spinel geobarometric calibration was applied to 21 specimens reported in the literature (Table 2.7). The calibration was only utilized where the reported assemblages were demonstrably in equilibrium, and at low  $f_{O2}$  conditions indicated by a  $\text{spl}_{Al/2} \ge 0.8$ , for consistent results. The thermodynamic values presented here are most consistent with the model of O'Neill & Wall (1987) and therefore their spinel activity model should be applied to samples with significant Fe<sup>3+</sup>.

Of the nine samples apparently in equilibrium, the calculated pressures replicate most reported pressures for those samples to better than  $\pm 1$  kbar. However the samples of Plimer (1977), Powers & Bohlen (1985) and Vielzeuf (1983) (Table 2.7) which fit the equilibrium criteria, but show a disparity between the reported pressure and the calculated pressure probably are in error because of poor temperature constraints.

Equilibration pressure estimates of rim-garnet and retrograde spinel in specimen 72045, Table 2.7 (Nichols & Berry 1991) provide a well documented and independent assessment of the precision of this barometer. A decompressional *P-T* path is documented for this meta-pelite, which passes through well-constrained peak conditions of  $7\pm1$  kbar &  $800\pm50^{\circ}$ C to  $5\pm1$  kbar &  $690\pm30^{\circ}$ C. The *P-T* conditions at the lower end of this path were defined by symplectitic reaction textures involving 3 independent reactions combined with grt-crd and grt-ilm thermometry on the retrograde phases. The garnet-spinel barometers indicate pressures of 4.8 and 5.3 kbar for the formation of symplectitic hercynitic-spinel, consistent with the values obtained for the other retrograde reactions.

The garnet-spinel barometers provide useful pressure constraints on mineral assemblages containing ZnO, where conventional calibrations have disregarded its stabilizing influence on this petrologically useful assemblage.

Run, Specimen Nº, Reference	Garnet	Spinel	T(°C)	$\Delta G_{err}(kl)$	P (kbar)	P <sub>calc</sub> (kbar) FASZn	P <sub>calc</sub> (kbar) MASZn
T-3176	Ahn56Prp43Zn1	Hc52Spl35Gah13 XAI0.991	1050	0.7	12.0	12.2	12.5
T-3182	Alm59Prp40Zn1	Hc51Spl33Gah16 XAl0.983	1050	-2.1	13.0	13.3	12.4
T-3190	Alm39Prp60Zn1	11c36Sp149Gah15 XA10,989	1050	1.3	12.0	12.1	12.7
T-3193	Alm58Prp41Zn1	Hc45Spl29Gah26 XAl0.994	1050	0.1	15.0	14.9	14.9
T-3201	Alm55Prp45Zn1	Hc44Spl30Gah26 XAl0.994	950	2.5	12.0	11.9	13.0
T-3267	Alm39Prp60Zn1	Hc33Spl48Gah19 XAl0.991	1100	-1.4	14.0	14.7	14.1
T-3270/72	Alm30Prp68Zn3	Hc36Spl51Gah13 XA10.988	1050	12.7	12.0	8.4	13.7
T-3276	Alm57Prp43Zn1	Hc58Spl29Gah13 XA10.958	850	8.5	12.0	6.0	9.5
T-3277	Alm56Prp44Zn0	Hc54Spl33Gah13 XA10.986	850	5.2	11.0	6.8	8.9
T-3310	Alm57Prp41Zn2	Hc36Spl23Gah41 XAl0.996	1050	-0.8	20.0	16.6	16.1
T-3320	Alm49Prp50Zn1	Hc28Spl23Gah49 XA10.990	1000	2.6	17.0	17.5	18.6
T-3335	Alm51Prp48Zn2	Hc40Spl33Gah26 XA10.996	1200	-0.6	20.0	18.0	17.7
T-3442	Alm50Prp43Zn5	IIc21Spl17Gah62 XAI0.988	1150	-2.7	25.0	25.2	24.1
Atkin 1978	Alm74Prp16Sp5Gr5	Hc74Spl11Gah15 XA10.926	725	9.3	2.6	5.0	9.0
Caporuscio & Morse 1978 †	Alm50Prp45Sp3Gr2	Hc53Spl47Gah0 XAl0.940	850	0.7	<6.6	6.7	7.0
Dietvorst 1980 †	Alm60Prp7Sp31Gr2	Hc32Spl8Gah59 XA11.000	650	-9.6	6.7	8.8	4.8
Ellis et al. 1980 †	Alm43Prp52Sp1Gr4	Hc49Spl51Gah0 XAl0.890	940	3.2	9.0	9.5	10.9
Hollerbach 1985 †	Alm74Prp19Sp1Gr5	Hc82Sp112Gah7 XA11.000	800	12.5	3.4	4.0	9.4
K12C, Hollister 1982	Alm80Prp16Sp7Gr3	Hc77Spt19Gah6 XA10.985	725	-5.5	4.5	4.0	1.7
252, Lal et al. 1987	Alm54Prp41Sp2Gr2	Hc65Sp131Gah2 XA10.962	760	11.1	5.0	3.0	7.6
302, Lal et al. 1987	Alm49Prp49Sp1Gr1	Hc51Spt48Gah() XAI().956	760	-2.0	5.0	5.2	4.3
320, Lal et al. 1987	Alm47Prp51Sp13Gr8	Hc52Spl46Gah2 XAl0.965	760	5.5	5.0	3.6	5.9
321, Lal et al. 1987	Alm49Prp49Sp13Gr6	Hc51Spl48Gah() XAI0.957	760	2.0	5.0	4.4	5.2
Loomis 1976 †	Alm61Prp28Sp1Gr1	Hc77Spl22Gah1 XAI1.000	800	10.6	6.07	2.6	7.0
72045, Nichols & Berry 1991	Alm59Prp37Sp2Gr2	Hc51Spl34Gah15 XAl0.955	710	-1.1	5.5	5.3	4.8
257, Norman & Clarke 1990	Alm68Prp30Sp2Gr4	Hc55Spl32Gah12 XAI0.977	750	-6.5	5.3	6.4	3.6
704, Norman & Clarke 1990	Alm64Prp32Sp9Gr3	Hc57Spl33Gah11 XAl0.971	750	-4.0	5.3	5.6	3.9
VO87-1017, Owen & Greenough 1991	Alm67Prp23Sp7Gr3	Hc71Spl29Gah2 XAl0.992	805	-3.8	2	4.5	3.0
Plimer 1977 †	Alm60Prp35Sp3Gr2	Hc57Spl38Gah5 XA11.000	700	-1.7	5.5	3.0	2.2
Powers & Bohlen 1985 †	Alm58Prp39Sp1Gr2	Hc61Spl25Gah14 XAl0.990	875	11.3	7.0	6.7	11.6
E6-1, Sengupta et al. 1991	Alm56Prp40Sp1Gr4	Hc57Spl42Gah1 XA10.960	960	-2.9	8.5	9.6	8.4
1, Stoddard 1979	Alm61Prp35Sp1Gr3	11c45Spl25Gah31 XAl0.940	750	0.0	7.0	8.9	8.8
2, Stoddard 1979	Alm60Prp36Sp1Gr3	Hc51Spl31Gah20 XAl0.982	750	-1.0	7.0	6.2	5.7
Vielzeuf 1983 †	Alm64Prp28Sp6Gr2	Hc72Spl28Gah0 XAI1.000	1100	1.3	7.0?	10.4	11.0
Wagner & Crawford 1975 †	Alm66Prp28Sp3Gr2	11c37Sp119Gah44 XA11_000	700	-3.8	8.0	9.4	7.8

# 2.5.7 Topological inversion of garnet-spinel equilibria

As the  $K_d \frac{\text{grt-spl}}{\text{FeMg}}$  is close to unity for all of the experimental and natural samples examined, the partitioning of Fe<sup>2+</sup> and Mg between equilibrium garnet and spinel pairs is necessarily small. Figure 2.6a, constructed at 1050°C in FMAS for relatively low  $f_{O2}$ s, projecting from quartz and sillimanite, displays a narrow garnet-spinel divariant field. In Fe-rich compositions  $\text{grt}_{Mg} > \text{spl}_{Mg}$  with an inversion point where  $\text{grt}_{Mg} = \text{spl}_{Mg}$  coinciding with the incoming of cordierite. Were cordierite to be unstable in this system the garnet-spinel field would invert around this singular point, and begin to rise with increasing bulk Mg N<sup>o</sup> thus  $\text{spl}_{Mg} > \text{grt}_{Mg}$ . In water saturated systems, cordierite is stabilized to increasingly Ferich compositions, and the incoming of cordierite cuts the garnet-spinel field so that  $\text{grt}_{Mg} >$  $\text{spl}_{Mg}$ . At lower temperatures (Fig. 2.6b), garnet-spinel is stable over an even narrower pressure range (in Zn absent systems), and  $\text{grt}_{Mg} > \text{spl}_{Mg}$  with garnet becoming increasingly more magnesian compared to its equilibrium spinel, with decreasing temperature.

Similar curved univariant reaction boundaries and topological inversions have been discussed (Hensen 1987) in magnesian compositions for relationships between opx, crd and grt. The garnet-spinel inversion is likely to only become important for the inter-relationship of these phases in rocks with high ZnO contents, or in zinc-bearing, quartz-undersaturated assemblages.

## 2.5.8 Spinel-quartz-cordierite barometry

The MASZn and FASZn systems were considered separately, by combining data from two of my experiments with four of Bertrand *et al.*'s (1991) experiments, who utilized the FMAS(H-C) system. The spinel-cordierite equilibria were assessed in conjunction with McPhail *et al.*'s (1990) hydrous cordierite model. The influence which  $H_2O$  and  $CO_2$  exert on stabilizing cordierite are comparable, although  $CO_2$  appears to be slightly less effective, in agreement with Bertrand *et al.*'s (1991) statement that  $CO_2$  has almost as great an effect on stabilising cordierite, as  $H_2O$ .

2.5.8.1 Spinel-quartz-cordierite barometry, MASZn Mg-crd = 2 spl + 5 βqtz ...(2.19)

$$P = \frac{12208 + 19.5T - RT \ln \frac{a_{\rm crd}^{\rm Mg-crd}}{(X_{\rm spl}^{\rm spl})^2} + 2RT \ln \gamma_{\rm spl}}{...(2.20)}$$



Figure 2.6 Pressure-composition diagrams calculated with the reported thermodynamic values, for the FMAS system, projecting from quartz and sillimanite at low  $f_{O2}$ . (a) At 1050°C the narrow garnet-spinel field is terminated by the incoming of cordierite for Mg-rich compositions, producing the garnet-cordierite and spinel-cordierite divariant fields (depicted in solid lines). Addition of water to the FMAS system stabilizes cordierite at the expense of the spinel and garnet only fields, and necessitates the coexistence of more Fe-rich garnet-cordierite and spinel-cordierite compositions (depicted with dashed lines). (b) At 750°C the *P*-*X* diagram displays the relative enlargement of the cordierite and garnet stability fields at the expense of the spinel field, with decreasing temperature. The hydrous cordierite fields (depicted with dashed lines) are enlarged compared to the anhydrous fields, and towards Fe-rich compositions. (c) At 1050°C, showing 1 kbar shift in the position of the garnet-spinel field produced by increasing  $X_{spl}^{Zn}$  from 0.0 to 0.05 (~ 2.6 wt% ZnO).

# 2.5.8.2 Spinel-quartz-cordierite barometry, FASZn Fe-crd = $2 hc + 5 \beta qtz$ ...(2.21)

$$P = \frac{-17566 + 22.63T - RT \ln \frac{a_{\rm crd}^{\rm Fe-crd}}{(X_{\rm spl}^{\rm hc})^2} + 2RT \ln \gamma_{\rm hc}}{...(2.22)}$$

$$T = \frac{29774 + 170P - 2 (RT \ln \gamma_{hc} - RT \ln \gamma_{spl})}{(X_{spl}^{hc})^2 a_{crd}^{Mg-crd}} \dots (2.24)$$
  
3.13 + Rln  $\frac{(X_{spl}^{hc})^2 a_{crd}^{Fe-crd}}{(X_{spl}^{spl})^2 a_{crd}^{Fe-crd}}$ 

where T is in K, P in kbar, RT  $\ln \gamma_{hc} \& RT \ln \gamma_{spl}$  from Eq. (2.18).

## 2.5.10 Application

The combined experimental spinel-cordierite thermometry data with that of Bertrand *et al* (1991), indicates a fit to within  $\pm 150^{\circ}$ C with a 1 $\sigma$  of 112°C. The quoted barometric values in Table 2.8 are listed for anhydrous and hydrous values, for the iron and magnesium systems. The anhydrous values reproduce the experimental conditions to  $\pm 1$  kbar, and a comparison with the calculated hydrous pressures suggests that the vapour-present experiments conducted by Bertrand *et al.* (1991) were not fluid saturated, which is supported by the presence of melt in three of their four experiments.

Calculated P and T 's for ten samples from the literature are shown in Table 2.8. Where the reported compositions give a temperature estimate within a  $1\sigma$  range of  $\pm 112^{\circ}$ C of the reported temperature, the calculated pressures for both Fe and Mg systems are always better than  $\pm 1.7$  kbar. The large standard deviation of the error in calculated temperatures for the experimental data, suggest that the thermodynamic values for the relatively few spinel-cordierite runs are overwhelmed by the rest of the data-base, and this calibration would be improved by additional experimental data.

Run, Specimen Nº, Reference	Cordierite	Spinel	T ( °C)	$T_{calc}(\mathcal{C})$	P (kbar)	P <sub>calc</sub> (kbar)	P <sub>calc</sub> (kbar)
						FASZn - H	MASZn - H
T-3258	Fe22Mg76Zn2	Hc43Spl41Gah17 XAl0.995	1050	1026	7.0	7.4	7.5
T-3303	Fe <sub>16</sub> Mg <sub>83</sub> Zn <sub>1</sub>	Hc38Spl48Gah14 XAl0.980	1050	909	9.0	9.0	7.9
T-1980, Bertrand et al. 1991	Fe32Mg69	Hc59Spl42Gaho XAl1.000	1050	1189	8.0	7.5	8.3
T-1995, Bertrand et al. 1991	Fe27Mg74	Hc54Spl47Gah0 XAI1.000	1050	1135	9.0	8.1	8.6
T-2124, Bertrand et al. 1991	Fe <sub>26</sub> Mg75	Hc53Spl48Gaho XA11.000	1025	1120	9.0	8.0 - 10.0	8.5 - 10.7
T-2132, Bertrand et al. 1991	Fe <sub>28</sub> Mg <sub>73</sub>	Hc <sub>61</sub> Spl <sub>40</sub> Gah <sub>0</sub> xAl <sub>1.000</sub>	1025	940	8.0	8.3 - 10.2	7.5 - 9.5
315, Arima & Gower 1991	Fe11Mg89	Hc35Spl59Gah5 XAl0.977	887	783	7.0	8.7 - 10.5	8.0 - 9.9
354a, Arima & Gower 1991	Fe10Mg90	Hc35Spl30Gah34 XAl0.988	887	498	7.0	9.1 - 10.9	4.2 - 6.1
Atkin 1978	Fe46Mg54	Hc74Spl11Gah15 XAl0.926	725	602	2.6	3.0 - 4.1	1.2 - 2.3
K12C, Hollister 1982	Fe34Mg66	Hc76Sp118Gah6 XAl0.985	725	596	4.5	5.1 - 6.6	3.3 - 4.9
252, Lal et al. 1987	Fe21Mg79	Hc66Spl32Gah2 XAl0.962	760	591	6.5	7.0 - 8.8	4.9 - 6.9
258, Lal et al. 1987	Fe19Mg81	Hc61Spl439Gah0 XAl0.964	760	653	6.5	7.0 - 8.9	5.9 - 7.8
72045, Nichols & Berry 1991	Fe <sub>28</sub> Mg <sub>72</sub>	Hc51Spl34Gah15 XAl0.955	710	969	5.5	3.8 - 5.5	5.5 - 7.3
257, Norman & Clarke 1990	Fe21Mg79	Hc58Spl31Gah12 XAl0.977	750	640	5.3	6.2 - 7.9	4.9 - 6.6
704, Norman & Clarke 1990	Fe16Mg84	Hc59Spl31Gah10 XAl0.971	750	490	5.3	7.8 - 9.5	4.5 - 6.2
E2-2, Sengupta et al. 1991	Fe16Mg84	Hc49Spl44Gah6 XAl0.990	960	698	8.5	9.5 - 11.5	6.9 - 9.1
2, Stoddard 1979	Fe <sub>20</sub> Mg <sub>80</sub>	Hc53Spl29Gah19 XAl0.940	750	631	7.0	5.6 - 7.6	4.1 - 6.1

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2.5.11 Garnet-Cordierite Thermometry, FMAS 2 prp + 3 Fe-crd = 2 alm + 3 crd ...(2.25)

$$T = \frac{113116 + 630P}{(a_{\rm Grt}^{\rm alm})^2 (a_{\rm crd}^{\rm Mg-crd})^3} \dots (2.26)$$
  
-31.37 - Rln  $\frac{(a_{\rm Grt}^{\rm alm})^2 (a_{\rm crd}^{\rm Fe-crd})^3}{(a_{\rm Grt}^{\rm prp})^2 (a_{\rm crd}^{\rm Fe-crd})^3}$ 

2.5.11.1 Garnet-Cordierite Barometry, FAS  

$$2 \operatorname{alm} + 4 \operatorname{sil} + 5 \beta \operatorname{qtz} = 3 \operatorname{Fe-crd}$$
 ...(2.27)

$$P = \frac{-151416 + 182.85T - RT \ln \frac{(a_{\rm crd}^{\rm Fe-crd})^3}{(a_{\rm Grt}^{\rm alm})^2}}{15300} \dots (2.28)$$

2.5.11.2 Garnet-Cordierite Barometry, MAS  

$$2 \text{ prp} + 4 \text{ sil} + 5 \beta \text{qtz} = 3 \text{ crd}$$
 ...(2.29)

$$P = \frac{-38300 + 151.48T - RT \ln \frac{(a_{\rm crd}^{\rm Mg-crd})^3}{(a_{\rm Grt}^{\rm prp})^2}}{...(2.30)}$$

# 2.5.12 Application

The garnet-cordierite thermometer can be applied to the experimental compositions to estimate the degree of equilibrium; excluding the disequilibrium pairs the calculated temperatures have a  $1\sigma$  of  $\pm 50^{\circ}$ C. Excluding the experiments where the temperature estimate lies outside of the  $1\sigma$ , the calculated pressures are within  $\pm 1.4$  kbar of the run pressures (Table 2.9). The calculated pressures are not sensitive to the chosen equilibrium temperature however, and in all cases the calculated pressures are within  $\pm 1.5$  kbar. The majority of barometric calculations fit better than  $\pm 1$  kbar with many  $\leq 0.5$  kbar.

Run, Reference	Garnet	Cordierite	vapour	T (°C)	T <sub>calc</sub> (C)	P (kbar)	P <sub>calc</sub> (kbar) FAS	P <sub>calc</sub> (kbar) MAS
7-4. Aranovich & Podlesskii 1983	Alm90Prp10	Fc56Mg44	1120	700	663	4.0	4.3	3.9
7-5. Aranovich & Podlesskii 1983	Almg5Prp15	Fe45Mg55	л Н2О	700	666	5.0	4.9	4.6
7-6, Aranovich & Podlesskii 1983	Alm76Prp24	Fe31Mg69		700	650	6.0	5.9	5.5
7-8, Aranovich & Podlesskii 1983	Alm49Prp51	Fe11Mg89	H <sub>2</sub> O	700	596	8.0	8.1	7.2
75-5, Aranovich & Podlesskii 1983	Alm88Prp12	Fe56Mg44	H <sub>2</sub> O	750	745	5.0	4.9	4.9
75-8, Aranovich & Podlesskii 1983	Alm56Prp44	Fe17Mg83	H <sub>2</sub> O	750	681	8.0	7.9	7.3
T-1256, Bertrand et al. 1991	Alm29Prp71	Fe9Mg91	H <sub>2</sub> O	900	868	10.0	10.4	10.2
T-1138, Bertrand et al. 1991	Alm27Prp73	Fe14Mg86	H <sub>2</sub> O	900	1293	10.0	8.5	10.5
T-1138, Bertrand <i>et al.</i> 1991	Alm29Prp71	Fe14Mg86	II2O	900	1195	10.0	8.8	10.4
T-890, Bertrand et al. 1991	Alm42Prp58	Fe16Mg84	H2O / CO2	900	925	11.0	9.7	9.8
T-1287, Bertrand et al. 1991	Alm43Prp57	Fe21Mg79	1120	1000	1128	10.0	10.0	10.7
T-878, Bertrand et al. 1991	Alm46Prp54	Fe21Mg79	H <sub>2</sub> O / CO <sub>2</sub>	1000	1036	10.0	10.3	10.5
T-970, Bertrand et al. 1991	Alm45Prp55	Fe20Mg80	CO <sub>2</sub>	1000	1020	10.0	10.4	10.5
T-1267, Bertrand et al. 1991	Alm41Prp59	Fe18Mg82	CO2	1000	1041	10.0	10.4	10.7
T-1288, Bertrand et al. 1991	Alm43Prp57	Fe17Mg83	CO2	1000	939	10.0	10.9	10.5
T-988, Bertrand et al. 1991	Alm32Prp68	Fe13Mg87	H <sub>2</sub> O	1000	1049	11.0	10.9	11.2
T-977, Bertrand et al. 1991	Alm41Prp59	Fe16Mg84	CO2	1000	950	11.0	11.0	10.7
T-985, Bertrand et al. 1991	Alm35Prp65	Fe14Mg86	CO2	1000	1014	11.0	10.9	11.0
T-1008, Bertrand <i>et al.</i> 1991	Alm31Prp69	Fe11Mg89	H <sub>2</sub> O	1000	956	12.0	11.5	11.2
T-2101, Bertrand et al. 1991	Alm47Prp53	Fe20Mg80	H2O	1025	966	10.0	10.9	10.6
T-2150, Bertrand <i>et al.</i> 1991	Alm42Prp58	Fe14Mg86	H <sub>2</sub> O	1025	815	11.0	12.2	10.7
T-1290, Bertrand <i>et al.</i> 1991	Alm45Prp55	Fe21Mg79	1120	1050	1065	10.0	10.9	11.0
1884, Hensen & Green 1971	Alm48Prp46Gr6	Fe20Mg80		1000	918	8.1	8.9	8.4
2395, Hensen & Green 1971	Alm37Prp57Gr6	Fe11Mg89		1000	805	9.3	10.3	8.8
2459, Hensen & Green 1971	Alm48Prp46Gr6	Fe19Mg81	·	900	889	9.0	7.6	7.5
1952, Hensen & Green 1971	Alm72Prp23Gr5	Fe48Mg52		950	1042	7.2	6.4	6.9
D1, Hensen 1977	Alm39Prp59Gr1	Fe18Mg82		1000	1056	9.0	8.8	9.1

Table 2.10 lists the results of the thermometer and barometers and compares the results with the thermometers of Thompson (1976) and Bhattacharya *et al.* (1988). Bhattacharya *et al.*'s calibration appears relatively insensitive to temperature variation compared with Thompson's and this thermometer, with its calculated temperatures consistently too low by 100-240°C at the high temperature end of the experimental data. The new calibration produces 11 close approximations of the reported temperatures for these specimens, compared with 9 good estimates using Bhattacharya *et al.* 's (1988) calibration, and only 2 with Thompson's (1976) thermometer.

The barometric values are separated into the Fe and Mg systems with respective anhydrous and hydrous pressures. The garnet-cordierite barometers provide a sensitive estimate of equilibration pressure, but are necessarily dependent upon correctly deducing water activities.

## 2.6 Discussion

Zinc exerts a significant stabilizing influence on spinel-bearing assemblages. This effect is quantified in terms of the increase of zinc in Fe-Mg aluminous spinels, in equilibrium with garnet, with increasing pressure and decreasing temperature. The compositions of the experiments were closely matched with the Mg N<sup> $\circ$ </sup> of many natural pelites, providing better accuracy in the formulation of activity models in this system, where projections from pure phase data alone were poorly constrained.

The garnet-spinel barometers are consistent with pressure estimates from other barometric calibrations based on spinel-absent equilibria. They provide additional constraints on the conditions of equilibration of assemblages containing zinc. The formulations involving cordierite produce similar P and T to other calibrations; the thermometer derived here, more accurately reflects the temperature range of samples than a recent calibration of Bhattacharya *et al.*(1988), and reproduces independently derived temperatures more accurately than the Thompson (1976) thermometer. The thermometers and barometers presented here, when carefully applied to coronas and symplectitic reaction textures, improve the resolution and interpretation of the tectonic processes affecting granulite facies terranes.

It is suggested (1) a delineation of zinc concentration in spinels and garnets when analysing these minerals in meta-pelitic assemblages and (2) that improvements in the purephase data of the MAS system would improve extrapolation of these geobarometers to more magnesian compositions. The present formulation should be applied with care in very magnesian compositions.

Specimen №, Reference	Garnet	Cordierite	T ( °C )	T T. ℃)	T B. (℃)	T calc ( ${\mathfrak C}$ )	P (kbar)	P <sub>calc</sub> (kbar)	P <sub>calc</sub> (kbar)
								FAS - FASH	MAS - MASH
Atkin 1978	Alm74Prp16Sp5Gr5	Fe11Mg89	725	679	762	770	2.6	3.6 - 4.3	4.0 - 4.8
S <sup>th</sup> India 104, Bhattacharya <i>et al</i> .1988	Alm64Prp33Sp1Gr2	Fe24Mg76	710	758(31)	756(9)	707(34)	6.0	5.0 - 6.3	4.9 - 6.2
Scotland 105765, Bhattacharya et al. 1988	Alm74Prp16Sp5Gr5	Fe31Mg69	710	764(31)	764(9)	735(63)	5.5	4.2 - 5.4	4.2 - 5.4
Scotland 99376, Bhattacharya et al. 1988	Alm75Prp15Sp5Gr4	Fe50Mg50	800	838(25)	795(18)	802(28)	5.5	4.4 - 5.5	4.5 - 5.7
Inari 194.III, Bhattacharya <i>et al</i> .1988	Alm63Prp32Sp1Gr3	Fe27Mg73	760	804(89)	778(36)	744(70)	5.0	5.3 - 6.4	5.4 - 6.6
Nain 2-893, Bhattacharya <i>et al.</i> 1988	Alm77Prp19Sp2Gr3	Fe44Mg56	760	809(92)	778(48)	763(90)	3.5	4.4 - 5.2	4.5 - 5.4
D56, Currie 1971	Alm69Prp26Gr5	Fe31Mg69	716	670	778	744	6.4	4.4 - 5.7	4.6 - 6.0
69-6, Currie 1971	Alm6()Prp36Gr4	Fe23Mg77	717	696	777	753	6.5	5.0 - 6.2	5.3 - 6.5
69-29, Currie 1971	Alm58Prp38Gr4	Fe20Mg80	732	673	755	723	6.7	5.5 - 6.8	5.5 - 6.7
49753, Harley 1986	Alm50Prp45Sp1Gr3	Fe9Mg91	680 - 530	531	604	528	8.5	11.3 - 12.7	7.2 - 8.7
BB13b, Harris & Holland 1984	Alm63Prp33Sp1Gr3	Fe19Mg81	670	585	692	598	4.5	5.1 - 6.2	4.4 - 5.6
BB20a rim, Harris & Holland 1984	Alm61Prp35Sp1Gr3	Fe17Mg83	670	577	679	589	4.5	5.3 - 6.4	4.6 - 5.7
BB20b rim, Harris & Holland 1984	Alm61Prp36Sp1Gr3	Fe20Mg80	670	636	718	655	4.5	4.8 - 5.9	4.7 - 5.9
K12C, Hollister 1982	Alm79Prp16Sp1Gr3	Fe44Mg56	725	658	726	711	4.5	4.0 - 5.0	3.8 - 4.9
B-2-2 252, Lal et al. 1987	Alm54Prp41Sp2Gr2	Fe21Mg79	760	735	782	784	5.0	5.7 - 6.8	5.9 - 7.0
C-1 259, Lal et al. 1987	Alm47Prp49Sp2Gr2	Fe16Mg84	760	715	735	751	5.0	6.2 - 7.3	6.2 - 7.4
72045, Nichols & Berry 1991	Alm59Prp37Sp2Gr2	Fe28Mg72	690	650	733	678	5.0	5.0 - 6.2	4.9 - 6.1
257, Norman & Clarke 1990	Alm67Prp30Sp2Gr1	Fe22Mg79	750	594	702	594	5.3	6.2 - 7.3	4.8 - 6.0
704, Norman & Clarke 1990	Alm65Prp34Sp1Gr1	Fe16Mg85	750	532	643	518	5.3	7.1 - 8.3	4.9 - 6.0
2, Stoddard 1975	Alm60 <sup>p</sup> rp36Sp3Gr1	Fe24Mg76	750	722	792	762	7.0	5.5 - 6.8	5.5 - 6.9

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## 2.6.1 Implications for petrogenetic grids

Considerable discussion has arisen regarding the construction of petrogenetic grids in the FMAS system, succinctly summarized by Sengupta *et al.* (1991). The debate is centred around the correct depiction of the stable invariant points. Hensen (1971) maintained that the invariant points [sa], [grt], & [crd] are metastable, but in answer to the criticisms of Vielzeuf (1983), he (Hensen 1986) suggested that at higher  $f_{O2}$ , these metastable invariant points invert becoming stable as the spinel fields enlarge with the incorporation of Fe<sup>3+</sup>. Sengupta *et al.* (1991) argue however, that the studies of Ellis *et al.* (1980) and Harley (1986) suggest that the bulk rock Fe-Mg ratio, and the presence of ZnO, have larger effects on the stability of these invariant points, than the equilibrium  $f_{O2}$  conditions. I suggest that these effects are relative, dependent on the abundance of ZnO and its availability to newly forming assemblages of spinel, and possible  $f_{O2}$  variations along the *P-T* trajectory.

The experimental modelling of garnet-spinel relationships (Figs. 2.6a, b & c) show the importance of considering the Fe-Mg partitioning, and validate the recent theoretical assertions of Sengupta *et al.* (1991), that  $spl_{Mg} > grt_{Mg}$  in magnesian compositions and at high pressures. For comparison the garnet-spinel field, calculated for an  $X_{Zn}$  of 0.05, is projected onto the FMAS plane (Fig. 2.6c) to demonstrate that the garnet-spinel field is stabilized to higher pressures, and for anhydrous systems at these higher pressures, cordierite will not coexist with garnet. However, for hydrous cordierite (Fig. 2.6b) the garnet-cordierite and spinel-cordierite fields are enlarged, so the garnet-spinel field  $(X_{Zn}=0.05)$  is terminated at more Fe-rich bulk-rock compositions.

The arguments discussed above demonstrate the extreme difficulty in projecting from simple system phase diagrams into natural rock compositions. The relative effects of Zn,  $Fe^{3+}$  and Cr vastly increase the spinel stability field over much of the simple system mineralogy. The recognition of invariant points in multi-component systems (7 and larger) requires more information about the stabilizing behaviour of minor components on individual phases, and their resultant inter-relationships.

2.7 Summary

The equilibrium

$$(Mg,Fe,Zn)_3Al_2Si_3O_{12} + 2 Al_2SiO_5 = 3 (Mg,Fe,Zn)Al_2O_4 + 5 SiO_2$$
  
grt + sil / ky = spl + qtz

was calibrated in the piston-cylinder apparatus between 11 and 30 kbar, and over the temperature range of 950 to 1200°C. Three experimental mixes of Mg N<sup> $\circ$ </sup> 40, 47 and 60, in

the FeO-MgO-Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub>-ZnO (FMASZn) system were used under low oxygen fugacities and anhydrous conditions. A ternary Fe-Mg-Zn symmetric mixing model is derived for aluminous spinels in equilibrium with garnet, to quantify the increase in gahnitic endmember of spinel with increasing pressure and decreasing temperature.

Further experiments in the spinel-cordierite-quartz-sillimanite field were combined with garnet-cordierite data from the literature to produce a consistent set of equations describing the exchange reactions in FMASHZn relevant to quartz-sillimanite bearing rocks at granulite facies conditions.

As spinel is an important mineral participating in many rocks of aluminous composition at granulite facies conditions, and as zinc contributes to an enlargement of spinel's stability field towards higher pressures and lower temperatures, the thermobarometric calibrations presented here will be most significant in delineating the prograde and retrograde trajectory of P-T paths.

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# Chapter 3

# THE DEFORMATIONAL HISTORY OF THE LAMBERT GLACIER REGION, EAST ANTARCTICA

#### PART I

### THE STRUCTURE OF THE REINBOLT HILLS

# 3.1 Introduction

A series of nunataks and hills, along the eastern margin of the Lambert Glacier, East Antarctica, include the Reinbolt Hills, Jennings Promontory and McKaskle Hills (Fig. 3.1). The largest of these Late Proterozoic (Grew & Manton 1977) basement exposures, the Reinbolt Hills (approximately 10 by 7.5 km) is composed predominantly of felsic, mafic granulites and a deformed charnockite. At Jennings Promontory, 30 km to the north, a relatively undeformed charnockite is exposed over an area of approximately 6 by 1.5 km. McKaskle Hills, 23 km further north and midway between the Reinbolt Hills and Prydz Bay, contains felsic and mafic granulites. These rocks are part of the extensive Late Proterozoic granulite province of East Antarctica, which crop out in Enderby Land (Rayner Complex), Prince Charles Mountains, Prydz Bay-Vestfold Hills (Rauer Group), Bunger Hills and the Windmill Islands (James & Tingey 1983). This belt includes Archaean cratonic blocks that are exposed to the east in the Vestfold Hills (Oliver *et al.* 1982) to the west in Enderby Land (Sheraton *et al.* 1980) and to the south-west in the southern Prince Charles Mountains (Tingey 1982).

The difficulty of undertaking field work and access, to Antarctica, favours detailed laboratory based petrological, geochemical and geochronological investigations, in contrast to field based structural studies. A notable exception being the work of Clarke (1988) on the structural evolution of both the Rayner Complex and older Archaean lithologies, west of Mawson. The Reinbolt Hills region lies  $\approx$ 500 km to the southeast of the areas reported by Clarke (1988) and midway between the Archaean cratonic terranes of the Vestfold Hills and the southern Prince Charles Mountains. This structural appraisal of the Reinbolts Hills is thus important in providing both a better understanding of the structure and of the possible crustal processes involved in the evolution of East Antarctica.

#### 3.1.1 Gneissic lithologies

The Reinbolt Hills' gneissic lithologies are dominated by felsic rocks, significant proportions of mafic gneisses, and subordinate volumes of pelitic, calc-silicate, ultra-mafic, and garnetiferous felsic gneisses. All gneissic rocks from this locality preserve granulite facies assemblages; the most diagnostic assemblages are Grt-Opx-Pl-Qtz bearing felsic assemblages, Grt-Sil-Spl-Crd-Bt-Rt-Ilm-Pl-Kfs-Qtz metapelitic rocks, and Cpx-Opx-Bt-Pl



Figure 3.1 Location map of the Reinbolt Hills, McKaskle Hills, Jennings Promontory, and Prince Charles Mountains, regions which are part of the Late Proterozoic Rayner Complex, relative to the three Archaean cratonic terranes, the Vestfold Hills, Enderby Land and southern Prince Charles Mountains. mafic assemblages. The methods, and derived peak as well as retrograde pressures and temperatures from these rocks are discussed in Chapter 4.

#### 3.1.2 Intrusive lithologies

#### 3.1.2.1 Meta-basaltic dykes

Only one example of a meta-basaltic dyke crops out in the Reinbolt Hills. The dyke has an outcrop width of 3 m and is poorly exposed along strike. It has dominantly a granoblastic texture and a weak foliation defined by Phl and Opx striking parallel to the dyke and most evident near its margins. The meta-basaltic dyke is composed of Opx-Phl-Hbl-Pl-Qtz and minor Ilm. Grain size varies between <0.5 to 2 mm. The encompassing foliation of the felsic gneisses, into which the dyke intruded, is clearly truncated, however the dyke contains a metamorphosed assemblage, and therefore emplacement is constrained to have post-dated  $D_1$  and  $D_2$ , but before the cessation of the third deformation.

## 3.1.2.2 Pegmatites

Pegmatites, containing coarse grained K-feldspar phenocrysts (usually  $\approx 2$  cm, but up to 3 cm long), occur in all lithologies of the Reinbolt and McKaskle Hills. However, pegmatites are common in the Reinbolt Charnockite, where they characteristically contain opalescent and frequently strained, partially rounded, K-feldspars. Zircons extracted from a Reinbolt Hills' pegmatite, have been dated by U-Pb methods at  $\approx 895$  Ma by Grew & Manton (1977); Th-Pb ages are however, discordant and calculated values of 1316-1793 Ma, are interpreted by these authors, to result from thorium loss after pegmatitic crystallization.

Cross-cutting relationships exhibited by the pegmatites in the post- $D_2$ , Reinbolt Charnockite, imply a intrusion succeeding the emplacement of the charnockite. Shearing is associated with some pegmatites in the Reinbolts Charnockite, similarly, fine grained pegmatites from the McKaskle Hills, and Jennings Promontory, commonly have mylonitic margins. The progressive grain-size reduction adjacent to the mylonitic margins of pegmatites from the McKaskle Hills, and the reorientation of the charnockitic fabric in the Reinbolt Hills (Fig. 3.2a & b), implies that shearing preferentially oriented along the pegmatites, has occurred since their emplacement.

Pegmatitic emplacement is therefore interpreted to be related to the fourth deformation, and the U-Pb age of 895 Ma, possibly dates this deformational episode.

#### 3.1.2.3 The Jennings Promontory Granitoid

Within the generally undeformed Jennings Promontory Charnockite, a 10 by 25 metre wide granitic to pegmatitic body crops out. The relative age of the charnockite is constrained to be



older than the shallow mylonites which truncate it (Nichols & Berry 1991): however the K-Ar whole-rock value of 405 Ma reported by Stuiver & Braziunas (1985), is not regarded here to represent time of crystallization, but rather some later cooling age.

The granitoid's major mineralogy is Opx-Pl-Kfs-Qtz-Bt, and is particularly interesting because it preserves a sub-horizontal graded layering of biotite and fine grained orthopyroxene. The better preserved layers grade from very Bt and Opx-rich to almost Bt and Opx-absent, over distances of 3-5 cm (Fig. 3.2c & d). The mineralogical grading is not dependent on the crystal sizes, but is entirely a modal grading. In other areas of the body, similar horizons, only retain concentrations of biotite in layers of  $\approx 0.5$  cm thicknesses, without discernible grading. Extremely coarse grained orthopyroxene crystals, up to 70 cm long, although more usually 15-20 cm, are frequently oriented sub-perpendicular to, and pierce the graded layering (Fig. 3.2e); other coarse Opx crystals lie sub-parallel to the layering and display many mineralogical features, on tens of centimetre scales, such as crystal rosettes and twinning (Fig 3.2f & g), usually observed on microscopic scales. Immediately adjacent to the coarse-grained orthopyroxenes, where they pass through the Opx-rich zones of the graded layering, the horizons are depleted of Bt and fine grained Opx, for a distance of 0.5-1.0 cm (Fig. 3.2e). Many of the coarse Opx crystals have hollowed centres or skeletal textures, now containing Pl-Kfs and Qtz (Fig. 3.2h).

#### 3.1.2.3.1 Genetic interpretation

These features are interpreted to result from a chamber situated within a slowly cooling, and possibly weakly convecting charnockitic magma body. The chamber was probably periodically filled by granitic magma, from a deeper source, possibly containing slightly higher abundances of dissolved fluids (H<sub>2</sub>O, CO<sub>2</sub>, Cl<sup>-</sup> & F<sup>-</sup>), although the relatively low abundance of biotite, implies that water did not make up a significant proportion of the total dissolved volatiles. An alternative proposed by Irvine (1987) to explain the formation of graded magmatic layering, describes the separation of an originally homogeneous volume of magma into distinct layers, as discrete convection cells are established, which are controlled by temperature differentials in the cooling melt.

The hollowed centres of the preserved orthopyroxenes may have formed by at least two processes, both of which elucidate the processes occurring within the chamber itself. If the centres of the Opx megacrysts were derived from a deeper source (that is, either as Opx crystals of different composition, or xenocrysts of a different mineral), and underwent resorption and resultant growth of the crystal margins, within the chamber, relatively slow crystallization times could be expected. However, the megacrysts have sharp inner and outer boundaries, features not compatible with resorption which normally produces rounded margins (Swanson *et al.* 1989). In contrast, if the hollowed or skeletal textures which are usually interpreted to demonstrate rapid crystal growth (e.g. Lofgren 1974, Donaldson 1976), represent rapid quenching, such crystal magnitudes would not normally be expected to have formed. These conflicting arguments can not be fully resolved here, however, observations of the crystal forms, and their juxtapositions do provide an indication of their formation processes. It appears unlikely that such large and delicate skeletal-crystals would have survived transportation by a magma, and the sharp inner and outer crystal-margins do not support the idea of resorption of previously derived crystals. The radiating crystal rosettes (Figs. 3.2f & g), as well as narrow zones of mafic-depletion surrounding the megacrysts, are both features supporting the favoured interpretation, that nucleation and crystal growth occurred in situ, probably in an environment slightly more volatile-rich than the enclosing charnockitic magma.

Successive injections of magma, with essentially similar compositions, were intervened by periods during which convection, and crystal settling occurred (cf. Sørensen & Larsen 1987). The displacement of the graded magmatic layering, at the margins of the Opx megacrysts, may have been caused by a reduction in the volume of successive layers, caused by melt extraction enhanced by compaction (cf. Parsons & Becker 1987). Diffusion of the mafic components from the graded layers into the Opx megacrysts (cf. Woodland 1963), effectively depleted the narrow zones immediately adjacent to these crystals, during their growth.

The in-situ graded magmatic layering in the pegmatite, provides further evidence that the Jennings Promontory Charnockite post-dates both the high-strain, pervasive deformation which produced the dominant gneissic layering, as well as the deformation which produced the alignment of K-feldspars in the post-D<sub>2</sub> Reinbolt Charnockite. Although magmatic layering is not necessarily horizontal, the fact that the graded layering is now horizontal, and preserves correct way-up indicators, strongly supports the interpretation that the Jennings Promontory Charnockite has not been re-orientated significantly since its emplacement.

#### 3.1.2.4 Adamellite emplacement

The three small islands, Landing Bluff, Nickols and Sansom Islands, on the eastern margin of the Amery Ice Shelf (Fig. 3.1) are composed entirely of very coarse grained, massive adamellite. Coarse, poikilitic, zoned K-feldspars are prevalent while the mafic phases include garnet, biotite and dark-green ferropargasite (Sheraton & Black 1988). A total-rock Rb-Sr isochron of 493±17 Ma (Tingey 1981) and a U-Pb zircon age of 500 Ma (L.P. Black unpubl. data) indicate an early Palaeozoic emplacement age, post-dating and unrelated to the Proterozoic granulite facies metamorphism (Sheraton & Black 1988). Stüwe & Powell

(1989) interpret a causal relationship between the final excavation of the Pyrdz Bay granulites, and an under-accretionary event producing these A-type, 500 Ma granitoids exposed as the Landing Bluff, Nickols and Sansom Islands.

An approximately 3 m thick adamellite sill crops out on the southeastern margin of McKaskle Hills. The sill exhibits unequivocal cross-cutting relationships with the granulites into which it intrudes, and preserves  $\approx$ 50 cm wide magmatic channels, eroded into its magmatic layering, indicating it has not been significantly deformed and remains in its emplaced orientation. Although undated, based on the intrusive relationships with the Proterozoic gneisses, and its mineralogy, the sill may be a temporal correlative of the adamellites on the northeastern margin of the Amery Ice Shelf. No structural features were recognised associated with this early Palaeozoic phase of magmatism.

#### 3.2 Deformational history

#### 3.2.1 Macroscopic structure

Five major deformational episodes have been recognized in the granulite-facies rocks of the Reinbolt Hills. Macroscopic layering which is parallel to the earliest recognizable foliation  $S_1$ , strikes east-west, dips southerly (Fig. 3.3a) and is folded by large reclined isoclinal ( $F_2$ ) folds. These isoclines are re-folded about northeasterly, southwesterly striking axial planes of tight  $F_3$  folds (Appendix 1). Post- $D_2$  faults truncate lithologies and most trend sub-parallel or parallel to the axial planes of  $F_3$  folds.

Charnockites in the southern Reinbolt Hills and Jennings Promontory were intruded at different stages in the deformational history suggesting protracted magma generation and emplacement. The Reinbolt Charnockite, which has a disconformable, probably faulted, contact with the layered granulites to the north, displays a well developed foliation subparallel to S<sub>2</sub> that is gently folded by F<sub>3</sub> folds. This together with evidence of strongly foliated, granulite facies xenoliths aligned sub-parallel to S<sub>2</sub> within the Reinbolt Charnockite, suggests emplacement either during or post-D<sub>2</sub>.

The Jennings Promontory Charnockite is coarser grained than the Reinbolt Charnockite and is characteristically unfoliated, although in places has a very weak magmatic(?) foliation defined by sub-parallel elongate feldspar megacrysts. In northern exposures, closer to the interpreted faulted contact with the granulites, gneissic xenoliths are more common, and their foliation often sub-parallels the weak foliation of the charnockite. Due to the charnockite's overall massive texture relative timing of emplacement is interpreted to be post  $D_3$ .



A summary of the deformational history and major phases of magmatism of the Reinbolt Hills, Jennings Promontory, McKaskle Hills and Landing Bluff region is presented in column two of Table 3.1.

# 3.2.2 The first deformation, $D_1$

The prominent compositional and gneissic layering  $S_1$ , varying from metre to kilometre scales, is the oldest recognizable structural feature occurring in the granulites of the Reinbolt Hills. The rocks exhibit many features of pervasive high-strain deformation (described below), and therefore early fabrics, and their formation, cannot be easily separated from later gneissosity and fold-forming episodes. As described below in further detail, the gneissic layering is essentially a composite fabric, including elements of possible progenitor layering, as well as  $S_1$ ,  $S_2$  and  $S_3$ . The macroscopic,  $S_1$ , southerly dipping gneissic interlayering (Fig. 3.3a) of mafic and felsic granulites that have layer-parallel clinopyroxene, orthopyroxene, phlogopite, garnet and quartz, is commensurate with granulite facies metamorphism, during  $D_1$  deformation.

First generation folds are difficult to distinguish from the more pervasive second and third generation folds, either by fold-style, or by fold orientation. However,  $F_1$  folds usually display attenuation of limbs which are difficult to trace within the foliation: hinge zones are usually so tightly folded that individual limbs are not separable for some distance away from the closure (e.g. Fig. 3.4b). Probable isoclinal,  $F_1$  fold closures can be seen in Figure 3.4 a & b.

The first, second and probably the early phase of the third deformational episode occurred during high strains which successively transposed earlier fabrics. The original orientation of  $F_1$  folds is thus undetermined. Since second and third generation folds progressively steepened the dip of the gneissic layering, which now has a moderate dip, it is plausible that  $F_1$  folds were originally reclined or recumbent.

The gneissic- $S_1$  layering from the northern nunataks of the McKaskle Hills, has a similar strike to that in the Reinbolt Hills, but dips more shallowly southeast and at the southern cliff exposures is sub-horizontal (Fig. 3.5a & 3.4f).

# 3.2.3 The second deformation, $D_2$

Folding the compositional layering are isoclinal, intrafolial folds characterized by an axialplane parallel texture,  $S_2$ , of elongate 2-5 mm quartz rods and elongate aggregates within an orthoclase-rich groundmass (Fig. 3.3b). This strong gneissic texture and associated axialplane parallel alignment of phlogopite, orthopyroxene and weakly elongate garnet and quartz, supports the contention that the second deformational episode also occurred



synchronously with granulite facies conditions.  $S_2$  is frequently sub-parallel to the compositional layering, however, this is dependent on the original orientation of  $S_1$ .

 $F_2$  isoclinal folds re-fold intrafolial isoclines which have a similar fabric (Fig. 3.4a & b), suggesting continual fold generation and deformation from  $D_1$  to  $D_2$ .  $F_2$  folds transpose the gneissic layering,  $S_1$ , thus obscuring any orientational distinction between  $S_1$  and  $S_2$  (Fig. 3.3a & b).

The limited number of folds exposed at McKaskle Hills have a well developed axial planar fabric comparable with the texture of the  $S_2$  defined in  $F_2$  folds from the Reinbolt Hills (Fig. 3.4d & e). The McKaskle Hills folds are also similar in style to the Reinbolt's  $F_2$  folds having tight hinge zones and a predisposition towards attenuated limbs (Fig. 3.4d & e). However folds from the McKaskle Hills plunge shallowly east or west whereas all folds in the Reinbolt Hills plunge steeply in southerly directions (*cf.* Fig. 3.5b & Fig. 3.3d & e). Large-scale reclined to recumbent isoclinal folds exposed at the southern end of McKaskle Hills (Fig. 3.4f), are interpreted on the basis of their style and orientation to be  $F_2$  folds. Measurements on the limited number of mesoscopic of  $F_2$  folds observed in the McKaskle Hills, confirm that this deformational episode produced characteristically reclined folds, apparently similar to the  $F_2$  folds described by Clarke (1988) for areas west of Mawson. Strain accompanying the D3 event in the McKaskle hills was possibly less significantly than that experienced in the Reinbolt Hills. Alternatively, the McKaskle Hills region lies in the hinge zone of a large-scale third generation fold, and therefore structures were effectively unrotated from their D<sub>2</sub> orientations.

#### 3.2.4 The third deformation, $D_3$

Macroscopic warping or gentle re-folding of  $F_2$  is conspicuous in the Reinbolt Hills (Appendix 1), however mesoscopic fold interference is not as common.  $F_3$  folds in the Reinbolt Hills, (Fig. 3.4a & g) display a larger variation in plunge direction than  $F_2$  folds, but overall have similar orientations to  $F_2$  (Fig. 3.3e), suggesting that  $F_3$  may represent a culminating attitude in a continuum of fold orientations, from  $F_2$ . This interpretation is further supported by the relatively weak or absent axial plane parallel fabric of  $F_3$  folds, implying a decrease in the intensity of deformation from  $D_2$  through to  $D_3$ . Two conceptually disparate models have been previously applied to explain similar observations of continuums in deformational orientations. The alternative hypotheses are, one of discrete deformational events reflecting different strain orientations (e.g. Ramsay 1967), and the other of rotational and progressive deformation, during which the overall stress regime is constant, but where fold structures nucleate at local stress perturbations, and then rotate into parallelism with the stretching direction (e.g. Flinn 1962, Etchecopar 1977, Goscombe



Figure 3.5 Lower hemisphere, equal-area, stereographic projections of structural measurements from the McKaskle Hills. (a) 8 poles to composite gneissic layering, (S<sub>1</sub>+S<sub>2</sub>+S<sub>3</sub>), (b) 4 poles of F<sub>2</sub> style folds and two great circle projections of axial planes, & (c) 3 great circle projections of mylonite planes from the McKaskle Hills (solid) and 2 mylonites from Jennings Promontory (dashed), with consistent easterly shear orientations.

1991). However, these models can not be discriminated between, using fold-orientation evidence alone. The progressive and rotational model is favoured, and is discussed below.

## 3.2.5 Mineral lineations

Mineral lineations of elongate pyroxenes, hornblende, phlogopite as well as extended aggregates of quartz and garnet, are interpreted to have been produced by tectonic stretching, and indicate its direction, during granulite facies metamorphism. These lineations, which lie within the plane of the gneissosity, trend sub-parallel to  $F_2$  and  $F_3$  fold axes (*cf.* Figs. 3.3d, 3e & 3f), and plunge moderately to the south. The relationship of sub-parallel fold axes and lineations is interpreted to result from rotational strain, directed in an orientation indicated by the mineral lineations (Hudleston 1986), during progressive D<sub>1</sub>, D<sub>2</sub> and D<sub>3</sub>, deformation. The mineral lineations which retain orientations indistinguishable from F<sub>2</sub> and F<sub>3</sub> fold axes, are therefore termed L<sub>2-3</sub>.

# 3.2.6 The fourth deformation $D_4$ : Mylonites

Narrow mylonite zones in the Reinbolt Charnockite have a maximum width of 10-15 cm and are laterally continuous over 10-20 metres. They have a microgranular, black, siliceous, phacoidal texture with relic quartzo-feldspathic augen up to one centimetre in diameter. The mylonite zones strike ENE-WSW, sub-parallel to the megacrystic foliation within the charnockite and the gneissosity of the fault bounded granulites to the north, and have lineations plunging E and SSE (Fig. 3.3g).

Mylonites are juxtaposed with aplitic dykes at the northern end of Jennings Promontory, and sub-parallel the weak magmatic foliation of this post-D<sub>3</sub> charnockite. In contrast the 2-3 cm wide mylonites at McKaskle Hills, occur as margins to aplitic dykes which cross-cut the gneissosity and compositional layering. The McKaskle Hills mylonites have porphyroclasts with sigmoidal trails of brown and green fine-grained biotite, conveying a reverse sense of shear, and are interpreted to indicate a transport direction toward 100° (Fig. 3.4h[I]). Mylonites from Jennings Promontory have similar shear indicators with sigmoidal phlogopite around orthoclase and garnet, suggesting reverse shear (left lateral) toward 067° (Fig. 3.4h[II]). Mineralogies of biotite and chlorite surrounding the porphyroclasts indicate lower temperatures and possibly lower pressures at the time of mylonite formation. Further, the mylonitization of aplitic dykes which truncate S<sub>2</sub> and S<sub>3</sub>, indicate post-D<sub>3</sub> mylonitization.

Mylonites produced during  $D_4$ , along the eastern margin of the Lambert Glacier, have consistent orientations and congruous shear directions of north-west block over south-east;

this configuration is not consistent with a conjugate shear orientation to the mylonites reported by Clarke (1988), which have a south over north block movement.

# 3.2.7 The fifth deformation, $D_5$

The last recognised deformation produced a locally penetrative spaced cleavage with domain intervals of 10-20 cm and is prominent in weathered homogeneous mafic-rich lithologies where it produces a distinctive rubbly outcrop. The disjunctive cleavage was not identified in McKaskle Hills lithologies, and is apparently restricted to the Reinbolt Hills with only infrequent occurrences at Jennings Promontory. The upright spaced-cleavage dips steeply northwest but has variable orientations with an average strike NNE SSW (Fig. 3.3h). This feature is dominantly a fracture surface and is not defined by an alignment of any mineral fabric, or the growth of new minerals, and therefore is probably a result of brittle deformation. It is suggested that the similar orientation of this fabric with the longitudinal Lambert and Radock Lake (eastern PCM) Grabens, may indicate their coeval formation, under the influence of an east-west directed, extensional stress regime. The Radock Lake Graben, its inferred correlative in eastern India the Son-Mahanadi Graben (Webb & Fielding 1992), and probably the Lambert Graben are filled with Permian-Triassic aged sediments (Fielding & Webb, 1992). East-west oriented extension therefore pre-dates the earliest dated Late-Permian aged sediments filling the Antarctic grabens, and based on apatite-fission track analysis, was probably initiated in the Late Carboniferous (Arne 1992).

# 3.3 Timing of metamorphism with respect to deformation

The granulites from the Reinbolt Hills preserve a segment of a decompressional *P*-*T* path which passes from 800°C & 7 kbar, to 690°C & 5 kbar, described by Nichols & Berry (1991), and in Chapter 4. These conditions are derived from the mineral chemistry of mafic, felsic and calc-silicate granulites combined with reaction grids constructed for these metapelites with disequilibrium reaction textures. These include the formation of (a) cordierite from garnet, (b) symplectitic intergrowths of spinel and cordierite from garnet and sillimanite, and (c) the reaction products ilmenite and sillimanite from garnet reacting with rutile. Calc-silicate lithologies preserve reaction textures of scapolite retrogressing to calcite and anorthitic plagioclase. Mineral compositions for this thermometric reaction provide evidence of metamorphic temperatures  $\geq 790^{\circ}C$ .

The metamorphic evolution of the McKaskle Hills is described in Chapter 5; the shape of the preserved P-T segment is similar to that interpreted for Reinbolt Hills rocks, however slightly higher peak and retrograde conditions are estimated from geothermobarometry, and from Opx + Spl + Mag + Pl intergrowths, breakdown products of andraditic-garnet. The metamorphic peak is inferred to have outlasted all major high strain deformation in the Reinbolt Hills and McKaskle Hills region. This interpretation is supported by the recrystallized nature of all fabrics except the later  $D_4$  mylonites, the lack of undulose extinction in either feldspars or quartz, rare kinking in biotite, and the preservation of delicate spinel-cordierite and orthopyroxene-spinel-plagioclase symplectites which formed during retrograde decompression after high strain deformation.

#### 3.4 Summary

The regional correlations of deformational episodes of the eastern Lambert Glacier Region with areas further east, the Larsemann Hills, the Brattstrand Bluffs, the Rauer Islands, and westward regions, the Prince Charles Mountains, and areas west of Mawson, are discussed at the end of Part II of this chapter.

In summary, the deformational evolution of the Reinbolt Hills and McKaskle Hills regions appear comparable. The orientation of the gneissosity in the McKaskle Hills is similar to that in the Reinbolt Hills, although strikes slightly more towards the northeast-southwest, and dips in southerly areas, more shallowly. Fold styles and orientations of axial planes are similar in both areas, however, in the McKaskle Hills fold axes plunge shallowly east and west, suggestive of re-folding about a north-south striking later fold generation. In comparison,  $F_2$  and  $F_3$  fold axes in the Reinbolt Hills plunge with consistent orientations, from the southwest to the south. The preserved deformational features, their superposition, and inferred relative timing, are consistent in both areas.
# PART II

# THE STRUCTURE OF THE NORTHERN PRINCE CHARLES MOUNTAINS

## 3.5 Introduction

The northern Prince Charles Mountains (nPCM) cover an extensive area of around 40000 km<sup>2</sup>, approximately the size of Tasmania, some 290 km south of Mawson base (Fig. 6.1). The region was first discovered in 1947 by an American aerial survey of Antarctica named "High Jump", but it wasn't until 1954 that the first visits of the most northern nunataks in the area were made, and included geologist, B. Stinear, who, working for the Bureau of Mineral Resources (BMR), was a member of the earliest overland ANARE (Australian National Antarctic Research Expedition) to the area (Tingey 1972). Crohn, who visited the area in 1955 and 1956, working for the BMR as a geologist, recognized that much of the area, was probably of Precambrian age, consisted of ortho- and paragneisses, charnockites, and later basaltic and pegmatitic bodies (Crohn 1959).

During the years 1968 to 1974, a second phase of geological reconnaissance-style mapping and sampling for geochronological studies was undertaken by BMR geologists, the results of which are reported by Tingey (1972 and 1982). By then, the Prince Charles Mountains had been divided into the southern and northern areas based on their respective Archaean and Proterozoic ages. The subdivision was supported by the inferred metamorphic-grade differences between the two areas, with moderate-grade assemblages such as Grt-Sil-Crd-Pl-Qtz occurring in the north, a transitional zone of amphibolite facies rocks towards the south, and the southern region having greenschist-facies assemblages. Mafic dykes, common in the Archaean Vestfold Hills, are another feature of the Archaean sPCM, distinguishing them from the nPCM. Although alkaline-basaltic dykes, emplaced in the nPCM over a protracted period of at least  $\approx 450$  Ma, and post-dating the high-grade metamorphic episodes, were recognized as early as 1955-56 by Crohn (1959). These geochemically heterogeneous basalts were initially investigated by Sheraton (1983), and as discussed below, place chronological constraints on later deformations.

# 3.6 Lithologies

# 3.6.1 Gneissic lithotypes

The lithologies of the northern Prince Charles Mountains are dominated by high-grade felsic and mafic gneisses; many of the felsic gneisses preserve coarse grained K-feldspars, and unassimilated mafic xenoliths, which are features implying that they had granitic or charnockitic progenitors. Metapelitic gneisses, and marbles, frequently associated with calcsilicates, are particularly important rocks types for the determination of the P-T evolution of the region (discussed in detail in Chapter 6), but are not volumetrically significant. No ultramafic rocks were discovered in the nPCM region.

# 3.6.2 Intrusive lithologies

Basaltic and granitic intrusives are notable features in the nPCM. Age dating of these rocks types, is relatively sparse, however, the available geochronological data are considered below, combined with the relative ages of the intrusives, to further constrain some of the deformational episodes, and the geological evolution of the nPCM.

#### 3.6.2.1 Charnockites

Charnockites and early deformed charnockitic gneisses are an important lithology in the nPCM. Amongst the regions visited in the nPCM the localities where these rocks types occur are the eastern extremity of the Fox Ridge locality, where a strongly gneissic body crops out. The gneiss preserves an alignment of K-feldspar phenocrysts entirely parallel with the gneissosity of the surrounding rocks. Mt Béchervaise is predominantly composed of an early, granitic to charnockitic body, that however, is strongly gneissic. The northwestern exposures of Lensink Peak are another example of a granitic-charnockitic body which was emplaced early in the main phase of deformation.

Charnockites which are generally only weakly gneissic, or massive, are interpreted to post-date the early high strain deformation, and are characteristically coarser grained than the deformed charnockitic bodies. The western margin of the Loewe Massif Charnockite is exposed along the McKinnon Glacier, and it exhibits a typically massive appearance, and contains mafic xenoliths.

Hensen *et al.* (1992) report a Rb-Sr age of  $882\pm140$  Ma for nPCM, Porthos Range charnockites, which they interpret as they most likely age of charnockite formation and metamorphism. However, it is not clear from this reference, if the charnockitic specimens pre or post-date the high strain deformational phase. Munksgaard *et al.* (1992) report that the nPCM charnockites have general similarities with other Mac.Robertson Land coastal charnockites, and Hensen *et al.* (1992) indicate similarities with the Mawson Charnockite. This charnockite is suggested to have been emplaced between D<sub>2</sub> and D<sub>3</sub> (based on the structural criteria of Clarke 1988), and has a U-Pb age for the low-Ti charnockite of 954±12 Ma and a not significantly different (at 95% confidence) age of 985±29 Ma for the high Ti charnockite (Young & Black 1991). Dated zircon cores, from a felsic gneiss xenolith within the charnockite, range in ages from 2500-1000 Ma. Zircon rims, with an age of 921±19 Ma

are interpreted to have grown during deformation post-emplacement, and are thought therefore to date  $D_3$  (Young & Black 1991).

# 3.6.2.2 Basaltic rocks

Basaltic rocks are exposed as dykes, xenoliths in the charnockites and charnockitic gneisses as well as an eruptive lava, with a wide range of emplacement ages in the nPCM. The apparently oldest episodes of basaltic magmatism are preserved as deformed and metamorphosed dykes, which are usually less than 2 m in thickness, and are frequently disrupted by later deformation, and are laterally discontinuous. They are rare features of the nPCM, one of the better exposures occurs along the southerly facing cliffs at Mt Lanyon (e.g Fig. 3.6d). The mafic xenoliths in the Loewe Massif Charnockite may have originated as basaltic dykes, however their relative age is only constrained to be earlier than  $D_3$ . Other apparently early and pre-metamorphic dykes outcrop at Mt Collins, Mt Gleeson, Husky Massif, and Mt Willing and are recorded by Tingey (1972). No radiometric dating or geochemistry of these intrusives has been reported, and it is unknown if they are affiliated with any of the well documented suites of dykes in the Vestfold Hills (e.g. Seitz 1991), northern Rauer Islands, or those in eastern India (e.g. Rao *et al.* 1990).

Basaltic dykes which post-date the granulite facies metamorphism have a range of K-Ar ages reported by Sheraton (1983), from  $504\pm20$  Ma (an alkali olivine basalt from Fox Ridge), 246±6 Ma (a calc-alkali basaltic dyke from Taylor Platform), 145-150 Ma (an alkaline picrite from Radok Lake, Laiba *et al.* 1987), 108-110±3 Ma (alnöite from Radok Lake), to 49.1-51.8±2.0 Ma (an olivine tristanite from Manning Massif [also reported as an olivine leucitite by Tingey, 1976]). These dyke suites are reportedly compositionally distinct from the tholeiitic dykes which cross-cut other Proterozoic and Archaean areas of East Antarctica (Sheraton 1983).

A basaltic rock (N<sup>2</sup> 77063) containing large phenocrysts of phlogopite and clinopyroxene was found on the south-easterly slopes of Mt Meredith. The rock comes from a small semi-circular outcrop, 2 m in diameter, and based on its mineralogy appears to have a lamphrophyric composition.

A number of basaltic rocks were collected from moraines, adjacent to the glacier which passes Mt Meredith. These specimens contain very coarse grained (1-2 cm), altered olivine phenocrysts, abundant chromite spinels ( $X_{Cr}^{spl}=0.45$ ), and fine grained perovskite in the

groundmass. Some of the specimens retain a weak layering, defined by the parallelism of slightly elongate olivine phenocrysts, and thin carbonate veins which cut through the olivines and the specimen. The specimen's mineralogy is comparable to that of alnöitic sills



reported from Radok Lake (Walker & Mond 1971, Sheraton 1983) show that they are similar, and they therefore may be petrographic equivalents.

Some deformational features which are pervasive throughout many of the nPCM outcrops, also deform the unmetamorphosed basaltic dykes. For example minor north-south striking faults on Taylor Platform offset the basaltic dykes ( $246\pm6$  Ma, Sheraton 1983), and therefore this minor deformational episode is younger than an age of  $246\pm6$  Ma. Along the easterly facing cliffs of the Hunt Nunataks, in the Athos Range, a narrow, unmetamorphosed basaltic dyke, truncates the gneissosity and a sub-horizontal pegmatite-associated shear zone (Fig. 3.7g). The gneisses are truncated at a shallow angle and are sheared, by a narrow mylonitic zone, which is cross-cut by the sub-horizontal fault that, like many shallow faults throughout the nPCM, is associated with pegmatites that have been emplaced either late in the shearing deformation, or, have intruded along zones of pre-existing anisotropy, after that episode.

Although there are presently few recognized and dated dyke-suites in the nPCM, the probable emplacement age of the Hunt Nunataks Basalt (HNB), and therefore the minimum age of the sub-horizontal deformation, may be estimated by amalgamating the relative chronology of deformational events, the known age constraints of basalts in the nPCM, and by comparing the basaltic petrography. As the HNB is not metamorphosed, it must postdate the oldest dyke suite and the granulite facies metamorphism dated at ≈1000 Ma (Sheraton 1983). Pegmatites have not been recorded from the Radok Lake sediments, the oldest of which are estimated to be of Late Carboniferous to Early Permian age, and are thought to be glacial strata deposited in the Radok Lake and Lambert Grabens immediately after the initiation of rifting in Late Carboniferous (≈280 Ma) times (Webb & Fielding 1992). If the HNB is related to the known dyke suites in the nPCM, the only known suite which is older than 280 Ma, but younger than the 1000 Ma metamorphism, is the alkali olivine basalt from Fox Ridge, dated at 504±20 Ma. Weaker evidence also supports this as the likely age of the HNB: (a) the Prydz Bay adamellites which outcrop at Landing Bluff, Sansom and Nickols Islands, are dated at 500 Ma (Tingey 1981), and may be related to the emplacement of the pegmatites throughout the nPCM, and along the sub-horizontal shear zones, and (b) the HNB has a similar appearance in hand-specimen, to the Fox Ridge basalt. Both are fine grained, with <1 mm feldspar phenocrysts, and have a similar dark weathering texture, with rare red-weathered grains that may be altered olivines; the weathered appearance of the younger Taylor Platform basalts is distinctly different, with shiny, smooth brown surfaces, and feldspar phenocrysts frequently >3 mm in length.

Geochemical comparisons of the Hunt Nunataks Basalt with the other dated basaltic dyke suites in the PCM, as well as the geochemistries of the shearing-associated pegmatites

and the Prydz Bay adamellites, are however, necessary to support the inference that subhorizontal shearing occurred around 500 Ma, in the nPCM.

## 3.7 Structure

# 3.7.1 Macroscopic structure

The structure of the northern Prince Charles Mountains, is dominated by a composite gneissic layering, the orientation of which is controlled by at least three early gneissosity and fold-forming deformations. These early episodes are characterized by continuous, rotational and extremely high strain deformation, discussed in detail below.

The structure of the nPCM region will be considered as six separate domains, with Mt Lanyon and Mt Meredith considered in Chapter six as one region, subdivided here for clarity, into two separate domains.

Three nunataks, Mt Béchervaise, the northern Hunt Nunataks and Mt Dovers were examined in the Mt Béchervaise region, the most north-western area visited. The gneissosity is tight to isoclinally folded about an east-west striking axial plane of a third generation synform. The foliation generally dips at angles less than 65° (Appendix 1), at Mt Béchervaise in the west, and shallows to <28° at Mt Dovers in the east. Mineral stretching-lineations plunge steeply in the west  $\approx$ 50-70° E, but shallow with the less steeply dipping gneissosity in the east to  $\approx$ 5-17° E at Mt Dovers (Fig. 3.8a). The fold axis of the F<sub>3</sub> synform was traced between the three nunataks, and between Mt Béchervaise and the Hunt nunataks the gneissosity and the interpreted fold axis, change orientation about a gentle warp, a probable fourth generation fold, which has an approximately north-south striking axial plane.

The Gorman Crags domain, consists of the Gorman Crags, nunataks to their west named here Gorman Crags West, and more southerly outcrops Wall Peak, Lensink Peak, Simon Ridge and Scanlan Peak. Most structural data comes from the Gorman Crags, Gorman Crags West, and Wall Peak. In this region the gneissosity is steeply dipping ( $\approx$ 70-80°NW), and mineral stretching-lineations plunge sub-vertically ( $\approx$ 75-85°) generally in the direction of the foliation (Fig. 3.8b). The orientation of the gneissosity of the region is controlled by a macroscopic, disharmonic antiform, plunging steeply northwards at Wall Peak and Lensink Peak. However, slightly further north, at the Gorman Crags, the gneissosity strikes east-west and is only weakly influenced by the southerly fold. The steeply dipping antiform has an inferred northeast-southwest striking axial plane (Fig. 3.8c), and in other areas of the nPCM, folds with this orientation deform east-west striking F<sub>3</sub> folds, this fold is therefore designated as an F<sub>4</sub> fold. East of the Gorman Crags domain are the Mt Lanyon and Mt Meredith domains. The gneisses on Mt Lanyon are deformed by east-west striking axial planes of  $F_3$  folds (Appendix 1). Lineations and fold-axes plunge, generally steeply towards the west, and the foliations are steeply dipping with strikes almost east-west (Fig. 3.8d). The southward facing cliff exposure at Mt Lanyon, discussed in detail below, provides an exceptionally well exposed along-strike section of steeply dipping granulites and marbles, allowing detailed observations of early deformational styles and probable mechanisms. The adjacent easterly Mt Meredith locality, does not have well exposed macroscopic folds, but is a domain where outcrop-scale fold interference is relatively common, providing the opportunity to compare fold-orientations with fold generations. Fold axes and mineral lineations at Mt Meredith plot along a great circle girdle (Fig. 3.8f), indicative of a macroscopic  $F_4$  fold.

The Brocklehurst Ridge domain includes the outcrops of the Brocklehurst Ridges themselves, Taylor Platform, the O'Leary Ridges and Mt Bech. Here the shallowly dipping gneissosity can be partly traced from the Brocklehurst Ridges across to Taylor Platform, and strikes at  $\approx 080^{\circ}$ . Here, the mineral-stretching lineations and sub-parallel fold axes plunge shallowly, westward (Fig. 3.8g). Outcrop scale fold interference also occurs at the Brocklehurst Ridges, but is not as well exposed or as common as the Mt Meredith exposures.

Finally, the Manning Massif, and Fox Ridge localities are combined as one domain (Fig. 3.8e). Manning Massif, as reported by Tingey (1981), is extensively covered by felsenmeer, frost-shattered generally in-situ rock fragments, which preserve the original positioning of rocks, but prevent the accurate measurement of structural data. Aerial-photographic interpretation of the Manning Massif area was applied to determine the outcrop pattern of the macroscopic folds (Appendix 1), which have styles and orientations characteristic of F<sub>3</sub> folds elsewhere in the nPCM.

The Fox Ridge domain is dominated by sub-vertical, northward dipping mylonite zones, which outcrop most prominently along a ridge immediately to the east of the Fox Ridge trig point, but also as scattered exposures and extensive felsenmeer fragments on the south-eastern slopes, outcropping across strike for a distance of at least 200 m.

## 3.7.2 The first deformation, $D_1$

The first and second deformations occurred under granulite facies conditions, and are responsible for the coarse grained granoblastic to gneissic foliation, transposing on all scales probable progenitor layering of all lithologies except the later magmatic rocks (described above). The resultant gneissic layering varies from centimetre to many hundreds of metres



thicknesses. As the early deformations were high strain, and rotational, there are no obvious orientational distinctions between the gneissic layering, and the axial planar fabric developed in early fold-hinges.

In pelitic lithologies the dominant  $S_{1-2}$  texture is defined by coarse grained minerals, and mineral aggregates, of sillimanite, garnet, phlogopite, feldspars and quartz. These minerals define a composite texture since the earliest fabrics of coarse grained minerals are occasionally folded isoclinally (F<sub>1-2</sub>) on microscopic scales, however foliation generations  $S_{1-2-3}$ , are indistinguishable away from these isoclinal fold hinges.

The early gneissic texture is defined by aggregates and the alignment of pyroxenes, feldspars, elongate quartz, garnet, and biotite, in both mafic and felsic lithologies. Marbles and calc-silicate lithotypes, are frequently recrystallized and do not preserve a strong foliation. However, where strongly deformed, for example at the southward facing cliffs of Mt Lanyon, their fabrics anastomose around weakly deformed and often partly rotated, porphyroblasts within their matrix.

Early, high grade mylonitic shallowly dipping zones, with dominantly southward and southeastern movement directions, from Mt Lanyon and Mt Meredith, are interpreted as part of the early deformational episode; detailed observations and interpretations are discussed in section 3.8.1.

Although discrete zones of particularly high early strains are distinguishable, almost all gneisses preserve evidence of high early deformational strains. In metapelitic lithologies sigmoidal trails, usually a composite fabric of sillimanite and biotite anastomose around garnet porphyroblasts, however, because deformation was synchronous with granulite facies high temperature metamorphism, many rotated fabrics normally preserved at lower metamorphic grades, are annealed. In specimen MB90/5 however, a sigmoidal garnet porphyroblast (Fig. 3.9d), preserves textures usually interpreted to have formed by porphyroblastic rotation during growth.

In many regions the early composite layering displays boudinage of the incompetent, usually mafic, lithologies (Fig. 3.7d).

### 3.7.3 The second deformation, $D_2$

The most pervasive feature of the second deformation are isoclinal, intrafolial, frequently rootless folds, which fold the composite  $S_{1-2}$  gneissosity. Occasionally  $F_2$  folds have sheath geometries, indicative of high layer-parallel strains (Figs. 3.7h & 3.10a). These folds are most common on outcrop scales, but also occur on the east facing cliff of Manning Massif, along the McKinnon Glacier. They are not distinguishable from  $F_3$  folds by orientation,













although the macroscopic fold at Manning Massif plunges at approximately 30° towards 225°, and its axial plane strikes  $\approx$ 225°, and dips shallowly ( $\approx$ 35°) NW. Generally however, F<sub>2</sub> folds have isoclinal styles, may be rootless, but the strongest criteria is that they are refolded by coaxial tight to open F<sub>3</sub> folds.

Intrafolial  $F_2$  sheath folds occur throughout the nPCM, being recorded at Mt Lanyon in the SE, at the Gorman Crags in the SW, and at Mt Dovers in the north. They plunge subparallel to the lineations developed on adjacent gneissosity surfaces, and deform felsic and metapelitic lithologies.

# 3.7.4 The third deformation, $D_3$

The third deformation produced folds which deform  $F_2$  folds, but are typically coaxial with  $F_2$ , and usually have close to tight styles (Figs. 3.10b). This folding generation is responsible for much of the east-west orientation of the gneissosity in the nPCM.

On microscopic scales, F<sub>3</sub> folds the foliation (Fig. 3.9g), and have weak axial planar fabrics of biotite (Figs. 3.9e & f) and occasionally sillimanite, but these fabrics do not differ from the fabrics developed in the folds they deform. The best fold interference patterns occur at Mt Meredith, were generally sub-horizontal, isoclinal  $F_{1-2}$  folds (Fig. 3.10c) are transposed about inclined to steeply dipping axial planes of coaxial F<sub>3</sub> folds (Fig. 3.10d).

Felsic granitic to charnockitic bodies at the western extremity of Fox Ridge, and those at Mt Béchervaise, have a strong gneissic foliation, parallel to aligned, what were originally K-feldspar phenocrysts, and are now porphyroblasts. Their fabrics sub-parallel the foliation of the adjacent gneisses, which are folded by third generation folds. These early granitoids, unlike the relatively massive charnockite at Loewe Massif, are interpreted therefore, to have been emplaced early in the deformation evolution of the nPCM, probably synchronous with, or in the later stages of  $D_2$ .

## 3.7.5 The fourth deformation, D4

The fourth deformation is recognizable on a macroscopic scale by close to open-warps of the composite  $S_{1-2-3}$  gneissosity, about north-south striking axial planes and with apparently a large variation in plunge angles. An example of this fold style with an apparently shallow plunge, is recognized in the Mt Béchervaise area, where east-west striking F<sub>3</sub> folds and early mineral-stretching lineations are warped around north-south striking axial planes, between Mt Béchervaise and the northern Hunt Nunataks. In contrast, the tight and dominant structure of the Wall Peak region, is a steeply plunging F<sub>4</sub> fold, however, its influence is localized to the southern Wall and Lensink Peaks area, and 3 km north at the

Gorman Crags the gneissosity's orientation is controlled by the earlier, composite fabric and  $F_3$  folds.

This folding generation is also interpreted to deform  $F_2$  and  $F_3$  fold axes, about a great-circle girdle (Fig. 3.8f), at Mt Meredith. The girdle dips moderately towards the northwest, and the inferred  $F_4$  fold axes plunges towards the southeast. The interpreted axial-planar orientation is consistent with that suggested for the  $F_4$  at Wall Peak.

#### 3.7.6 Mineral lineations

Mineral lineations in the nPCM are frequently moderately to strongly developed on most gneissosity surfaces. They are usually defined by elongate mineral grains (e.g. biotite & pyroxenes) and aggregates of more equant minerals such as, garnets, quartz, and feldspars. In rocks which either did not reach high peak temperatures (> 750°C), or which have re-equilibrated at lower temperatures ( $\approx 600^{\circ}$ C), mineral lineations are defined by amphiboles, biotite, as well as the mineral aggregates. Rocks preserving higher grade equilibration conditions, frequently have mineral lineations defined by pyroxenes in mafic compositions, and sillimanite in meta-pelites. However, in some aluminous-composition lithologies, occasional coarse sillimanite is not aligned with the lineation of the specimens.

Lineations defined by pyroxenes, aggregates of garnets and sillimanite, are interpreted as indicating the stretching direction at, or near, peak metamorphic conditions. Despite the apparent and calculated changes in metamorphic grades across the nPCM (Chapter 6), reflected by the change in mineralogy of mineral lineations from pyroxenes to amphiboles, there are no discernible, systematic variations in the orientation of lineations, relatable to the changes in estimated peak-metamorphic grades. This important observation indicates that early deformation was pervasive, and that at least the first three deformational features, are common to lower and higher grade rocks.

Lineations in all domains examined, plot with relatively well defined groupings, parallel with the fold axes in that domain. Their formation appears to be mainly related to the early deformational episodes, however, the gneissic fabric is a composite feature, and mineral lineations are therefore difficult to assign to a particular deformational episode. Based on the isoclinal fold styles of  $F_1$  and  $F_2$  fold generations, it appears that  $D_1$  and  $D_2$  were the most intense deformations, and are therefore possibly responsible for the majority of mineral stretching lineations. However, in local areas, where  $D_3$  is strong, or where  $F_4$  structures are the dominant feature (e.g. Wall Peak), the mineral lineations are totally transposed, or deformed into new orientations parallel with the tectonic-movement directions of these later deformations.

The parallelism of mineral lineations, with fold axes which deform preceding fold structures, is strong evidence that the early deformational episodes ( $D_{1-2-3, and 4?}$ ) occurred during progressive rotational strain conditions.

Mineral lineations in early mylonite zones  $(MY_1)$ , described below, plunge at shallow angles, suggestive of an early thrust dominated tectonic regime (discussed in Chapter 7). Later, second generation mylonites  $(MY_2)$  have prominent sub-vertically plunging mineralstretching lineations which define the direction of shear movement during their formation. Third generation mylonites, associated with pegmatites, do not usually have well defined lineations. A later retrograde shear-zone, has a well defined mineral-lineation defined, by white micas. Adjacent fault surfaces, have completely transposed lineations, but defined by the minerals within the gneisses.

### 3.8 Thrusts, mylonites and shear-zones

# 3.8.1 Early $MY_1$ mylonites and their thrust direction

Zones of intense early shearing interpreted from recrystallized early  $MY_1$  mylonites, are preserved at Mt Meredith and along the southerly facing cliffs at Mt Lanyon. The Mt Meredith early mylonite is a sub-horizontally dipping zone of recrystallized biotite-bearing gneisses, preserving elongate quartz and feldspar ribbons, and a strongly anisotropic fabric comparable with mylonitic fabrics reported from the Himalayan Main Central Thrust (Bouchez 1982). The early mylonite preserves a weakly folded, strong stretching lineation defined by biotite, quartz rods, feldspars and minor hornblende, which plunge shallowly, between 04-07° towards 053-081°. The shear sense, was ascertained by the asymmetry of S-C fabrics (e.g. Lister & Snoke 1984), and weakly rotated garnet porphyroblasts, and the specimen is strongly recrystallized; however, a right-lateral shear component (Fig. 3.11c), or movement of the south-westerly block towards the east (Fig. 3.12a), is suggested here.

Immediately above the layered Bt-Hbl gneisses at the eastern cliff-end, Mt Lanyon, one of two major remobilized carbonate-layers, described in section 3.9.2, crops out. The lower contact between the layered Bt-Hbl gneisses and the carbonate body is partly obscured by moraine, however in clear exposure adjacent to the contact the carbonate exhibits injection veins (Fig. 3.6c) into, and around, large rafts of strongly layered gneisses (Fig. 3.13a). The adjacent rafts and disrupted layers are folded by the carbonate, and their strongly asymmetric geometry indicate a consistent component of right-lateral movement sense during carbonate emplacement or mobilization. This component of movement is in agreement with the north over south, right-lateral, direction derived from the nearby mylonitic felsic gneisses (Figs. 3.12a & 3.13b).

The upper contact between the homogeneous, poorly foliated felsic gniesses, and the carbonate, is well exposed. The contact strikes at  $\approx 060^{\circ}$  and consists of an anastomosing series of mylonites, with an outcrop width of approximately 50-100 cm. At this locality a prominent mineral lineation, defined by elongate aggregates of green amphibole, rods of carbonate and recrystallized but extremely fine grained, mylonitic feldspars and quartz, lies within the plane of the mylonites, and plunges  $\approx 22^{\circ}$  to the north-west. Figure 3.6d depicts the mylonitic off-sets of an early metamorphosed basaltic dyke whose emplacement postdates that of the homogeneous felsic gneisses; the secondary movement-sense, in the plane of the cliff is mainly right-lateral, although the dominant (primary) movement-sense, indicated by the intense mineral lineation and asymmetric porphyroclastic-sphene rotation tails (Fig. 3.11f), is top towards the south. A subordinate amount of secondary left-lateral movement (in the cliff plane) displaces the meta-basaltic dyke along sub-horizontal shearplanes, which emanate from a ramp in the shear-plane, where the surface changes from a ramp to a locally shallow apparent dip (Fig. 3.6d). This shear-band's opposite and local secondary, left-lateral movement sense, is almost certainly due to the shear-plane's divergence around the ramp and the consequent change of local stress gradients.

Probably early thrusting, as outlined here, was layer parallel, and the extensive development of necking, boudinage and mylonitic fabrics supports this interpretation. The use of the word 'thrusting' for early MY<sub>1</sub>-faulting, implies a sub-horizontally directed compressional stress regime. Such a regime is supported by the shallow dip of the upper mylonitic contact between the carbonate described above and the felsic gneisses; shallowly plunging, intense stretching mineral lineations; shallowly dipping fault-surfaces, with drag folds which indicate a southerly directed movement-sense (Fig. 3.13b). Latter F<sub>3</sub> folding however, steepened the dip of much of the layering (e.g. the western margin of the cliff at Mt Lanyon, Fig. 3.13c), and many rocks have suffered significant recrystallization removing much of the MY<sub>1</sub> mylonitic (pre-D<sub>3</sub>), layer-parallel fabrics. The only remnants of high strain are usually isoclinal folds, wispy and attenuated contacts between rock units, and the remobilized features preserved in the carbonates.

The equivalent orientations of primary mylonite movement (top towards the south), and secondary right-lateral shear-sense, with the shear-sense determined from drag fold asymmetry adjacent to the carbonates, supports the interpretation that early deformation (pre- $D_3$ ) involved significant thrusting. Third generation folds on Mt Lanyon, and Mt Béchervaise, responsible for the orientation of the macroscopic layering, have axial planes striking approximately east-west. This orientation is perpendicular to the trend of the mylonitic mineral lineations, suggesting that the compressional regime responsible for early high strain thrusting, also produced F3-folds in its waning stages.

# 3.8.2 Later MY<sub>2</sub> and MY<sub>3</sub> mylonites

Mylonite zones which post-date the gneissosity forming and folding deformations are a common feature of the gneissic lithologies of the nPCM, and are reported, as later deformational events from localities covering an extensive area of East Antarctica, for example from Enderby Land (Sandiford & Wilson 1984), from the Rauer Islands (Harley 1987), the Reinbolt Hills (Nichols & Berry 1991) and the nPCM (Fitzsimons & Thost 1992).

Second generation mylonites, MY<sub>2</sub>, occur at Fox Ridge, where they have a northeastsouthwest strike (varying between 035-080°) and a sub-vertical, northward dip: their movement sense, interpreted from well developed vertically plunging, mineral-stretching lineations, non-cylindrical sheath folds, both  $\sigma$  and  $\delta$ -type asymmetric garnet porphyroclasts (after Hanmer & Passchier 1991), indicate a consistent right-lateral shear sense (Fig. 3.11e), that is, the north block up, relative to the south block (Fig. 3.12b). Their mineralogies are variable, dependent upon the lithologies through which they pass, however, they frequently have quartz and feldspar-rich extremely fine grained (ultramylonitic), groundmasses, with garnet, feldspar and occasionally quartz porphyroclasts, generally less than 2 cm in diameter in the most strongly strained areas. The Fox Ridge mylonite preserves fragments of sillimanite in its groundmass, and garnet porphyroclasts occasionally contain spinel inclusions; the lack of biotite implies relatively high grade metamorphism, compared with other amphibolite-grade mylonites discussed below, but probably at conditions post-dating the thermal peak. Towards the poorly outcropping margin of the Fox Ridge mylonite, along the southern slopes of Fox Ridge, the shear zone passes through pegmatitic grain-size felsic gneisses. Here, the porphyroclasts are commonly 2-4 cm in diameter and make up 60-70% of the rock, by volume. The mylonitic fabric is however very strongly developed in anastomosing zones between the feldspar and quartz porphyroclasts. The field relationships with the well exposed MY<sub>2</sub> along Fox Ridge to the north, were mostly obscured by snow, however, the porphyroclastic mylonites may be third generation mylonites formed during reactivation of mylonitic deformation along the strongly anisotropic MY<sub>2</sub> zone.

Pseudotachylyte veins are associated with narrow shear-zones in many lithologies in the nPCM, however, they are most noticeable in the homogeneous felsic gneisses, and are prevalent at the margins of the major Fox Ridge mylonite, where they have similar steeply dipping orientations to the mylonite. The localities in which they occur cover an extensive area of the nPCM, for example at Manning Massif, Wall Peak, Lensink Peak, and are also reported from many areas in East Antarctica, e.g., David Range, near Mawson (Clarke 1988), Mawson (Clarke 1990), and are attributed to Proterozoic features of the Vestfold Hills (Passchier *et al.* 1991). However, shallowly dipping pseudotachylytes not associated with large mylonite zones, were also observed in the Loewe Massif Charnockite, and at Manning Massif. Possibly they are related to the events which produced the later  $MY_3$  mylonites (described below).

In the nPCM they commonly vary between 0.5 to 2 cm in thickness, usually outcrop over 2 to 3 m, and have a black glassy appearance in hand-specimen. The pseudotachylytes often occur along very narrow shear-zones, which enlarge into 1 or 2 cm wide zones filled with the glassy material, and have veinlets emanating from the shear-planes which project into the sheared-host (Fig. 3.11d). In thin-section, the glassy material is totally de-vitrified and contains porphyroclastic fragments. These features are interpreted to result from melt generated along the shear-planes by individual episodes of frictional heating generated during faulting (e.g. Grocott 1981).

In the Gorman Crags region, the steeply dipping gneissic foliation preserves layerparallel shear zones which in some areas are mylonitic. Figure 3.10e depicts the field relationships of sub-vertically dipping gneisses, along cliffs at the Gorman Crags. Here a layer-parallel mylonite (GOR90/15), is deformed by a sub-horizontal shear-zone (MY<sub>3</sub>) that has an approximately 25 cm wide pegmatite emplaced along its length, with sharp boundaries and almost no internal fabric. The gneisses are deformed about asymmetric dragfolds which indicate a right-lateral shear movement component in the plane of the cliff. The shear-sense of the mylonitic layer-parallel gneiss, interpreted from  $\sigma$ -type garnet and feldspar porphyroclasts, and oblique biotitic shear-bands, is also right-lateral, that is, a relative west-block up movement (Fig. 3.12b), once the foliation is rotated anti-clockwise, into its original orientation before deformation by the later drag-folds. This mylonitic zone has biotite shear-band fabrics and deformation appears to have occurred at the lower grade conditions than experienced by the Fox Ridge mylonite. However, the rocks from the Gorman Crags region, in general, have slightly more hydrous assemblages, than the northern areas. The layer-parallel orientation of the mylonite, supports the interpretation that it is a second generation, MY<sub>2</sub>, structure.

Further relative movement criteria are interpreted from a 2-3 m wide mylonitic zone in the Gorman Crags area (specimen GOR90/22), which is intruded at an oblique angle by a pegmatite approximately 30 cm across (Fig. 3.10f). The mylonitic zone displays a sequence of felsic veins and pegmatites, which have been emplaced at different times and increments of shear deformation along the zone of anisotropy, and therefore record progressive changes in the strain history of the mylonite. The mylonite strikes at  $\approx 215^{\circ}$ , and dips sub-vertically, northwards; strong stretching-mineral lineations on the foliation surfaces, plunge subvertically towards  $\approx 300^{\circ}$ . The movement sense interpreted from shear-bands and  $\sigma$ -type porphyroclasts, is northwest block up relative to the southeast block, with a small left-lateral movement component (Fig. 3.12b). This zone display features of both  $MY_2$  and  $MY_3$  structures; it has a layer-parallel, sub-vertical orientation like  $MY_2$ , but has clearly experienced multiple pegmatitic emplacements, the last of which preserves a shallower dip than the higher strain portions of the mylonite, analogous with  $MY_3$  structures. These features are interpreted to result from an early  $MY_2$  structure, which was reactivated and intruded by several generations of pegmatite, during later  $MY_3$ -shear, that preferentially occurred along this zone of pre-existing anisotropy, but which also restrained  $MY_3$ -shear's orientation to a steeper than normal dip. The strong stretching mineral-lineation, identified in the higher strain regions of the zone, retains early  $MY_2$ , shear orientations consistent with those from other  $MY_2$  structures in the area (Fig. 3.12b).

These field relationships place important constraints on the relative timing of the layerparallel mylonites which are truncated by the sub-horizontal, pegmatite-associated shears. The mineralogies of the layer-parallel mylonites, in these samples are not particularly diagnostic of upper amphibolite, or lower granulite facies metamorphic conditions, however, the dominance of aligned biotite along shear-bands, is suggestive of upper amphibolite facies conditions. In contrast, the pegmatite-associated shears (MY<sub>3</sub>-mylonites), which cross-cut the mylonites, are usually encapsulated by ≈50 cm wide haloes of biotite and amphiboles, indicative of the introduction of dissolved fluids in the granitic magmas, and probably at lower metamorphic temperatures. The association of sub-horizontal shearing and granitic to pegmatitic rocks is a feature common to the nPCM, the Reinbolt Hills, and other East Lambert Glacier (ELG) outcrops including Jennings Promontory and the McKaskle Hills. The ELG examples have similar shear directions and sub-horizontal orientations, however, the mylonitic component of these shear zones is approximately 20%; in contrast the nPCM MY3-mylonites, only have weakly mylonitic margins, and thus the relative proportion of mylonite to pegmatite is much less. MY3-mylonites in the ELG truncate the lithologies with little or no disruption of the gneiss's orientation, whereas the same generation of sub-horizontal mylonites produce dramatic right-lateral drag fold asymmetry of the nPCM gneisses they transect (Figs. 3.10e & h).

The relative timing of the sub-horizontal MY<sub>3</sub>-mylonites, in the northern Mt Béchervaise area, was interpreted to pre-date the emplacement of the  $504\pm20$  Ma olivine-phyric unmetamorphosed basalts (section 3.6.2.2), and are temporally associated with the emplacement of granitic magmas, that at Prydz Bay are dated at 500 Ma. Since the pegmatite-associated sub-horizontal shear zones deform and truncate the Gorman Crags' layer-parallel MY<sub>2</sub>-mylonites, at high angles and the gneissic layering at other localities, the stress orientation during the later episode must have significantly changed from the stress which produced the layer-parallel mylonites. Such evidence strongly suggests that the layer-

parallel MY<sub>2</sub>-mylonites were produced by deformation which significantly pre-dated the inferred 500 Ma sub-horizontal shearing episodes. These arguments are not consistent with the interpretation of Fitzsimons & Thost (1992) that mylonitization occurred as a single event, around 500 Ma.

# 3.8.3 Summary of mylonite generations

In summary, three mylonite forming deformations are distinguished, two of which are interpreted to have occurred before 500 Ma, in decreasing age they are: MY<sub>1</sub>, the early high strain, layer-parallel mylonites, usually with relatively shallow dips, possibly indicative of thrust-geometries, which occurred at granulite facies conditions, MY<sub>2</sub>, east-west striking, sub-vertically oriented, low grade granulite to upper amphibolite facies, mylonites with associated pseudotachylytes, and MY<sub>3</sub>, sub-horizontal, pegmatite-associated, amphibolite-facies, shear zones, occasionally mylonitic, who's relative chronology suggests they occurred  $\geq$ 500 Ma. MY<sub>1</sub> probably occurred during the formation of the early gneissosity, and thus are correlated with D<sub>1-2</sub>. MY<sub>2</sub> truncate the early post-D<sub>2</sub> granitoids and the gneissosity, but strike sub-parallel to it, and occurred at moderate metamorphic grades and are therefore interpreted to have occurred late in D<sub>3</sub>. The relative chronological relationships between D<sub>4</sub> and MY<sub>3</sub> are not clearly defined as no mesoscopic F<sub>4</sub>, or S<sub>4</sub> features were truncated by MY<sub>3</sub>. However, MY<sub>3</sub> mineralogies are typically amphibolite facies, in both nPCM and ELG areas, and therefore MY<sub>3</sub> is interpreted to post-date D<sub>4</sub>.

Interpreted MY<sub>1</sub> movement directions are consistently southeasterly, to easterly (Fig. 3.12a); MY<sub>2</sub> directions are consistent (except for LAN90/10) north, and northwest block up, relative to the south and southeastern blocks (Fig. 3.12b), and MY<sub>3</sub> shear orientations are all west block to the east, along shallowly oriented shear-planes, including outcrops from the East Lambert Glacier region (Figs. 3.12c & 3.3g).

#### 3.8.4 Later faults, and retrograde shear-zones

Later faulting and retrograde shear-zones are not common features of the nPCM region. The southward facing cliff at Wall Peak, has one of the better exposures of the later generation MY<sub>3</sub>-mylonites (Fig. 3.10h), which are truncated by a steep north-westerly dipping, NE-SW striking shear-zone ('i' on Fig. 3.10g), containing a greenschist facies assemblage dominated by chlorite and muscovite. One other shear-zone with a similar chloritic mineralogy, and orientation, was observed along the southerly cliffs at Mt Lanyon (Fig. 3.12d). The interpreted movement sense at Wall Peak, in the plane of the shear-zone is left lateral, or southeastern block up, relative to the northwestern block. Fault-surfaces immediately adjacent to the shear-zone, have a steeply NW-plunging mineral lineations,

defined mainly by amphiboles, and mineral aggregates of garnet and biotite, in the faulted gneisses are re-aligned by the shear-zone.

Later north-south striking, and apparently steeply dipping faults displace the unmetamorphosed basaltic dykes (dated at  $246\pm 6$  Ma, Sheraton 1983) on Taylor Platform. The total wrench displacement is usually less than 5 metres on the surface. This minor faulting deformation may be associated with surficial deposits of partly brecciated whitequartz which overgrows plates of calcite (10 cm in diameter), for example at Mt Lanyon, and the Brocklehurst Ridge region.

# 3.9 Deformational features of granulite facies carbonates

# 3.9.1 Introduction

Calcareous lithologies, predominantly coarse grained marbles, calc-silicate layers and boudins, are a significant rock type in the northern Prince Charles Mountains. The marbles in particular, and their porphyroclasts, exhibit deformational features which provide insights into the behaviour of rocks with different rheological properties, at high temperatures and pressures. Two significant localities in the nPCM, portraying a variety of deformational features, are described below.

# 3.9.2 Southern Mt Lanyon cliff exposure

The exceptional exposure along the southerly facing cliffs of Mt Lanyon allow detailed studies of the structural interactions between calc-silicates within marbles, the adjacent massive felsic granulites, and strongly layered mafic gneisses. The cliffs section about 2500 metres of variable, sub-vertically and north north-westerly dipping rocks, and have approximately 450 metres of elevation above the ice, at their highest point. At their eastern margin, the cliffs are dominated by a regularly layered series of mafic Bt-Hbl gneisses which represent the lowest outcropping package of rocks (Appendix 1). The mafic gneisses have suffered high strain deformation, sub-parallel to their layering, and preserve features such as incipient necking between rheologically disparate layers, attenuated rootless isoclinal folds, and elongate inter-fingering of the mafic gneisses into the felsic rocks, which possibly originated as early injection veins (Fig. 3.6a). Parallel with the layering, at the eastern cliffend, an approximately one metre wide micaceous zone suggests reactivated shear movement (Fig. 3.6b), during the re-introduction of hydrous fluids. The stability of a predominantly muscovite-chlorite assemblage in the shear zone suggests that reactivation occurred at low temperatures, probably a long time-interval after peak conditions, and the orientation of later shearing was confined by the strongly anisotropic rheology of the previously sheared gneisses. A similar 'sequence' of mainly mafic gneisses occurs at the south-western

extremity of the cliffs, and this repetition may represent the 'upper' limb of an isoclinal fold, although there is speculative.

Within the carbonate masses, abundant high strain deformational features are made visible by compositional layers which, during high strain, have been dramatically elongated. The dominant textures are suggestive of a low viscosity fluid deforming around only weakly deformed clasts, and boudins of rheologically much stronger rocks, such as mafic-rich pods and felsic gneisses (Figs. 3.6e & f). These features indicate that the ratio of the relative strengths, of the matrix and the clasts, is large, about 50 (approximately equal to the rheological contrast of quartz and calcite at 700°C, from Rutter 1976), and that the carbonate's rheology is predominantly determined by the matrix, that is, the clasts usually behaved as passive rotational markers (cf. Domain 3, Handy, 1990). Calc-silicates, preserved mainly as diffuse rafts or boudins, display rheological behaviours intermediate between the strong mafic and felsic gneisses, and the ductile marbles. In some examples the calc-silicates are complexly folded (Figs. 3.6g & 3.7b) or exhibit elongate rotation-tails on porphyroclasts (e.g. around porphyroblasts of grossular-garnet, Fig. 3.7a), indicative of high-strain deformation of moderately competent rocks: in contrast, aggregates of finegrained porphyroclasts, or elongate layers trailing away from poorly defined raft-edges merge with the relatively homogeneous marbles, and are indicative of extremely high strains. Analogous and familiar fluid-flow features can be observed when a blob of whipped cream slowly dissolves in a cup of hot coffee, producing diffuse white edges, and anastomosing elongate white trails in the fluid. In contrast, some boudins, or clasts preserve highly deformed textures suggesting entrainment synchronous with deformation (e.g. Fig. 3.6h), and such textures are characteristic of high strain.

At the western extremity of the cliffs, steeply northward dipping mafic gneisses preserve features consistent with layer parallel shearing. Leucocratic layers anastomose around mafic boundins and necked mafic layers (Fig. 3.7c). In one zone (marked 'i' on Fig. 3.13c) leucocratic and mafic layers have apparently suffered intense shear sub-parallel to layering, and are effectively homogenized. Latter shallow northward dipping fault surfaces truncating the layering appear to be associated with minor movement, whose sense is top towards the north.

# 3.9.3 Eastern Manning Massif cliff exposure

The east north-east facing cliff on Manning Massif, along the McKinnon Glacier, provides an excellent exposure of a south-westerly plunging isoclinal  $F_2$ -fold. The synformal fold plunges gently between 25° at the northern cliff end, to around 20°, where the hinge is best exposed, and also has a gently dipping axial plane. The fold deforms a homogeneous Opxbearing brown to red weathering felsic gneiss (an early granitoid), which outcrops as the upper (southern) and lower (northern) fold-limbs. The hinge zone is recognized by repetition in a sequence of interlayered felsic and mafic gneisses. Clear sections of the central hinge zone are revealed in small valleys along the cliff, which allow views subparallel to the fold axis. From such vantages the layered mafic gneisses appear as variably boudinaged blocks, within the more competent, anastomosing leucocratic felsic gneisses (Fig. 3.7d). The mafic layers, in highly strained sections of the cliff, therefore preserve a macroscopic rod-like geometry.

At the centre of the hinge zone, a strongly deformed marble layer contains remnant folded and boudinaged fragments of the surrounding mafic and felsic gneisses. The marble is strongly recrystallized, and the only features which belie its early high strain episodes, are the inclusion of deformed boudins (Fig. 3.7e). The marble does however preserve distinct compositional zonations, along its contacts with the surrounding, more silica-rich felsic gneisses (Fig. 3.7f). These features support the interpretation that the marble was deformed relatively early, and then remained at high temperatures, allowing the formation of the mineralogical zonations. The marbles are composed of calcite, bright orange forsteritic olivine, and spinel; the adjacent zone is dominated by pale micas, in a xenoblastic groundmass of dark green amphiboles; the penultimate zone, before the felsic gneisses, is mainly composed of pale amphiboles.

### 3.10 Relative timing of metamorphism and deformation

The metamorphic pressure and temperature conditions which are preserved as peak and retrograde trajectories of samples covering an extensive proportion of the nPCM, are detailed in Chapter 6. Here, the mineralogies of the composite fabrics which combine to make the pervasive layering throughout the region are described and a relative chronology of metamorphism is outlined, with respect to the peak and retrograde metamorphic conditions.

#### 3.10.1 Early fabrics

The dominant microscopic fabric of nPCM lithologies, is equivalent to, and has the same orientations as, the gneissic layering, that is composed of elongate minerals and mineral aggregates. The preserved fabric represents combinations of  $S_1$ ,  $S_2$  and  $S_3$  foliations (Fig. 3.11b), which have been transposed by high strains, also responsible for the rotation of the layering, lineations and fold-axes, into parallelism with the shear direction.

Meta-pelitic rocks make up a relatively small proportion of rocks of the nPCM, and of any particular region. Compared to the surrounding, generally homogeneous felsic, or mafic lithologies, the pelites represent zones of rheologically incompetent material, and have therefore experienced preferential deformation. In high stress regimes or localized regions of high strain, this means that fabrics will be totally transposed into the orientation of the last deformation; in zones or regimes of lower stress however, the pelitic rocks have a greater probability of recording successive fabric orientations. In reality, metapelitic rocks preserve the greatest diversity of microscopic fabric-elements, however, aligned sillimanite and biotite are the most noticeable fabric-forming minerals, and combine with elongate, or rotated garnet porphyroblasts (Figs. 3.9a & c), quartz and feldspar aggregates or occasionally ribbons, to produce the dominant foliation. Their microtextures are generally recrystallized, and have straight extinction, indicating that except in the MY<sub>3</sub>-mylonites, temperatures remained high enough for complete annealing of plagioclase, quartz, sillimanite and pyroxenes, at least until the cessation of the main kinematic phases.

Felsic gneisses frequently, are dominated by gneissic-foliations of biotite, orthopyroxene, and aligned aggregates of quartz and feldspars. In many areas, the felsic gneisses retain coarse-grained K-feldspar porphyroblasts, which suggest that these gneisses are metamorphosed granitoids. Usually the 1 to 2 cm K-feldspar porphyroblasts have an almost opalescent lustre, and are partly rounded; asymmetric porphyroblastic rotation tails are frequently preserved in felsic gneisses which have experienced high-strains (e.g. Fox Ridge & Mt Béchervaise).

Carbonates are usually relatively coarse grained, and except where deformed in later mylonite-zones, preserve a partially or totally recrystallized, microscopic fabric. On mesoscopic scales they preserve layering which anastomoses around porphyroclasts, and has orientations sub-parallel with the composite gneissosity of the surrounding lithologies. Calc-silicates, associated with the carbonates, usually preserve reaction zoning between silica-rich porphyroclasts, and the calcium-rich enclosing carbonates. Microscopic fabrics of samples from the Manning Massif region (McKinnon Glacier), are dominated by the postdeformation reaction zonations (Fig. 3.7f). In contrast, the calc-silicates within remobilized marbles exposed along southward facing cliffs at Mt Lanyon (section 3.8.2) do not preserve the same reaction-zone thicknesses, but coarse-grained grossular-garnets (Fig. 3.7a), are rotated and attenuated by the later deformation. Highly strained calc-silicate boudins (e.g. specimen MB90/8), within Grt-Opx bearing felsic gneisses at Mt Béchervaise, preserve reaction-zonations with the surrounding gneisses, but internally are dominated by granoblastic aggregates of Cpx, Pl and Cal. In this example, high strain deformation producing layer-parallel boudinage occurred relatively early and at high metamorphic conditions; partial recrystallization occurred after the diffusional growth of the reactionzonations, and the final cooling history of the specimen is recorded by the growth of grossular-garnet rims on clinopyroxene and anorthitic-plagioclase (P-Ts in section 6.4.2.1).



# 3.10.2 Fabrics and folding

Micro- and mesoscopic folds are not particularly common features of most areas of the nPCM, with the exception of the Mt Meredith region. Early folds are intrafolial, often rootless, and display extremely attenuated doubly plunging fold-hinges, that is, sheath geometries. Internally they fold the gneissic layering of sillimanite, biotite, and elongate garnets, on microscopic scales however, almost all minerals are recrystallized and rarely preserve deformational features, such as kinking, undulose extinctions in quartz or feldspars, normally acquired during folding. Sheath folds axes parallel the plunge of well developed mineral lineations, however, they do not have strong axial-planar fabrics.

Later  $F_2$  and  $F_3$  folds usually display mesoscopic axial-planar alignments of biotite (Fig. 3.9f) and occasionally sillimanite, in pelitic rocks, or amphibole, biotite and pyroxenes in mafic compositions. Microscopically however, the axial-planar fabrics are parallel with the composite gneissosity, and only cross-cut the foliation in hinge-zones. Localized zones where rotation tails of garnet porphyroblasts curve into parallelism with the gneissic layering (Fig. 3.9b), in places, retain the outline of tight  $F_3$  folds defined by the trace of sillimanite grains. However, individual grains are not kinked, suggesting annealing post-deformation (Fig. 3.9g).

Garnet porphyroblasts in highly strained pelitic rocks, often have rotated asymmetric textures (Fig. 3.9c), and in specimen MB90/5, particularly well preserved 'snowball' garnets (Fig. 3.9d). Such textures are frequently interpreted, for example Vernon 1976, Powell & Vernon 1979 and Simpson & Schmid 1983, to form through porphyroblastic rotation during garnet growth. In Chapter 6 (section 6.4.2.1), lower temperatures and pressures are calculated from rim compositions compared with the core compositions, supporting the hypothesis, that cooling and deformation continued during garnet growth. The retrograde metamorphic conditions post-date the peak deformational phase, however, deformation and cooling were probably contemporaneous.

#### 3.10.3 Later fabrics

## 3.10.3.1 Rotation and shear textures

Less pervasive deformational features are preserved in some pelitic rocks. The earliest of these features are narrow, 1-2 mm, shear-bands (Fig. 3.11a), usually within the leucocratic portions of the pelites, along which biotite is realigned, and in which there has been grain-size reduction. Their orientations are variable; in some specimens they transect the foliation at low-angle, in others, they are almost perpendicular to the foliation. The recrystallized shear-bands are also developed, and their geometries are controlled, where garnet porphyroblasts are closely juxtaposed. Despite displaying grain-size reduction, quartz in the



shear-bands has annealed granoblastic textures, with straight extinction. This implies that the shear-bands developed during cooling; temperatures were not high enough to remove grainboundaries and form coarser grains, but were still enough to anneal strained unduloseextinction from the quartz and feldspar grains. Specimen MB90/9, a pelitic rock dominated by garnet-porphyroblasts and dark biotite, contrasts with most pelites in which biotite is annealed, having strongly kinked biotites (Fig. 3.11h). The assemblage, although containing more biotite than is normal for pelitic rocks from the nPCM, does not appear to be a low grade mineralogy. The preservation of kinked biotites may be explained by late deformation equivalent to that which developed the shear-bands in more leucocratic pelites and felsic gneisses, but as biotite alone makes up the groundmass, it was necessarily deformed in preference to the rheologically stronger garnets. In this rock, kinking is the deformational mechanism, equivalent to the development of narrow shear-bands in more incompetent leucocratic-zones of pelitic and felsic lithologies.

Minor dislocations cross cut the foliation, at high angles (Fig. 3.11g); in some samples, the dislocations are associated with the localized formation of very fine grained ilmenite. At Mt Dovers this cross-cutting fabric is identifiable in hand specimen. The foliation is defined by fine grained biotite which cuts across garnet-porphyroblasts, and in places also through the  $S_{1-2-3}$  foliation. However, its orientation is often variable and may be refracted into parallelism with the early foliation, by anisotropic zones, rich in garnet. As the fracture cleavage is difficult to detect in hand-specimen (particularly in the field), its orientation was not comprehensively quantified, however, its usually truncates the generally moderately dipping gneissosity sub-perpendicularly, and its formation may therefore be temporally associated with the development of MY<sub>3</sub>-mylonites.

In the more leucocratic layers, the truncations are most noticeable dislocating sillimanite, frequently with the development of larger grains of ilmenite, which appear to acted as nucleation sites for its growth; the dislocations are more difficult to trace away from these grains, but usually the discrete fault planes are distinguishable by the trace of very fine grained ilmenites. East-west striking minor, conjugate shear sets, dipping at approximately  $35^{\circ}$  to the north and south, truncate the sub-vertical mylonites at Fox Ridge. This relatively minor deformation therefore post-dates the formation of the gneissosity and the development of the second generation mylonites (MY<sub>2</sub>). The third generation mylonites, MY<sub>3</sub>, have sub-horizontal orientations, and are associated with pegmatites. Frequently they are encapsulated by zones rich in biotite and hornblende, indicating the influx of partly hydrous fluid, with the pegmatite. Significantly, both MY<sub>3</sub> and the narrow microscopic shear-zones have sub-horizontal orientations, and the alignment of fine grained ilmenite in the narrow shear-zones



may be associated with the influx of late fluids. If this association is correct, the development of the microscopic shears probably occurred at the same time as  $MY_3$ , (probably about 500 Ma, see section 3.8.2).

## 3.10.3.2 Retrograde fabrics

Retrograde textures in pelitic, calc-silicate and felsic gneisses are used in Chapter 6 to interpret cooling trajectories accompanied, particularly in the east, by some decompression. Spinels were classified into three distinct morphologies; third generation spinels, Spl<sup>3</sup>, occur between boudinaged sillimanite (e.g. Fig. 3.9a), in an assemblage of biotite, and cordierite. They form fine-grained delicate symplectitic forms within the enclosing biotite. Where well developed, the fabric is formed at a high angle to the foliation, and may form an interconnected "foliation" between successive boudin necks. The brittle deformation style of sillimanite, and the orientation of the Spl<sup>3</sup> fabrics suggests that the deformation responsible for their formation post-dated the early gneissosity-forming and folding episodes, and probably occurred relatively late in the cooling trajectories of these rocks.

#### 3.10.4 Timing summary

The early high strain deformational episode which produced layering, successive transpositions of gneissosities, the first generation high grade mylonites (MY<sub>1</sub>), and at least the first three, sheath, isoclinal, close to tight,  $F_1$  to  $F_3$ , and possibly the  $F_4$  fold generations, are interpreted to have occurred at or very near peak metamorphic conditions. During retrograde cooling and decompression minerals underwent re-equilibration and reacted to produce new assemblages, while deformational strains are considered to have waned. During the thermal relaxation, but before the early deformational strains had completely abated, Spl<sup>3</sup> symplectites developed in the interboudin necks of boudinaged sillimanite.

At least two generations of mylonites post-date the development of the peak assemblages: the earlier mylonitization,  $MY_2$ , occurred at low grade granulite, to high grade amphibolite facies conditions, and although they strike sub-parallel to the gneissosity, they truncate the gneissic layering. The later  $MY_3$  event which occurred at probably middle amphibolite facies conditions, post-dates the second generation mylonites, and appears to be the deformation responsible for the microscopic shear-zones.









# 3.11 Discussion

# 3.11.1 Introduction

Significant regional similarities and differences occur in the structural interpretations of the exposed Archaean and Late Proterozoic granulites in East Antarctica, from the northern Prince Charles Mountains, the Reinbolt Hills, and along the Antarctic coastline, to outcrops in the west, Kemp Land, and those in the east, the Rauer Islands. The structural scenario of the nPCM is compared here with descriptions of structural interpretations reported in the literature, and are schematically summarised and correlated in Table 3.1.

Correlation of the deformational histories is based on the recognition of (a) an early progressive, rotational deformation developing coaxial structures, (b) the similarity of fabrics in the Mawson and Reinbolt charnockites, (c) the assumption that the recorded peak metamorphic conditions in all regions were reached simultaneously, (d) that decompression described in these areas was initiated at a similar time, (e) the correlation of steeply dipping mylonitic-zones, with MY<sub>3</sub> described above, and (f) the possible correlation of later, frequently greenschist facies retrograde shear zones, or MY<sub>3</sub> mylonitization, which probably record a synchronous response to an equivalent deformational episode in the extensive areal regions.

# 3.11.2 Correlation with the Reinbolt Hills

The deformational evolution and structural relationships of the Reinbolt Hills described in Part I, of this chapter, correlate well with the structures of the nPCM (Table 3.1). The fold, and fold-interference relationships, which post-date the development of the high-grade gneissic foliation, have comparable features. For example, F<sub>1</sub> folds are intrafolial and often rootless, F<sub>2</sub> folds have high-strain characteristics such as a quartz rodding axial-planar fabric in the Reinbolt Hills, and sheath geometries in the nPCM. Succeeding, or in the latest stages of D<sub>2</sub>, the emplacement of charnockitic magmas appears to be a correlatable feature of these areas, and of other Late Proterozoic East Antarctic complexes. Third deformation folds in both the Reinbolt Hills and the nPCM are characterized by close to open geometries, and relatively weak biotite or absent, axial-planar foliation. These three early deformations are interpreted to have been high strain, progressive, and rotational, concomitant with highgrade metamorphic conditions in both regions. Gneisses from the Reinbolt Hills have granoblastic, equigranular textures indicating that metamorphism outlasted the major kinematic episodes. Whilst unmylonitized nPCM gneisses have annealed quartz and feldspar textures, the degree of annealing is less, and fine-grained partially annealed shear-bands (Fig. 3.11a), sigmoidal garnet-porphyroblasts (Figs. 3.9c, d & g), and boudinaged sillimanite (Fig. 3.9a) mineral fabrics strongly suggest that although the major kinematic

northern Prince Charles Mountains	Reinbolt Hills, McKaskle Hills, & Jennings Promontory	porthem Prince Charles Mountains, Fitzsimons & Thost 1992	Radok Lake, McKelvey & Stephenson 1990	Dépot Peak, Stüwe & Hand 1992	Kemp Land, Clarke 1988	Larsemann Hills, Stüwe <i>ei al</i> 1989	Brattstrand Bluffs, Fitzsimons & Harley 1991	Rauer Islands, Hartey 1987
Protolith development, from felsic volcanies, mafic i gneous(?) rocks, and minor mæbled and meda-polities from sectimentary progenitors	Protolith development, accretion of Archaema(?) blocks; large scale compositional layering developed	Protolith formation, composed of granitic intrusion, with minor sediments Mafic dyke intrusion	Gross lithological layering varying from em to 108 of m.existed before meamorphism, but modified by deformation				Archaram(?) protolith D1 M1 S1 in mafic bodies, crosscut by surrouding gneisses Opx mell segregations, migmatics, felsic & pelitic protolith emphacement * D2 M2 S2 nurely preserved in P3 hinges	Archaem(?) protolith D1 M1 S1 in mafic bodies, possibly S1 in pelites, Archaean D2 F2 folding S1 & Opx segregations, Archaean? Intrusion of mafic to felsic orthogneisses & charnockites, 1400- 1200 Ma
* D1 S1.2 F1.2 rotational, high strain deformation wanpooling layering, defined by high grade mineralogies, tooclinal intrafolial folds. MY1 high strain, layer- parallel high metamorphic grade mylonites, consistently, easterly or southerly transport direction	* D <sub>1</sub> S <sub>1</sub> F <sub>1</sub> development of the gnessic fabric, probable initial formation of intrafolial rootless folds, granulite factes	D1 S1 L1 veriably developed in mafic boutins D2 F2 low amplitude folds deform S1 in mafic boutins D3 S3 pervasive development of S3 foliation, tentatively dated at 1000 Ma	D1 S1 proterved as an alignment of minerals and metamorphic layering in the oldest observed folds, isoclinal folding assumed pegmatile emplacement	D1 F1 S1 L1 NS oriented sillimanite lineation, and the development of the strong layer- parallel foliation. F1 rarely observed Partial melts, syn or post metamorphic peak	* D1 F1 NS to NE-SW tending recumbent folds, retarded curved hinges, retringrade S1 foliation of sil + bt, intense L1 EW to SE- NW with an incipient rodding fabric, suggested westerly shear		* Da Ma (6 kber, 840°C) strong Sa La Facerly toochand folds & partial melting of pelitic lithologies producing migmatites 1000 Ma Intrusion of the granitic orthogneiss	* D3 M3 (7-9 kbw, 800- 850°C) S3 L3 F3 isoclinal, steeply plunging, regarded hy Harley to be >1200 Ma Orthogeneisses & leucogneisses Suite of dolorist dykes emplaced 1000-1100 Ma
* D2 L2.3 F2 isoclinal, intrafolial, rootless & sheath folds. Rare macroscopic F2 folds, e.g. McKinnon Giscier	* D2 L2.3 F2 S2 isoclinal, intrafotial folds with characteristic quartz rodding axial planar fabric, plunging southerly, granulite facies	D4 recumbent isoclines deform \$3 partial melts	D2 S2 F2 isoclinal, rootless, similar-style, intrafolial folds, mainly preserved as hinge-zones, and producing a surong steeply dipping \$2/\$1 gneissosity		<ul> <li>D2 F2 variable folding isoclinal-tipht-gentle warps, EW S2 of realigned bt</li> </ul>			
Emplacement of the K- feldspar-bearing, and foliated granitoids at Fox Ridge and Mt Béchervaise	Emplacement of the Reinbolt Charnockite	Emplacement of coarse grained charnockite	post-D2, pegmatites		Emplacement of the Mawson Charnockite, dated at 954±12 & 985±29 Ma. Young & Black 1991			
* D3 L2.3 F3 tight to close to open, folds, coaxial with F2	* D3 L2.3 F3 tight-open folds with equivalent crientations to F2, alignment of K. feldspar megacrysts within the Reinbolt charnockite into parallelism with S3. Besaltic dyke emplacement late D3. M3 recorded peak granulite conditions 7 bos 800° C, outlesting deformation, Nichols & Berry 1991	Ds Ls F3 open to tight symmetrical folds with an eastward plunging mineral lineation partial metts	D3 L3 F3 tight to close, upright similar to concentuic-style folds, axial planes with a ligned biotitic fabric, strike ENE, with hinges plunging 30-40° ENE. Lineations plunge 35-40° ENE	D2 F2 macroscopic folding producing the purposition of https://www.com/ lithelysis at Depot Peak, no microscopic features recognized with this episode.	* D3 L3 F3 open-isoclinal folds with steep F dippung S1 & L3, S3 within the Mawson Charnockite defined by alignment of K- foldspar megacrysts and bt	D1 F1 S1 assemblages of sill + spl M1 (4.5 kbar 750°C)		
MY2 high strain, cross- cuting but sub-parallel, low granulite to high simphibilite facies grade myionites. Strong, sub-verticelly plunging mimeral- stretching lineations with consistent relations with consistent relations frequently associated with similar orientation resuduate/vitation		D6 S6 L6 east plunging. east-west trending folds, upright high- strain zones						
	Pegmatite emplacement 895 Ma (Grew & Manton 1977)	Felsic intrusives						
Emplacement of the Loewe Messif Charnockite	Emplacement of the Jennings Promoniory Chernockite. The 405 Ma value reported by Stuiver & Braziunas 1985, represents a cooling age				Â			
D4 F4 open folds, deforming L2.3						D2 F2 isoclinal to open, asymmetrical folds	D4 L4 F4 recumbent to shallow, asymmetric limbs attenuated where	* Da La Fa upright SE plunging folds, coaxial

phase occurred during peak metamorphic conditions, significant deformation occurred during the waning stages of metamorphism.

After the main kinematic evolution, a second suite of charnockitic magmas were emplaced, as the Jennings Promontory Charnockite along the East Lambert Glacier, and the Loewe Massif Charnockite in the nPCM.

Later,  $F_4$  folds which outcrop at Wall Peak in the nPCM were not recognized in the Reinbolt Hills. Significant decompression is calculated for the Reinbolt Hills rocks, the McKaskle Hills gneisses along the East Lambert Glacier, and similar decompressional or cooling trajectories are estimated for the nPCM gneisses (Chapter six). This is a feature common to most of the East Antarctic gneisses for which *P*-*T* paths have been reported.

Mylonites with shallowly dipping shear-surfaces, and common eastward movement directions, were found in the McKaskle Hills, Jennings Promontory, and Reinbolt Hills, and probably correlate with the MY<sub>3</sub> mylonitic event of the nPCM. The right-lateral shear-component, and west block towards the east of MY<sub>3</sub>, matches the interpreted movement-sense of East Lambert Glacier mylonites.

Differences in the structural evolutions of the two regions are not significant. Early  $MY_1$  and  $MY_2$  mylonitic fabrics were not differentiated in the Reinbolt Hills, perhaps because the nPCM area underwent more extensive annealing than the Reinbolt Hills, obliterating early layer-parallel structures. The fifth deformation which produced the spaced cleavage in the Reinbolt Hills, was not observed in the nPCM localities studied, although is reported by McKelvey & Stephenson (1990) (section 3.11.4). This feature is mooted to be related to the Late Carboniferous, or Permo-Triassic aged development of the Lambert and Radok Lake Grabens, and probably therefore is localized to regions immediately adjacent to these extensional structures.

# 3.11.3 Correlation with the Amery Peaks & Porthos Ranges

In Fitzsimons & Thost's (1992) description of the deformational history of the Amery Peaks and Porthos Ranges in the nPCM, eight deformational episodes are defined, following the formation of a granitic protolith, intruded by mafic dykes. Their first deformation,  $D_1$ , is recognizable by an S<sub>1</sub> foliation and L<sub>1</sub> lineation, within mafic-gneiss boudins. Low amplitude, disharmonic F<sub>2</sub> folds deform the S<sub>1</sub> foliation within the mafic-gneiss boudins, and define the second deformation,  $D_2$ . Their third deformation, D<sub>3</sub>, produced a pervasive flat-lying S<sub>3</sub> gneissosity in the basement gneisses, and boudinage of the mafic and ultramafic gneisses. Fitzsimons & Thost (1992) tentatively correlate this with the pervasive metamorphic 1000 Ma event, which affected this region of East Antarctica. D<sub>4</sub>, is characterized by 2-5 m, half-wavelength, recumbent F<sub>4</sub> isoclines, which fold S<sub>3</sub>. Postdating D<sub>4</sub>, they recognize a partial melting episode, the intrusion of coarse grained charnockites  $\approx$ 960 Ma, succeeded by the intrusion of two or more mafic-dyke generations. Their fifth deformation, D<sub>5</sub>, produced open to tight symmetrical and upright folds ("<150 mm" *op cit*), and an eastward shallowly plunging mineral lineation, L<sub>5</sub>, defined by quartz ribbons, and mafic mineral. Further partial melting post-dates D<sub>5</sub>: D<sub>6</sub> which they suggest occurred at 920 Ma, deformed the gneissosity to produce its east-west orientation by folds, and formed eastward trending high strain zones with an east-plunging L<sub>6</sub> lineation, and an intense upright S<sub>6</sub> foliation. Planar, and irregular felsic intrusives post-date D<sub>6</sub>. D<sub>7</sub> is characterized by shallowly dipping shear-zones, some of which are associated with pegmatites. Their eighth deformation, D<sub>8</sub>, produced pseudotachylytes and mylonites, which they claim have "sub-horizontal to shallow-dipping" orientations whereas "wider mylonite zones ... are usually steep" (Fitzsimons & Thost 1992). Finally, they report that alkali basalt and alkali mela-syenite post-date all other lithotypes and deformations.

Fitzsimons & Thost (1992) recognize many features which are common to the structural history described here. The most important features which provide the basis for a regional structural correlation, depicted in Table 3.1, are (a) the observation of an early gneissosity produced during a pervasive deformation, and which was deformed by isoclinal folds, (b) probably synchronous emplacement of charnockitic and granitoid bodies, in both areas, (c) evidence for the deformation of early isoclinal folds by later, more open styled folds (d) the probable similarity of what Fitzsimons & Thost (1992) describe as upright high-strain zones, with the second generation mylonites, MY<sub>2</sub>, (e) equivalent post-peak metamorphic histories, and (f) the correlation of their seventh and eighth deformations, small-scale shears associated with pegmatites, and their undifferentiated mylonitic deformations, with the MY<sub>3</sub> event described above. The largest difference in the structural histories is that Fitzsimons & Thost (1992) interpret textures from mafic-gneiss boudins, that are included within felsic gneisses, as features which were produced during deformations that pre-date the development of the pervasive gneissic foliation. They describe the earliest structures as a foliation,  $S_1$ , and lineation  $L_1$ , defined by a compositional and mineral alignment, which are deformed by low-amplitude disharmonic F<sub>2</sub> folds. In section 3.12 the arguments for favouring a progressive and rotational deformational mechanism are discussed. Regardless of which deformational pathway is considered the most realistic, it must not ignore the abundant and incontrovertible evidence that early deformation was extremely high strain. For example, high strains, incremental deformation, and reorientation in basic dykes east of Edward VIII Gulf, Antarctica, has been reported by Trail (1970) and Sheraton et al. 1988; while significant strains recorded by interboudin / boudin ratios of 20-30, are reported by Sandiford & Wilson (1984) for Archaean rocks of the Napier Complex. If this is acknowledged, any interpretation of early episodes of deformation from boudins should be considered carefully.

Despite these interpretational differences, Fitzsimons & Thost's (1992) deformationalhistory is compatible with the succession of episodes described here, once their early two deformations are amalgamated into the deformational phase which produced the pervasive gneissosity,  $D_1$ .

# 3.11.4 Correlation with the Radok Lake area

McKelvey & Stephenson (1990) give a relatively brief description of the deformational history of gneisses from the Radok Lake area, in the north-easterly area of the nPCM. They recognize two folding generations which post-date the development of a metamorphic layering aligning an  $S_1$  mineral foliation. As shown in Table 3.1, their respective fold generations appear correlatable with the second and third folding deformations observed in the nPCM and the Reinbolt Hills; in both regions,  $F_2$  and  $F_3$  folds preserve similar styles, textures and relationships with the earliest recognized tectonic fabric, the metamorphic gneissosity. McKelvey & Stephenson (1990) also report pseudotachylytes, but are only able to constrain the relative timing of their formation to post-date the high-grade metamorphism. They describe a steeply dipping joint set, striking SSE, with typical domain widths of 1-5 m, and also of 5-10 cm. Similar and correlatable features were observed in the Reinbolt Hills, with a possible conjugate NE-SW strike orientation.

# 3.11.5 Correlation with Kemp Land and the Larsemann Hills

Clarke (1988) in describing granulite facies rocks from Kemp and MacRobertson Lands, delineates three major deformational episodes he terms the "Rayner Structural Episode". Clarke's D<sub>1</sub> is characterised by recumbent isoclinal F<sub>1</sub> folds with an S<sub>1</sub> fabric defined by sillimanite and biotite that retrogressively overprint garnet and cordierite. Curved F<sub>1</sub> fold axes, only observed in incompetent lithologies such as calc-silicates and migmatites, were interpreted to have rotated into parallelism with an intense, gently east and west plunging mineral and rodding lineation, during D<sub>1</sub>. However, unrotated F<sub>1</sub> folds, in felsic and quartrich gneisses, retain hinge-trends either, NS or NE-SW. Clarke's D<sub>2</sub> and D<sub>3</sub> have open to tight folds with axial planes striking E-W and NE-SW, defined by lower grade axial-plane foliations of biotite. The Mawson Charnockite has a fabric alignment of feldspar megacrysts which Clarke correlates with S<sub>3</sub>, and is truncated by D<sub>4</sub> mylonites and pseudotachylytes (Clarke 1990). The charnockite has an U-Pb zircon age of 954±12 and 985±29 Ma (Young & Black 1991). The D<sub>4</sub> mylonite zones have an interpreted south over north sense, with right-lateral shear components.

The deformational evolution of Kemp Land described by Clarke (1988) correlates well with that described for the nPCM and that of the Reinbolt Hills (Table 3.1). These areas have similar successions of fold generations, and the deformed Mawson Charnockite has characteristics similar to both the Reinbolt Hills Charnockite and foliated granitoids in the nPCM. Clarke (1988) suggests that the early deformations, were produced during progressive deformation. He suggests that  $F_1$  fold hinges, originally with NS orientations, were reoriented by progressive shear, to EW trends during D<sub>1</sub>. However, L<sub>1</sub> mineral lineations are sub-parallel to F<sub>2</sub> fold axes, and it therefore appears that F<sub>1</sub> fold hinges were deformed into parallelism with the shear orientation accompanying D<sub>2</sub>. Clarke (1988) surmises that the polarity of the shear deformation was towards the west, based on the orientation of the L<sub>1</sub> lineations, and the asymmetry of F<sub>1</sub> fold limbs. However, he presents little data supporting this assertion. An alternative interpretation of the data he presents is that shear deformation synchronous with D<sub>2</sub>, had an east-west polarity, indicated by L<sub>2</sub> minerallineations, and rotated originally north-south oriented F<sub>1</sub> fold-axes preserved in incompetent lithologies, into the east-west orientation.

In summary, the nPCM and Kemp Land structural histories can be correlated with moderate confidence. The main similarities include the succession of similar fold generations, the recognition of equivalent superposition of structural episodes accompanied by metamorphic conditions which under went similar changes with respect to the deformational evolution. The differences are the interpreted early transport directions (W? in Kemp Land, and S to SE in the nPCM), and the opposite movement sense of postmetamorphic peak mylonites, although a right-lateral shear-component of movement is common to both structural scenarios.

The deformational history of the Larsemann Hills described by Stüwe *et al.* (1989) for dominantly meta-pelitic lithologies of this area, is characterised by lower peak metamorphic grades (3.5-4.5 kbar, 800-750°C) and the development of  $F_1$  folds with accompanying  $S_1$ assemblages of sillimanite and spinel. Decompression occurred during  $D_2$  with the contemporaneous formation of open to isoclinal asymmetric folds (Stüwe *et al.* 1989). The third major deformation  $D_3$ , which Stüwe *et al.* (1989) believe occurred around 500 Ma, is characterised by regional  $F_3$  folding at pressures of about 3 kbar. The relative timing of  $D_2$ in the Larsemann Hills, is constrained to accompany decompression (Stüwe *et al.* 1989), an event which is assumed here to have occurred synchronously throughout much of East Antarctica. As there is little evidence for pervasive macroscopic folding episodes in the East Antarctic region succeeding decompression (Table 3.1), it is assumed that the Larsemann Hills D3 occurred before decompression. Their first recorded deformation, during which the
gneissosity was formed and isoclinally folded, is tentatively correlated with the third deformation in the Reinbolt Hills and nPCM.

# 3.11.6 Correlation with the Rauer Islands and Brattstrand Bluffs

Fitzsimons & Harley (1991) describe the deformational history of granulite facies gneisses from Steinnes Peninsula and Brattstrand Bluffs area, Prydz Bay, and their correlatives in the Larsemann Hills (to the west), and with the findings of Harley (1987) in the Rauer Islands. In both the Rauers and Brattstrand region Fitzsimons & Harley delineate D<sub>1</sub> as an event which produced a foliation defined by pyroxene, amphibole and feldspar in mafic "bodies". They suggest that orthopyroxene segregations formed post-D<sub>1</sub>, and that folds deforming them, and  $S_1$ , were produced during  $D_2$ . However  $D_2$  in the Brattstrand region is only preserved as isoclinal folds, and as folded S<sub>2</sub> within D<sub>3</sub> garnets, and so they suggest that S<sub>1</sub> and  $S_2$  formed in the same episode.  $D_3$  in the Rauer Islands occurred with peak metamorphic conditions of 7-9 kbar and temperatures of 800-850°C, and post-dates the emplacement of the felsic orthogneisses. F3 isoclinal, steeply plunging folds were produced during D<sub>3</sub> contemporaneously with S<sub>3</sub> and L<sub>3</sub>; a zircon age of 1030 Ma (Kinny & Black 1990) is interpreted as the age of D<sub>3</sub> in the Rauers. Fitzsimons & Harley (1991) tentatively correlate the Rauer Island's D<sub>3</sub> with D<sub>3</sub> in the Brattstrand region where peak metamorphic conditions of 6 kbar and 840°C were experienced concomitant with the formation of a strong S<sub>3</sub>, L<sub>3</sub> fabric, rare isoclinal F<sub>3</sub> folds and partial melting of meta-pelitic lithologies.

 $D_4$  in the Rauers is typified by upright  $F_4$  folds with a well developed  $L_4$  lineation and ductile shear zones. These features contrast with the recumbent to shallowly dipping  $F_4$ folds with sheared asymmetric limbs from the Brattsrand area. In both regions, decompression continued until the end of  $D_4$ , to pressures around 3-5 kbar in the Rauers and 3.5-4 kbar in the Brattstrand area. Two further folding deformations, at amphibolite facies conditions, are described by Fitzsimons & Harley (1991) for the later region; both are characterized by changes in the orientation of  $L_4$  and  $S_4$ . Brittle style mylonites develop as the last deformation in both study areas.

The correlations of the Rauer Island and Brattstrand Bluffs structural evolutions are depicted in Table 3.1. The structural interpretation of both areas incorporates a nomenclature for an early S<sub>1</sub>, deformed by F<sub>2</sub> folds, which is only preserved within mafic boudins. As explained above such interpretations are hazardous considering the recognized high strains pervasive during early deformation. Therefore in this correlation, the D<sub>1</sub> and D<sub>2</sub> events interpreted by Harley (1987) and Fitzsimons & Harley (1991), are amalgamated with the third deformation, the main gneissosity forming phase. Despite this difference, the structural evolutions for these areas are similar to the nPCM and the Reinbolt Hills. However, they were unable to differentiate between early and later mylonitic generations, and contrary to the nPCM structure described here, place the formation of mylonites and shear-zones, as the ultimate deformational episode.

# 3.11.7 Correlation with Depot Peak

The structural history of Depot Peak, which lies approximately half-way between the nPCM and the Mawson coastline, is briefly described by Stüwe & Hand (1992), who recognize two early pervasive deformations. They define  $D_1$  as the deformation which produced the layer-parallel foliation, rare  $F_1$ -folds, and an  $L_1$  lineation of sillimanite which trends NS. Partial melts are layer-parallel but are not deformed by  $D_1$  structures, and they therefore interpret that melt was present either during or after, peak metamorphic conditions. They therefore correlate peak metamorphic, with peak kinematic conditions. They suggest that the second deformation produced the outcrop-scale open folds, but Stüwe & Hand (1992) do not recognize any microscopic features related to D<sub>2</sub>. Shallowly northward dipping, normal shear-zones, post-date D<sub>2</sub>, however, they have a northward plunging L<sub>2</sub> sillimanite lineation. As  $L_2$  is sub-parallel to an alignment of K-feldspars in  $S_1$ , they suggest that  $D_1$ and D<sub>2</sub> formed "during a continuum" (Stüwe & Hand 1992). The shallowly dipping shearzones apparently change along dip, from normal to reverse movement senses, and they interpret this as the rotation of sheared layers into the shortening stress field, resulting in folding. Pegmatite veins were intruded along the shallowly dipping shear-zones, and some are deformed by movement along these faults. The shallowly dipping geometries described by Stüwe & Hand (1992) for these shear-zones, their association with pegmatites, and the typical drag-fold deformation of the surrounding gneisses, are features common to the MY<sub>3</sub> mylonites described here throughout the nPCM. On this basis, this deformational episode appears common to Depot Peak and the nPCM area.

Stüwe & Hand (1992) are unable conclude between two possibilities for the macroscopic distribution of a garnet-bearing granite, which occurs as the upper and northern portion of the Depot Peak outcrop. They suggest that either it represents the hinge of a large "D2 fold", or is "part of a north over south verging sequence". If the latter suggestion is correct, then the early north towards south, shear direction interpreted from nPCM MY<sub>1</sub> mylonites, was possibly a widely distributed, and pervasive deformational event.

The correlation of Stüwe & Hand's (1992) deformational synopsis is shown in Table 3.1, the main features which appear common to the nPCM and Depot Peak, are the recognition of early folds which deform the high grade gneissosity; their second deformation  $F_2$  folds, on the basis of geometry, appear to be most similar with the  $F_3$  of the nPCM and the Reinbolt Hills. The shallowly-dipping shear-zones, associated with pegmatites are

correlated with  $MY_3$  of the nPCM. Finally, the possibility of north towards south vergence, may be an equivalent to the early shear directions determined for the nPCM.

3.11.8 Correlation with the Proterozoic re-working in the Napier Complex The structural evolution of the Fyfe Hills in the Khmara Bay region, East Antarctica, is described by Sandiford & Wilson (1984), and Sandiford (1985). The coastal Khmara Bay area lies within the Archaean Napier Complex, and is approximately 40 km from the inferred boundary between the Rayner Complex, reworked late in the Proterozoic (Sheraton *et al.* 1980), and the Napier Complex. The preserved structural features of the Rayner deformations, termed by Sandiford & Wilson (1984) D<sub>4</sub> and D<sub>5</sub>, are the development of an S<sub>4</sub> foliation within the retrograde shear zones, frequently defined by high-pressure kyanitebearing assemblages, and the formation of discontinuous and continuous sub-vertical, D<sub>5</sub> mylonite zones. They attribute their formation to rotational strain during progressive deformation. Sandiford (1985) also describes a third high-grade mylonite variety which is characterized by orthopyroxene-bearing assemblages, however the relationships with their D<sub>5</sub> mylonites are not discussed.

The discontinuous mylonites, typically have EW trends, amphibolite-grade mylonitic fabrics, and sheath-folds with sub-vertical axes which are sub-parallel to an L<sub>5</sub> mineral-aggregate lineation. They thus interpret an almost vertical movement sense within the discontinuous mylonite zones. Continuous mylonites zones, have variable strikes, sub-vertical dips, and based on Sandiford & Wilson's (1984) Figures 11e & f, they deform the surrounding gneisses with drag-fold geometries. Furthermore, the continuous mylonites are associated with variably deformed pegmatites. The displacement sense of a particular continuous mylonite-zone with an observed southerly plunging lineation at  $\approx 70^{\circ}$ S, on McIntyre Island, is described by Sandiford & Wilson (1984) and is depicted in their Figure 11e. However, they state that the displacement sense has a left-lateral component, contrary to the right-lateral component, suggested by drag-fold asymmetry, displayed in their Figure 11e and reproduced as Figure 3d in Sandiford (1985).

Despite the uncertainties in shear-geometries, the mutually cross-cutting relationships of the D<sub>5</sub> mylonite generations described by Sandiford & Wilson (1984) suggest that they were formed contemporaneously, or at least underwent contemporaneous reactivation, and have many similarities with the nPCM MY<sub>2</sub> and MY<sub>3</sub> mylonitic generations. The discontinuous mylonites have similar grades to some MY<sub>2</sub> mylonites in the nPCM: continuous mylonites like MY<sub>3</sub> mylonites, are associated with pegmatites and deform the adjacent gneisses with drag-folds. It can therefore be speculated that the discontinuous mylonites are equivalent to the earlier nPCM MY<sub>2</sub> mylonites, and were reworked during a

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comparable MY<sub>3</sub> episode. However, as insufficient shear criteria are described by Sandiford & Wilson (1984) and Sandiford (1985), it is unclear whether their  $D_5$  and the nPCM MY<sub>2-3</sub>, represent the same deformations, or are the same but conjugate-orientation deformations, or are simply similar style deformations affecting rheologically-comparable high-grade rocks and thus producing equivalent textures, fabrics and field relationships. The possible correlation of these events, described here, is conjectural.

# 3.12 Progressive rotational deformation in East Antarctica

Implicit in the nomenclature of the deformational history of the northern PCM is the concept that during the preserved peak metamorphic conditions, deformation occurred in a progressive manner. Structures developing during  $D_{1-2}$  were successively and variably transposed by  $D_3$  fabrics.

The progressive nature of ductile, rotational deformation in the Reinbolt Hills and nPCM, from D<sub>1</sub> through to D<sub>3</sub> is strongly supported by continuous fold generations having equivalent orientations which parallel L<sub>2-3</sub> stretching lineations. Implicit in this model is the concept that differing fold structures (i.e.  $F_1$ ,  $F_2$  or  $F_3$ ) may form at the same time, although separated in space, their formation being controlled by local stress gradients with respect to previously formed fabrics. Thus  $F_2$ - $F_3$  interference patterns (e.g. Fig. 3.10c) preserve a relatively unevolved, although probably coeval, equivalent of  $F_{1-2}$ - $F_2$  fold geometry (Fig. 3.10d).

A constant strain orientation throughout deformation is recognized by Clarke (1988), from  $D_1$  to  $D_3$  where an east-west polarity is interpreted from mineral lineations. Fitzsimons & Harley (1991) concede the difficulty in determining the relative timing of S<sub>2</sub> foliations, preserved in garnets and rare F<sub>3</sub> fold hinges, and infer that their  $D_2$  is an earlier episode of  $D_3$ . Given that these criteria have been recognized in areas to the east and west of the Reinbolt Hills, and that transposition of successive fabrics is common, it is suggested that deformation along this part of East Antarctica is correlatable within a continuous ductile, progressive rotational deformational regime.

While high-strain deformation is recognized by Sandiford & Wilson (1984) and Sandiford (1985), Clarke (1988) suggested that it was also progressive, and the term has been applied in a general sense by Fitzsimons & Harley (1991) and Fitzsimons & Thost (1992). However, the concept that early deformation could be considered as progressive and rotational, was introduced by Nichols & Berry (1991) for the Reinbolt Hills area.

As there are many clear similarities between the early ubiquitous high strain structures of the nPCM, the Reinbolt Hills, Kemp Land, the Rauer Islands, Brattstrand Bluffs, and Depot Peak, it is suggested that progressive rotational deformation was pervasive throughout much of this region of East Antarctica, during the Late Proterozoic.

# 3.13 Summary

The structural features of the Reinbolt Hills and the northern Prince Charles Mountains are dominated by early high strain deformational episodes, during which the gneissosity was transposed, in many areas suffered layer-parallel extension, and was deformed by at least three, and four (in the nPCM) identifiable, fold-styles. The parallelism of mineral-stretching lineations and fold axes, is interpreted to result from high strains, accompanying the early structural phase, during which early-formed structures were progressively rotated into the orientation of tectonic movement. Sub-horizontal, northward dipping, fault zones at Mt Lanyon and Mt Meredith, with inferred south-eastward and eastward reverse movements, are interpreted as early mylonitic thrust zones ( $MY_1$ ). There are no metamorphic-grade distinctions between mineralogical fabrics associated with the gneissic layering,  $MY_1$  mylonites (in the nPCM), or with the early fold generations which deform the layering, as all features were apparently produced during peak granulite-facies conditions. In most other regions, later deformation has rotated the orientation of early mineral-stretching lineations into generally steeper plunging orientations, with both easterly and westerly trends.

Coaxial  $F_2$  and  $F_3$  folds responsible for the orientation of much of the gneissic layering, were produced synchronously with peak metamorphic conditions, and during a continuation of the northwest-southeast directed stress regime, which is first recognizable, by the development of MY<sub>1</sub> thrusting. Later F<sub>4</sub> folds, macroscopically significant at Wall Peak and at Mt Béchervaise, are suggested to have formed in response to an east-west directed shortening, during the waning stages of metamorphism.

In the nPCM region, second generation mylonites, MY<sub>2</sub>, formed after peak metamorphism at low granulite to upper amphibolite conditions, and are characterised by sub-vertical dips, and northeast-southwest strikes. They consistently have reverse movement, and except for one specimen from Mt Lanyon (LAN90/10), they have a northwest block up, shear sense. It is feasible that MY<sub>2</sub> mylonites were produced in response to sub-vertical crustal movements, responsible for crustal exhumation that is recorded in the metamorphic cooling and decompressional trajectories throughout the northern Prince Charles Mountains and Eastern Lambert Glacier region. Alternatively they record crustal movements during the diminution of metamorphic conditions.

Once substantial uplift had occurred, and the crust had cooled significantly,  $MY_3$  mylonitization occurred, probably around 500 million years ago. They may have been related to additional crustal heating evidence by the localized production of granitic-

pegmatitic magmas, which are frequently emplaced along MY<sub>3</sub>'s fault zones. They consistently depict right-lateral, or eastward tectonic transport.

In summary, the approximately east-west orientation of the northern Prince Charles Mountains and the Reinbolt Hills' structures, together with consistent top to the southeast transport interpreted for early thrusting directions, followed by relative northwest block up movements, and an ultimate episode of easterly, right-lateral shear movement, are features consistent with a northwest to southeast compressional regime, which accompanied metamorphism from peak granulite to retrograde amphibolite, and finally greenschist facies conditions.

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# Chapter 4

# THE METAMORPHIC HISTORY OF THE REINBOLT HILLS

## 4.1 Introduction

The Reinbolt Hills form part of a north-south trending belt of nunataks, exposed on the eastern side of the Lambert Glacier, which include Jennings Promontory and McKaskle Hills some 300 km south-west of Davis Base (Fig. 3.1). The 10 km long by 7.5 km wide exposure of Late Proterozoic (Grew & Manton, 1977) basement forming the Reinbolt Hills is composed of mafic to felsic granulites facies gneisses and charnockite. These rocks are part of the extensive Late Proterozoic granulite province of East Antarctica, which crop out in Enderby Land (Rayner Complex), Prince Charles Mountains, Prydz Bay-Vestfold Hills (Rauer Group), Bunger Hills and the Windmill Islands (James & Tingey 1983). This belt includes Archaean cratonic blocks that are exposed to the east in the Vestfold Hills (Oliver *et al.* 1982), to the west in Enderby Land (Sheraton *et al.* 1980) and to the south-west in the southern Prince Charles Mountains (Tingey 1982).

The Reinbolt Hills form an important link in the correlation of the intensively studied Rauer Group with Lower Proterozoic rocks exposed in the northern Prince Charles Mountains.

# 4.2 Timing of metamorphism and deformation

The deformation history of the Reinbolt Hills is described in Part I of Chapter 3, and is schematically correlated with other East Antarctic regions in Table 3.1. Three early deformations are recognized which produced three coaxial fold generations, that post-date and deform the layer-parallel gneissosity. The parallelism of fold-axes with mineral-stretching lineations is considered to indicate a regional high-strain stress regime, where early structures formed in response to progressive and rotational deformation. The mineral chemistry in  $F_2$  hinges, where  $S_2$  is strong (a microscopic quartz-rodding fabric), and in  $F_3$  hinges is identical to that found throughout the gneisses and is superimposed upon by a pervasive granoblastic texture. Since textural equilibrium has been attained in the hinges of  $F_3$  folds, it is concluded that all the mineral chemistry had been reset after D<sub>3</sub>. All minerals, including garnet are unzoned, except in very narrow rims related to corona textures described below, therefore they experienced re-equilibration at this stage. The *P-T* path described here is thus entirely post-kinematic, with respect to the early deformation phases.

### 4.3 Mineral assemblages of lithotypes

The Reinbolt Hills are composed of seven major granulite facies lithotypes (Appendix 1). Of these the mafic granulites, felsic gneisses and charnockite are the most abundant. The mineral assemblages of the lithotypes are typical of granulite facies metamorphism and are summarized in Table 4.1. The felsic gneisses contain Opx-Pl-Qtz-Kfs±Phl with varying amounts of Grt, giving rise to two varieties; the dominant variety is the granoblastic felsic gneiss, while the subordinant type, the garnetiferous felsic gneiss may contain up to 50% garnet, but more usually contains 30%. The mafic granulites contain two pyroxenes with Pl and Phl and or Hbl, while the relatively rare ultramafics only contain two pyroxenes, Spl and Hbl. The Reinbolt Charnockite is typified by Opx-bearing granitic assemblages and in places contains minor Grt. Calc-silicates contain equilibrium assemblages of Scp-Wo-Cpx-Grt-Qtz and the phases Cal-An as reaction products from the breakdown of Scp.

Nº	Lithology	Mineralogy
72020	Granoblastic felsic gneiss	Grt-Opx-Pl-Qtz-Kfs±Phl±Ilm±Mag
72024	Calc-silicate	Scp-Wo-Cpx-Grt-Qtz±Sch-(Cal-An)
72026	Mafic granulite	Opx-Cpx-Pl±Phl±Ilm±(Hbl)
72027	Ultra-mafic granulite	Opx-Cpx-Spl-Hbl
72036	Meta-basaltic dyke	Opx-Phl-Pl-Qtz-Ilm-(Hbl)
72042	Reinbolt Charnockite	Opx-Pl-Qtz-Kfs-Phl±Grt±Ilm
72045	Meta-pelitic gneiss	Grt-Sil-Pl-Qtz-Kfs-Phl-Rt-(Crd-Spl-Ilm)

Table 4.1 Mineral assemblages of Reinbolt Hills lithotypes, with exemplary specimen number; phases not in equilibrium are shown in parentheses.

The pelitic gneisses contain eight equilibrium phases, Grt-Sil-Pl-Qtz-Kfs-Phl-Rt-Crd, and the retrograde phases IIm-Spl and symplectitic Crd. These phases are essentially homogeneous although garnets have very narrow rims which are weakly enriched in Mn. There are three optically identifiable varieties of cordierite in the pelites. Primary cordierite occurs as large unaltered grains at some distance from garnets, within the Kfs-Qtz groundmass. This variety is interpreted to have been an equilibrium phase during formation of the granoblastic texture and was used to calculate Grt-Crd temperatures. Reactant phases in the pelites include two varieties of cordierite, ilmenite and spinel. Cordierite occurring as optically continuous grains as coronas on garnets, is itself rimmed by a symplectite of cordierite and quartz; it is these microstructures that constitute the critical evidence which is indicative of a decompressional P-T path.

#### 4.4 Geothermometry

# 4.4.1 Conditions during the formation of granoblastic texture

A granoblastic texture is well preserved in most felsic and mafic gneisses. The mafic gneisses are two pyroxene, plagioclase assemblages but are all garnet absent so that they provide minimal pressure control. Equilibrium temperatures in these rocks based on the pyroxene solvus are much higher than all other techniques (e.g. Wells 1977, gives  $880^{\circ}$ C) with the exception of the Bertrand & Mercier (1985) calibration which suggests  $750^{\circ}$ C consistent with the Fe-Mg exchange reactions in the felsic gneisses. We suggest that these unusually high numbers are due to errors in the application of these geothermometers, outside the temperature range of their calibrations, and in relatively Fe-rich compositions. The reaction textures in the calcareous gneisses indicate that the gneisses cooled through 790°C after the equilibrium textures were established (see below). This reaction is well constrained by thermodynamic data so our preferred temperature of formation for this granoblastic texture is  $800\pm50^{\circ}$ C.

The most suitable mineralogy to determine the pressure of formation of this granoblastic texture are found in the felsic gneisses. For example the rock 72020 contains the assemblage Grt-Opx-Pl-Kfs-Phl-Ilm. Fe-Mg exchange reactions provide minimum estimates of the peak temperature. Calibrations of the garnet orthopyroxene Fe-Mg exchange geothermometer indicated an equilibration temperature of 750-800°C (e.g. Sen & Bhattacharya [1984] =760°C). Garnet - biotite Fe-Mg exchange reactions have been reset to much lower temperatures in the range 500-600°C (Ferry & Spear 1978) and are not relevant to the granulite facies assemblage.

Pressure estimates in this assemblage depend on garnet-orthopyroxene reactions (e.g. Harley & Green 1982, Harley 1984b, and Wood 1974,) which are more temperature sensitive, than the calibrations of the barometer Grt-Opx-Pl-Qtz (e.g. Perkins & Newton 1981; Bohlen *et al.* 1983). These calibrations are shown in Figure 4.1. At the preferred temperature of 800°C, Perkins & Newton's, Bohlen *et al.*'s and Harley & Green's calibrations indicate a pressure of  $7\pm1$  kbar, while Wood's Grt-Opx calibration lies just outside this range at 8.8 kbar.

Further evidence for the pressure of equilibration can be found in the pelitic gneisses. All potential geothermometers for the early granoblastic texture in the pelitic gneisses have been reset during corona formation but the plagioclase and garnet show little reaction so that the Grt-Sil-Pl-Qtz geobarometer can still be applied. At 800°C this geobarometer gives a pressure of  $7\pm1$  kbar and is consistent with the felsic gneisses (Fig. 4.2). Here an early temperature of  $800\pm50^{\circ}$ C and pressure of  $7\pm1$  kbar are the final estimates of the conditions at which the granoblastic textures were established.



Figure 4.1. Metamorphic P-T estimations for the felsic gneiss, sample 72020. At the preferred temperature of 800°C, a pressure of 7±1 kbar is indicated by most calibrations. Calibrations are: 1. Grt-Opx, Harley 1984a; 2. Grt-Opx, Sen & Bhattacharya 1984; 3. Grt-Opx, Wood 1974; 4. Grt-Opx Harley & Green 1982; 5. Grt-Opx-Pl-Qtz Bohlen *et al.* 1983; 6. Grt-Opx-Pl-Qtz Perkins & Newton 1981, 7. Grt-Opx, Harley 1984b.



Figure 4.2 Metamorphic P-T estimations for pelitic gneiss (sample 72045) indicating a pressure around 7 kbar. Calibrations are: 1. Grt-Sil-Pl-Qtz Bohlen et al. 1983; 2. Grt-Crd-Sil-Qtz Aranovich & Podlesskii 1983; 3. Grt-Bt Ferry & Spear 1978; 4. Grt-Crd Thompson 1976; 5. Grt-Sil-Pl-Qtz Haselton & Newton 1982; 6. Grt-Sil-Pl-Qtz McKenna & Hodges 1988; 7. Grt-Sil-Pl-Qtz Perchuk et al. 1985.

# 4.4.2 Corona and symplectite textures

The pelitic gneisses contain several reaction textures which, by their mutual relationship, constrain the retrograde part of the *P*-*T* path in these gneisses. The earliest reaction on the decompressional path, is identified by thin (0.1-0.2 mm) rims of optically continuous cordierite immediately adjacent to garnet (Fig. 4.3c). These appear to have developed at the expense of garnet and sillimanite by reactions of the type 4Sil + 5Qtz + 2pyrope = 3Crd (reaction 1, Fig. 4.4). As local areas between garnet and sillimanite became silica undersaturated, bottle-green hercynitic spinel with cordierite were produced in a symplectitic fabric, by the reaction pyrope + 2Sil = Spl + Crd (Fig. 4.3b and reaction 2, Fig. 4.4) and its Fe analogue. In compositional zones rich in Ti, the phase rutile reacted with garnet to form a symplectitic texture of quartz and cordierite, intergrown with grains of ilmenite (Figs. 4.3a & c); via the reaction 12Rt + 2pyrope + 4almandine = 3Crd + 12Ilm + 3Qtz (reaction 3, Fig. 4.4).



# 4.5 Reaction grid for pelitic gneisses

The breakdown of garnet to cordierite, in the sillimanite stability field, indicates a cooling path which is steeper than reaction 1 (Fig. 4.4), and thus demonstrates a decompressional or clockwise P-T path for these granulites. In order to assess this cooling path in greater detail, it is necessary to assume that cordierite, spinel and ilmenite grew in equilibrium with respect to garnet. The validity of this requisite assumption is supported by the close similarity of the results obtained for 3 independent reactions. If these minerals grew outside the stability field of the garnet then the reaction lines shown in Figure 4.4 represent maximum pressures only, and a steeper path is implied but no formal calculation of this P-T path is possible.



Figure 4.4 Reaction isopleths for important reactions in the pelite 72045, calculated after Berman (1988). Reaction isopleths discussed are shown in bold lines. A segment of the *P*-*T* path from  $800\pm50^{\circ}$ C & 7 kbar crosses the garnet breakdown reaction, thence passes through the cordierite plus spinel forming reaction as local areas become deficient in silica, and finally passes through the rutile plus garnet reaction isopleth, producing symplectites of cordierite, quartz and ilmenite at  $690\pm30^{\circ}$ C & 5.0 kbar. Estimated errors are shown on each isopleth. Reactions: 1. 4Sil + 5 $\beta$ Qtz + 2pyrope = 3Crd, 2. pyrope + 2Sil = Spl + Crd, 3. 12Rt + 2pyrope + 4almandine = 3Crd + 12Ilm + 3 $\beta$ Qtz, & 4. almandine + 3Rt = Sil + 2 $\beta$ Qtz + 3Ilm.

The cordierite producing reactions, either through the breakdown of garnet (reaction 1, Fig. 4.4) or as symplectites with spinel (reaction 2, Fig. 4.4) or from rutile and garnet (reaction 3, Fig. 4.4) can be quantitatively constrained using the Fe-Mg exchange geothermometers. Using retrograde cordierite and garnet (which is homogeneous) gives a T of  $670\pm50^{\circ}$ C (Thompson 1976). Since the prograde cordierite gives higher T we assume the Fe-Mg exchange here closes at the growth of the cordierite and reflects the temperature of that growth. At this temperature the cordierite forming reactions are pressure dependent. To gain an appreciation of the errors on these reactions Powell & Holland's (1988) 'Thermocalc' programme was used, and suggests for their data-set, an error range of 0.4-0.5 kbar for their independent reactions 2Sil + pyrope = 3Spl + 5\betaQtz and 4Sil + 5\betaQtz + 2pyrope = 3Crd (activity models for cordierite - ideal 2 site; pyrope - based on Haselton & Newton, 1982).

Reaction 3 involves the formation of new ilmenite so that the Fe-Mn exchange geothermometer (Pownceby *et al.* 1987) between garnet and ilmenite was used to obtain the temperature at which ilmenite formed. Again it is assumed that the Fe-Mn exchange closes with the growth of this grain and therefore reflects the temperature of the reaction. The temperature determined in this way is a minimum value. The *T* estimated in sample 72045 is 690°C and this indicates a closure pressure of  $5.0\pm1$  kbar for reaction 3. (Detection limits for MnO in these analyses are  $\pm 0.02$  wt%. Errors in the calculated temperature deriving solely from analytical error are  $\pm 24^{\circ}$ C, which are additional to the calibration error of the geothermometer,  $\pm 30^{\circ}$ C, as quoted by Pownceby *et al.* 1987).

Here three independent reactions describing the retrograde textures which are in excellent agreement and provide a strong constraint on the P-T path. The greatest difficulty in this assessment is the determination of the retrograde temperature as the path crosses the reaction isopleths in Figure 4.4. In this analysis it was therefore necessary to assume that the minerals closed to Fe-Mg and Fe-Mn exchange as they grew. If some later exchange has occurred the retrograde temperature estimates are too low and therefore the P-T path was steeper than shown in Figures 4.4 & 4.7. The consistency between the two independent reaction textures supports the assumption employed here.

# 4.6 Determination of fluid composition during metamorphism4.6.1 Calc-silicates

Calc-silicates have increasingly been used to estimate the molar component of  $CO_2$  in fluids and hence to decipher metamorphic fluid compositions (e.g. Hiroi *et al.* 1987). Sample 72024, from the south-western Reinbolt Hills, is a calc-silicate containing the equilibrium assemblage Cal-Scp-Wo-Qtz-Cpx-Grt. The peak temperature in this rock was greater than 790°C based on the retrograde reaction of Scp  $\Rightarrow$  An + Cal (Figs. 4.3d & 4.5a) using the scapolite activity model of Oterdoom & Gunter (1983), and the Berman (1988) database. This is temperature consistent with those estimated for the early granoblastic assemblages of other lithologies in the area. At the preferred condition of 800°C and 7 kbar the  $a_{CO_2}$  implied by this assemblage is less than 0.33 (Fig. 4.5b). There is no evidence of reaction zoning around these calc-silicates and they are very small, about 20 cm thick within massive mafic gneisses. Thus, this  $a_{CO_2}$  is probably a maximum value for the surrounding gneisses. There is no evidence that the calc-silicates have reacted with an external CO<sub>2</sub>-rich fluid.



Figure 4.5 (a) Pressure-temperature plot for the break-down reaction of scapolite to calcite and anorthite, which is indicated by reaction textures in the calc-silicate 72024. This isopleth indicates that peak metamorphic temperatures cooled from  $\geq$ 790°C. (b) Activity-temperature plot indicating that during peak metamorphic temperatures, around 800°C, CO<sub>2</sub> had an activity less than 0.33.

#### 4.6.2 Felsic gneisses

The water activity of granulites is monitored by the stability of coexisting phlogopite and Kfeldspar. Phlogopite is a prograde phase in the felsic gneisses; it is in complete textural equilibrium with orthopyroxene and K-feldspar and does not display any replacement textures to indicate that it is a late phase. Reactions involving the dehydration of phlogopite can be written for many granulite assemblages and have been used in a number of areas to estimate the water activity where the P and T conditions have been constrained by anhydrous reactions (e.g. Lamb & Valley 1988). Unfortunately these phases seldom preserve their prograde composition. The K-feldspar exsolves albite to form perthites and the phlogopite exchanges Fe-Mg, as indicated by the low temperatures obtained using garnet-biotite exchange reactions. The composition of the K-feldspar can be recalculated assuming equilibrium with plagioclase at the appropriate temperature (Stormer 1975). The phlogopite composition can be adjusted so that Fe-Mg exchange with garnet gives the correct composition at the preferred temperature of 800°C (assuming garnet maintains a constant composition, as suggested by the lack of zoning). The aphl calculated using an ionic model and including OH<sup>-</sup> determined by difference implies an  $a_{H2O}$  of 0.07. The position of the reaction isopleth 3enstatite + Kfs +  $H_2O = Phl + 3\beta Qtz$  is shown in Figure 4.6 (calculated with the Berman [1988] dataset) using the corrected compositions of the phases.



In combination with the low activity of  $CO_2$  and the relatively oxidised nature of the mineral assemblage (e.g. magnetite-ilmenite) the low activity of H<sub>2</sub>O strongly suggests the granoblastic assemblages were produced in a vapour absent condition. This conclusion is compatible with the absence of any melt phase and probably reflects the fact that the observed assemblage was formed relatively late in the metamorphic history.



Figure 4.7 Closely matching *P*-*T* paths from the Reinbolt Hills (stippled) with paths from the northern (lower boxes) and southern Rauer Group granulites (Harley 1988), as well as the Larsemann Hills (Stüwe *et al.* 1989). Error rectangles are constructed on estimated errors of 800±50°C, 7±1 kbar, 690±30 & ±50°C (Grt-Ilm & Grt-Crd), 5.0 ±0.5 kbar.

# 4.7 Summary

A decompressional P-T path has been established for the Reinbolt Hills, which passes through the equilibration conditions of 800°C and 7 kbar, and crosses 3 independent retrograde reactions that produce Crd, Spl and Ilm, terminating at 690°C and 5 kbar. The calculated segment of the P-T path is similar in slope and magnitude to decompressional paths from the McKaskle Hills (see Chapter 5), the Rauer Group, in the Late Proterozoic Complex (e.g. Harley 1988), and the Larsemann Hills, which display a decompressional path with an equivalent slope, although of smaller magnitude and commencing at higher crustal levels (Stüwe *et al.* 1989) (Fig. 4.7). These similarities support general correlations of a widespread Late Proterozoic orogeny throughout this part of Antarctica, and incorporated with the structures, are discussed in section 3.11.2, of Chapter 3.

# Chapter 5

# THE METAMORPHISM OF THE MCKASKLE HILLS

# 5.1 Introduction

The McKaskle Hills are a small group of nunataks and cliff exposures, along the eastern margin of the Lambert Glacier and Amery Ice Shelf, located approximately 70 km north of the Reinbolt Hills (Fig. 3.1). This small area is isolated from the larger exposures of rock, the Prince Charles Mountains, the Reinbolt Hills, and the Larsemann Hills, and is sufficiently far inland to ensure that no reconnaissance mapping or sampling has been recorded. The most detailed information about this area is an incomplete set of oblique black and white photographs, taken at some distance from the outcrops.

The lithologies of the McKaskle Hills are generally more mafic than those of the Reinbolt Hills, with dominantly inter-layering of two pyroxene-Pl granulites, amphibole Pl-Bt-Qtz gneisses, although Grt-bearing felsic gneisses are common in the northern McKaskle exposures.

A number of interesting specimens which are important for the elucidation of the metamorphic history of this small area, are presented below.

#### 5.2 McKaskle Hills, Specimen M2

This granulitic gneiss is dominated, in thin-section, by orthopyroxene coronas developed around magnetite, which appear as a later assemblage after partly reacted garnet and plagioclase (Fig. 5.1a). Plagioclase is unzoned and retains optical continuity of twin lamellae on either side of the Opx-Mag intergrowths. Garnet is essentially unzoned, except for very thin rims which are slightly more magnesian, and depict a depletion in CaO of  $\approx 0.7$  wt% (Fig. 5.2). Apatite occurs throughout the specimen but does not appear to have participated in diagnostic reactions. Pale biotite occurs as coarse grained, isolated acicular blades within the Opx-Mag-Pl groundmass, and probably formed relatively late.

The Opx-Mag intergrowths are considered to have formed via the isochemical andradite-garnet breakdown reaction, under quartz saturated conditions:

 $3 \text{ Alm} + \text{Adr} + 2 \text{ Qtz} = 4 \text{ Fs} + \text{Mag} + 3 \text{ An} \qquad \dots (5.1)$  $3 \text{ Fe}_3 \text{Al}_2 \text{Si}_3 \text{O}_{12} + \text{Ca}_3 (\text{Fe}^{3+})_2 \text{Si}_3 \text{O}_{12} + 2 \text{ Si}_2 \text{O}_2 = 4 \text{ Fe}_2 \text{Si}_2 \text{O}_6 + \text{Fe}_3 \text{O}_4 + \text{Ca} \text{Al}_2 \text{Si}_2 \text{O}_8$ 





At peak conditions, the spinel formed a solid solution of magnetite and hercynite. This inference is confirmed by the presence of bottle-green hercynitic spinel blebs included within, and preferentially developed as rims on magnetite (Fig. 5.1a). These spinels contain between 5 to 10 wt%  $Fe^{3+}$ , recalculated by stoichiometry. At high magnifications, under reflected light, or with scanning electron images, numerous exsolution lamellae developed along crystallographic orientations are visible.



in specimen M2, McKaskle Hills.

Usually the lamellae have hercynitic compositions, with between 10 and 50 wt% recalculated Fe<sup>3+</sup>. Adjacent magnetite compositions characteristically contain less than 1 wt% Al<sub>2</sub>O<sub>3</sub>, however, a few analyses, apparently without beam overlap, have 5 to 10 wt% Al<sub>2</sub>O<sub>3</sub>. The lamellae vary between 1 to 3  $\mu$ m wide, and are typically 10  $\mu$ m long. Rarely they contain <1  $\mu$ m areas, too small to focus the microprobe beam without overlap, which are predominantly composed of Al<sub>2</sub>O<sub>3</sub>. These small areas of corundum may have formed by the post-peak influx of oxygen, where reaction of the form may be important:

hercynite +  $O_2$  = magnetite + corundum ...(5.2)

However, given the interpretations negating the possible influx of oxygen-bearing vapour (section 5.4.2), the formation of corundum is thought to have occurred during cooling by continued exsolution, in an environment effectively isolated, within magnetite, from quartz.

As many of the more  $Fe^{3+}$  rich spinels have very low Mg N<sup>2</sup> ( $\approx$ 5-10), the magnetite-hercynite binary, experimentally determined under varying oxygen fugacities and at 2 kbar by Turnock & Eugster (1962), was used with spinel lamellae and adjacent magnetites, to estimate peak formation temperatures. While a number of hercynitic spinels have between 10 to 30 wt% calculated Fe<sup>3+</sup>, their adjacent magnetites frequently have relatively low corresponding Al<sub>2</sub>O<sub>3</sub>. As a consequence the binaries plot on the solvus with the magnetite end-member giving temperatures of 400-500°C, while the corresponding

hercynite shows temperatures between 600-800°C. However, a few pairs retain compositions, presumably close to those attained during peak conditions, and they demonstrate equilibrium temperatures of at least 775°C (Fig. 5.3).



Figure 5.3 The magnetite-hercynite solvus, taken from the experimental formulation of Turnock & Eugster (1962), and used to estimate a minimum peak temperature of 775°C, at which the hercynitic lamellae in magnetites of specimen M2, were exsolved.

Significantly, the hercynite limb consistently indicates equilibration at higher temperatures than the magnetite limb. This is understandable because the spinel lamellae in specimen M2, are a hercynite-spinel±gahnite solid solution (analyses are given in Appendix 2), thus the use of the magnetite-hercynite solvus alone, is a simplification, although justifiable here, given the predominantly hercynitic compositions. As a precaution the equilibration temperature was estimated from a more conservative median value:

$$T$$
 (°C) =  $\frac{T_{\text{est}} \text{ magnetite} + T_{\text{est}} \text{ hercynite}}{2}$ 

Solvus joins were rejected where the adjacent hercynitic value differed from the magnetite value by more than 50°C. The difference between the hercynitic and magnetitic temperature values, however increases with falling temperature. A minimum peak temperature of 775°C is the preferred estimate using this technique.

### 5.2.1 Thermobarometry

The McKaskle Hills specimen M2 is used in Chapter Six (section 6.3.2.1), to compare a selection of Grt-Opx-Pl-Qtz barometers, as well as Grt-Opx thermometers. The favoured calibrations Bohlen *et al.* (1983a) and Sen & Bhattacharya (1984), respectively, are reproduced here (Fig. 5.4). The most magnesian-garnet core compositions were applied to estimate peak pressures and temperatures, whilst conditions during the formation of the Opx-Spl-Pl symplectites were constrained by using Grt rims and Opx coronas. The preferred *P*-*T* path passes through the peak conditions of 850°C & 8 kbar, to 700°C & 4 kbar, and has a similar *P*-*T* trajectory to that of the Reinbolt Hills samples (detailed comparisons in 6.8.1). The relatively high calculated retrograde temperature is consistent with the observation of the optical continuity of plagioclase lamellae within the symplectites, and the development of spinel exsolution from magnetite.



Figure 5.4 Preferred pressure-temperature constraints for specimen M2; Grt-Bt calculated temperatures are low, even though Grt cores were used, and are consistent with the textural interpretation that Bt formed relatively late.

The cumulative evidence of minimum Mag-Hc solvus temperatures ( $\approx 775^{\circ}$ C), supports the thermobarometric derivations of 850°C & 8 kbar for peak assemblages.

## 5.3 McKaskle Hills, Specimen M2A

Specimen M2A is compositionally similar to specimen M2. It contains, in addition to Pl-Opx-Qtz and Mag with Spl exsolution along rims, Cpx-Amph, and is Grt absent. Ortho- and clinopyroxenes with equant equilibrium textures allow an accurate assessment of the temperature of equilibration using the thermometry of Kretz (1982) and Wells (1977); the selection of thermometers and barometers is discussed in detail in Chapter 6, section 6.3.

The Wells (1977) thermometer on adjacent Opx-Cpx pairs estimates temperatures ranging from 830-870°C; in comparison Kretz's (1982) thermometer produces a significantly larger range of values, for the same mineral pairs, between 634 and 784°C. Such a wide range of temperature estimates is difficult to interpret with confidence, however, the Wells (1977), and the majority of the Kretz (1982) data broadly point to an initial equilibration temperature of at least 750°C, and probably higher than 800°C, followed by retrograde partial equilibration to  $\approx$ 700°C. Temperatures consistent with those established for the nearby specimen, M2.

# 5.4 McKaskle Hills, Specimen M3

Specimen M3, is an unusual Amph-Opx-Spl-Pl-Qtz-Bt bearing mafic granulite, which displays textural and compositional similarities with specimens M2 and M2A. The predominant micro-textural features are an early assemblage of coarse green-amphiboles, some preserving kinked cleavages (suggesting that they were constituents of an early assemblage), and a groundmass of bottle-green spinel (exsolving magnetite), rimmed by orthopyroxene, within a matrix of calcic (An<sub>0.98</sub>) plagioclase (Fig. 5.1b).

The primary difficulty in determining the equilibration conditions of this specimen arises since the intergrowth of Spl-Opx-Pl requires the reaction of another phase, in addition to early amphibole. Such a phase was volumetrically significant, assuming the equilibration-volume was closed to the flux of components, as the retrograde intergrowths occupy  $\approx$ 30-50 volume percent of the rock.

The phase which has completely reacted was assumed to be garnet, of equivalent and raditic composition estimated for specimen M2, which has a less calcic groundmass plagioclase of  $An_{0.58-0.87}$ . The assumption about the reacted phase, and its composition, necessarily removes the independence of the estimated *P-T* conditions for this sample.

To assess these assumptions, Holland & Powell's (1990) internally consistent computer programme was employed utilizing the known and assumed mineral compositions; if retrograde pressures were approximately those derived for the other specimens in the area, the choice of phase, and its composition would be supported. The independent reactions

$$Alm + 2 Prp = 3 En + 3 Qtz + 3 Hc \qquad ...(5.3)$$
  
6 Ed + 10 Alm + 32 Prp = 63 En + 12 An + 6 Ab + 30 Hc + 6 H<sub>2</sub>O ...(5.4)

were derived, intersecting at 700°C with an average pressure of  $4 \pm 1.5$  kbar. Similar postpeak pressure estimates, based on the Spl compositions (ZnO < 0.15 wt%), were derived by applying the Nichols *et al.* (1992) Grt-Spl barometer, and assuming (a) a Grt composition, & (b) that it was in equilibrium with Sil and Qtz. A value of 4 kbar at 800°C, although unconstrained, also supports the selection of Grt for the unknown reactant.

Peak equilibration conditions can not be assessed thermobarometrically, although mineralogical criteria do place constraints on the probable temperatures of equilibration. The spinel is a spinel (*sensu stricto*) -hercynite-gahnite-magnetite solid solution; the presence of magnetite exsolution suggests that the original spinel formed at relatively high temperatures, or alternatively, at lower oxygen fugacities. Continuous plagioclase twin-lamellae, between the intergrowths, further supports the interpretation of moderately high temperatures, during the retrograde growth of plagioclase.

5.4.1 A Reaction for the formation of the Opx-Spl-Pl retrograde textures The Fe end-member reaction considered to have been relevant at the time the Opx-Spl intergrowths formed is equivalent to that described for specimen M2, however, occurring in quartz under-saturated conditions:

 $5 \text{ Alm} + \text{Adr} = 6 \text{ Fs} + \text{Mag} + 2 \text{ Hc} + 3 \text{ An} \qquad \dots (5.5)$  $5 \text{ Fe}_3 \text{Al}_2 \text{Si}_3 \text{O}_{12} + \text{Ca}_3 (\text{Fe}^{3+})_2 \text{Si}_3 \text{O}_{12} = 6 \text{ Fe}_2 \text{Si}_2 \text{O}_6 + \text{Fe}_3 \text{O}_4 + 2 \text{ Fe} \text{Al}_2 \text{O}_4 + 3 \text{ Ca} \text{Al}_2 \text{Si}_2 \text{O}_8$ 

The actual formation of the Opx-Spl intergrowths would have involved the analogous Mg end-member reaction, where Prp + Adr = En + Mag + Spl + An. The inferred silica saturation thus produces discernible differences in the spinel solid-solution products. When andraditic garnet breaks down in a quartz saturated environment, the spinel product has a predominantly magnetitic composition, with a subordinate volume of hercynitic spinel exsolution. In contrast, retrogression within a silica undersaturated state, produces approximately equal proportions of spinel and magnetite (*cf* Fig. 5.1a & b).

# 5.4.2 The possible importance of fluxing by O<sub>2</sub>-rich vapour

Spinel solid-solutions in specimen M3 are relatively magnetite rich, whereas magnetites in specimen M2 are characterized by spinel rims and exsolutions. These somewhat different textures are thought to have been produced by the breakdown of andraditic Grt under differing silica saturations.

An alternative reaction pathway worthy of consideration, is the oxidation of garnet:

$$2 \operatorname{Alm} + \operatorname{Gr} + \operatorname{O}_2 = 3 \operatorname{Qtz} + 2 \operatorname{Mag} + 3 \operatorname{An} \qquad \dots (5.6)$$

Where the volume of oxidizing fluids fluxing the system would thus control the relative proportions of magnetite and spinel produced. Large fluxes of very oxidized fluid would result in a magnetite-rich product, whereas smaller volumes of a more reduced fluid would react with Grt to produce greater proportions of spinel.

Examination of the differing mineral chemistries of the spinel solid-solution products in specimens M2 and M3, demonstrates that the spinels in M2 are significantly more oxidized than those in M3. For example M2 spinels typically contain an average of  $\approx 30 \text{ wt\% Fe}_2O_3$ , whereas spinels from M3 have an average of  $\approx 6\text{wt\% Fe}_2O_3$ : equilibrium  $f_{O2}$  conditions can be estimated from the Fe<sup>3+</sup> component of the spinels, e.g. Ghiorso & Sack (1991). These observations mitigate against the derivation of these textures by oxidation of garnet (reaction 5.6), since the more oxidized spinels are from the specimen preserving embayed Grt. If O<sub>2</sub>-fluid fluxing was important, M2 with the more oxidized spinels would necessarily have suffered greater fluxing, and would therefore not be expected to preserve garnet. Similarly, the specimen which is garnet absent and therefore must have experienced greater volumes of O<sub>2</sub>-fluid fluxing, contains spinels which are not as oxidized.

Oxidized fluxing fluids would be also be expected to produce a significant amount of corundum, a feature not observed in either specimen, although M2 does contain very small  $<1\mu m^2$  areas of corundum, these appear to have developed in a silica undersaturated environment, during post-peak cooling.

The spinel-magnetite chemistries of specimens M2 and M3 are not consistent with post-peak derivation from oxidized fluid flushing, and are more succinctly explained by the andraditic garnet breakdown under varying silica activities.

# 5.5 McKaskle Hills, Specimen M5b

The two-pyroxene, biotite granulite, M5b, is characterized by alternating Pl-Qtz and Pl-Bt-Amph-Opx-Cpx mineralogical layering. Reaction textures which post-date the generally equigranular peak assemblages, place constraints on the retrograde cooling history of this specimen, however, no absolute pressure estimations were possible as the rock is garnet absent.

The two-pyroxene solvus thermometer of Wells (1977) was employed with adjacent mineral pairs, to establish equilibration temperatures between 814 and 876°C (ave  $840\pm24^{\circ}$ C). These are relatively high values but are consistent with the temperature estimations of the specimens discussed above.

Retrograde reaction textures include Opx reacting to Phl, and the symplectitic development of Qtz+Kfs after Phl. Quantification of retrograde temperatures was possible with Holland & Powell's (1990) internally consistent computer programme, using rim

pyroxene compositions and the less firmly constrained amphibole end-members. For the rehydration reaction:

$$3 \text{ En} + 2 \text{ Ksp} + 2\text{H}_2\text{O} = 2 \text{ Phl} + 6 \text{ Qtz}$$
 ...(5.7)

the calculated temperature is  $760\pm40^{\circ}$ C, at 7 kbar.

## 5.6 Synopsis

The *P*-*T* trajectory of the McKaskle Hills is most strongly constrained by specimen M2, where Grt-Opx-Pl-Qtz barometry combined with Grt-Opx thermometry, and Mag-Hc solvus temperatures constrain peak and retrograde conditions. The preferred trajectory estimate passes from the preserved peak conditions of  $850^{\circ}$ C & 8 kbar to  $700^{\circ}$ C & 4 kbar.

Two pyroxene thermometry in adjacent samples supports the >800°C peak temperature estimates, however, their mineralogies do not allow pressure estimates.

The comparative study of spinel solid-solutions with Opx intergrowths in specimens M2 and M3, provides evidence for the localized equilibrium chemistries, and importantly provides constraints on the P-T evolution of the McKaskle Hills. These reaction and corona textures are best explained by the breakdown of andraditic garnet, under quartz saturated, and quartz under-saturated equilibrium conditions. The alternate explanation that oxygen fluxing produced the magnetitic solid-solutions, is not compatible with the detailed interpretation of textures and mineral chemistry.

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# Chapter 6

# THE METAMORPHIC HISTORY OF THE NORTHERN PRINCE CHARLES MOUNTAINS

# 6.1 Introduction

The metamorphic history of the Prince Charles Mountains has not, to date, been clarified in any detail, although the reconnaissance work of Australian BMR geologists in the early 1970s (Tingey 1972) combined with the exploratory work of Crohn (1959), suggested a decrease in metamorphic grade from the northern to the southern Prince Charles Mountains. The nature of this change, in absolute terms, and its spatial variation, is an important problem assessed here by examining the P-T histories of similar composition samples collected over a large portion of this area, while examining recent interpretations about the P-T estimates and paths from the northern PCM ranges (Thost & Hensen 1992, Fitzsimons & Thost 1992 and McKelvey & Stephenson, 1990). Russian geologists and geophysicists have worked in the area since 1956, however their work remains reported almost exclusively in Russian, and unfortunately very few manuscripts or maps have become available.

The Prince Charles Mountains consist of a series of east-west trending ranges and isolated nunataks, and to the east, massifs, separated by eastward flowing glaciers (Fig. 6.1). Good exposure occurs along the cliffs of most nunataks, but access is frequently made difficult by cornices and wind scours in the adjacent glacial ice. Outcrop on the top of many of the relatively peneplainar massifs is disrupted by frost-shattering, restricting detailed structural analysis mainly to cliff bases, however, aerial photographs are helpful to discriminate fold structures which are not readily recognizable on the ground.

Many localities in the nPCM sampled during the nineteen-seventies ANARE research expeditions have been dated using Rb-Sr methods, of particular relevance are the ages of 904 $\pm$ 175 Ma, for a felsic gneiss collected from Mt Béchervaise, and 1139 Ma for the Fox Ridge locality (data of Arriens, compiled by Tingey [1981] and recalculated with his recommended decay constant,  $\lambda$  of 1.42E-11 yr<sup>-1</sup>).

Figure 6.1 Locality map of the northern Prince Charles Mountains.



#### 6.2 Mineral Assemblages

The regions examined in the northern Prince Charles Mountains (nPCM) are composed predominantly of sequences of felsic gneisses, inter-dispersed with biotite  $\pm$  garnet  $\pm$ orthopyroxene bearing felsic gneisses, marbles and calc-silicates which frequently retain mineralogically diverse reaction zonations. Felsic gneisses at Fox Ridge and Mt Béchervaise preserve K-feldspar phenocrysts and contain mafic xenoliths, suggesting an igneous origin for these lithotypes. Similarly, the charnockitic bodies of demonstrable igneous origin along the north-east side of Mc Kinnon Glacier, are composed of K-feldspar phenocrysts, Pl. Otz. Opx and phl, and are also a volumetrically important rock-type, in the north-eastern part of the nPCM. These bodies may be equivalents of the Proterozoic (954±12 & 985±29 Ma) charnockites along the Mawson Coast, dated with zircons using U-Pb systematics by Young & Black, 1991, Rare layers of pelitic gneisses, partly migmatitic, were collected from many areas, and often preserve the most diagnostic assemblages for the determination of the changes in the metamorphic conditions. Pegmatite and adamellite dykes and pods are interlayered between, and cross-cut these gneisses. Basaltic dykes cross-cut all lithologies, and those on Taylor Platform have a K/Ar radiometric age of 246 Ma. (Tingey 1976). Rare lamprophyre bodies were located on Mt Meredith (77063), and are possibly consanguineous with the Cretaceous (110 Ma. Walker & Mond 1971) äolinitic sills located on the south eastern side of Radok Lake. An area on the north-western portion of Manning Massif has an olivine leucitite flow, with an Eocene age ( $50\pm 2$  Ma Tingey 1976). Table 6.1 lists the range of mineral assemblages from the PCM, with typical specimens indicated.

Lithotype	Early mineralogy	Late mineralogy	e.g. Specimen
Basaltic dykes	Pl±Ol±Phl+glass		H90/4, TP/13
Calc-silicate	Cpx-Pl-Wol-Cal	Grt-Cal-Cpx±Cor	BRO/6, TP/14, MB90/8
Charnockite	Qtz-Pl-Kfs-Opx-Phl		MAN/4
Felsic gneiss	Qtz-Pl-Kfs-Grt-Opx	±Phl	GOR90/16
Felsic orthogneiss	Qtz-Pl-Kfs-Grt-Opx	±Phl±Amp	MAN/23, LAN/15, MB90/1
Lamprophyre	Ol-Cpx-Phl-Pl-Spl-Prv		MER/27
Marble	Cal+Ol	Cal±phl±Spn	MER/23
Mafic gneiss	Opx-Cpx-Hbl-PL±(Grt)	±Phl	MER/26, LAN/45
Pegmatites	Qtz-Pl-Kfs-Phl		
Pelitic gneiss	Grt-Sil-Pl-Spl-Qtz	Grt-Sil-Crd-Spl±Ilm±Rt	LAN/19, D90/2, MB90/7

Table 6.1 Mineralogy of lithotypes in the Prince Charles Mountains

Other lithotypes or mineral associations, constitute a very small proportion of the nPCM rocks, and are not discussed in detail, they include: Metamorphosed pyrrohite-rich pods, with minor pyrite veins, and occur within felsic gneisses and marbles at the southern Mt Lanyon cliffs (e.g. LAN/39A); late stage sulphides, mainly pyrite associated with early granitoids (e.g. MAN/3); brecciated calcite-plates, overgrown by white quartz, frequently associated with late faulting (e.g. LAN/48); small graphite pods which occur in pelitic rocks at Mt Dovers (e.g. D90/4), which may be part of the near-peak metamorphic pelitic assemblages, of these gneisses.

# 6.3 Selection of calibrations for geothermobarometry

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# 6.3.1 Selection of reliable geobarometers

A number of established barometers were applied here to estimate the peak metamorphic, and retrograde conditions. Many of these calibrations are included in the computer programme Thermobarometry, written by Spear & Peacock (1990) & Spear et al. (1991), and this was used to produce many of the P-T plots presented below. For some specimens, P-T conditions were estimated with the internally consistent data base computer programmes, of Powell & Holland (1988) and Holland & Powell's (1990) THERMOCALC, and Berman's (1988) GEO-CALC. The former programme quantifies P-T and also provides informative estimates of the standard deviation in the calculated pressure or temperature, and/or errors on the estimated average pressure/temperature intersections, with diagnostic errors for each mineral's activity. The advantage of the Berman (1988) programme however is that it provides graphical pseudo-sections with calculated (stable or metastable) isopleths in the desired system (i.e. diagrams of P-T, P-X,  $T-X \& \log_2 - \log_2$ ). Berman (1988) uses simple system, pure phase experimental data, biased towards the Mgrich mineral end-members, in compositions where there are the most experiments. In contrast, Powell & Holland (1988 & 1990) have additionally included less reliable thermodynamic data, with explicit reliance on activity models of phases in complex experimental systems, expanding the number of possible phases to encompass the more Ferich end members. Therefore more phases are available to the modeller, although the actual results rely on implicit assumptions regarding the choices of activity models, which are not therefore, as flexible to the user as other programmes, such as Berman (1988). Yardley & Schumacher (1991) note the similarity of results calculated with these programmes, however *P-T* conditions of Fe-rich specimens are probably more accurately estimated with Powell &

Holland (1988), whilst interactions between equilibria are more easily visualized with Berman's (1988) approach.

Garnet zoning profiles were used with included plagioclase, to assess the relative change in pressure conditions from core-rim; this technique appeared to be more informative than Gibb's relative finite difference thermobarometry techniques described by Spear & Peacock (1990).

# 6.3.2 Evaluation of the Hoisch (1990) barometer

The calibration of the Grt-Bt-Pl-Qtz barometer, is one of six empirical barometers derived for assemblages of Qtz-Mu-Bt-Pl-Grt, by Hoisch (1990) from natural mineral data. It allows pressure estimations with rocks containing fewer phases than the aluminous metamorphic rocks, for which many experimentally derived calibrations exist, and as Grt-Bt bearing felsic rocks are more common than aluminous pelites in the nPCM, the barometer potentially provides for a consistent assessment of the spatial pressure variation in the area.

A direct comparison of this calibration with other barometers is graphically presented in Figure 6.2. The best comparative data are taken from specimens with assemblages that permit the use of calibrations based on separate phase equilibria. For additional discrimination, data were also included where pressure estimates had been made with other calibrations on separate specimens, with the proviso that these rocks were essentially from the same locality. Part (a) of Figure 6.2 represents data compared at 700°C, a near-peak, "mid-range" temperature, selected to minimize extrapolation errors from both specimens with demonstrable resetting, and those preserving higher temperatures.



Near-peak pressures estimated with the Hoisch (1990) barometer (Fig. 6.2a), are both significantly higher, and lower than those estimated with other geobarometers. Such behaviour is unlikely to result from a single calibrational deficiency, that would be expected to produce either consistently higher, or alternatively, lower values. Of the thirteen data points, only four are approximately similar to those estimated with the other geobarometers, and further are only within these values when an error of  $\pm 1$  kbar is allowed. An array of much lower, and much higher than estimated pressure values determined with the Hoisch barometer may be the result of a calibration that is overly sensitive to cation exchange. If the selected compositions of garnet, plagioclase and biotite were not in equilibrium at near peak conditions, or if the compositions were modified significantly during retrograde cooling, the estimated pressures would not compare favourably with other calibrations less sensitive to such exchange re-equilibration. Garnet and biotite are subject to continuous Fe and Mg exchange until the rate of reaction becomes infinitely slow as the assemblage reaches relatively low temperatures; such an exchange mechanism is utilized to explain the extremely low calculated temperatures in some of the nPCM specimens discussed below. This phenomenon would also explain the lower than anticipated pressures calculated with Hoisch (1990). The Hoisch pressure estimates which are significantly higher than values estimated using the other barometers, may result from an exchange interaction with other minerals not considered in the calibrational system. For example it is conceivable that if present, cordierite or spinel could exchange both Fe and Mg with biotite during cooling, and thus modify its equilibrium composition.

To assess the possibility that exchange may influence the Hoisch barometer, pressure



Figure 6.2 (b) A graphical comparison of the Hoisch (1990) geobarometer with other barometers (abbreviations in Fig. 6.2a), determined at 500°C.

comparisons were also made at a lower temperature of 500°C, and these are presented in Fig. 6.2 (b). The comparitive Hoisch data measured at 500°C display a similar array of values which are both much higher, and lower than the other barometers. There is a weak tendency for the Hoisch (1990) calibration to estimate slightly higher values, when the other barometers estimate low pressures between 0.5 and 2 kbar. However, in some specimens, the pressure values estimated with the Hoisch calibration are as much as 4 to 4.5 kbar lower than the compared barometers.

Like the higher temperature comparative data, this discrepancy is thought to originate from disequilibrium between garnet and biotite, and possibly plagioclase, caused by cation exchange with other minerals during the retrograde path. If exchange between garnet and biotite alone, was the sole cause of the observed pressure differences, the Hoisch (1990) barometer would be expected to calculate lower pressures than the other calibrations, at 500°C, which is not observed.

Selected samples below, provide specific comparisons of the Hoisch (1990) barometer with calibrations in the systems: Grt-Opx-Pl-Qtz, Grt-Cpx-Pl-Qtz, Grt-Pl-Sil-Qtz, Grt-Crd-Sil-Qtz and finally with Grt-Rt-Sil-Ilm.



Figure 6.3 (a) A comparison of results of the Hoisch (1990) barometer with pressures calculated using Grt-Opx-Pl-Qtz calibrations, for a specimen from the Gorman Crags, nPCM. Darker filled circles represent the favoured estimates of peak conditions, and lighter filled circles, the retrograde conditions. The Hoisch barometer under-estimates peak pressures (indicated by darker hatched square) when compared with the Newton & Perkins (1982), Powell & Holland (1988) and Bohlen *et al.* (1983a) derivations.



Figure 6.3 (b) Another comparison of the Hoisch (1990) barometer, with calibrations in the Grt-Opx-Pl-Qtz and Grt-Cpx-Pl-Qtz systems. Hatched circles represent the favoured peak and retrograde conditions. The trajectory is inferred from a combination of textural and thermobarometric evidence described in the text. Hatched squares indicate peak and retrograde conditions, calculated by applying the Hoisch barometer.

The compositional range of specimens in this comparative study covers two Grt-Opx bearing felsic gneisses, and a calc-silicate boudin within a Grt-Opx bearing felsic gneiss. In GOR90/17 (Fig. 6.3a) a maximum preserved pressure of 6 kbar at 660°C is indicated by the Newton & Perkins (1982) and Powell & Holland (1988) calibrations. However, the Hoisch (1990) geobarometer produces spurious results, with an intersection of the Fe and Mg calibrations around 2 kbar. Despite the fact that there is demonstrably little Fe/Mg resetting to explain this result, suggested by the agreement of core and rim temperatures estimated with Grt-Bt (Ferry & Spear, 1978), and those estimated applying the Grt-Opx calibration of Sen & Bhattacharya (1984).

The Mt Béchervaise sample (MB90/8, Fig. 6.3b) is a particularly good sample to compare the results of the calibrations. A very well constrained retrograde path is interpreted based on the development of grossular garnet rims on Cpx within the core of the calc-silicate boudin. Here the Grt-Cpx thermometers of Ellis & Green (1979) and Powell (1985) calculate a temperature of 600°C as the condition at which the garnet rims grew. Maximum temperatures and pressures are constrained by applying the Grt-Opx thermometer of Sen & Bhattacharya (1984), with the Grt-Opx-Pl-Qtz barometers of Newton & Perkins (1982) and Powell & Holland (1988). Pressure conditions during which the garnet rims grew were established at 4.5 kbar, with the Grt-Cpx-Pl-Qtz barometer of Newton & Perkins (1982). In comparison, whilst the Hoisch (1990) barometer does detect a change in P-T conditions

based on garnet core-rim analyses, the magnitude of both pressure and temperature change differs from that described above (Fig. 6.3b), and a steeper trajectory would thus be inferred. These results suggest that the pressure and temperature changes calculated with Hoisch (1990), using Grt core and rim compositions, are primarily controlled by the variable Fe/Mg ratio.

Pressure comparisons for specimen GOR90/1, from the Gorman Crags are shown in Figure 6.3 (c). In this example, the pressure values obtained with Hoisch's (1990) geobarometer, are consistent with those of the Grt-Pl-Sil-Qtz calibrations of Newton & Haselton (1981) and Ganguly & Saxena (1984), at a temperature of 620°C. Ganguly & Saxena's Grt-Pl-Sil-Qtz calibration produces consistent values to the Grt-Crd-Sil-Qtz pressure estimate calculated with the Nichols *et al.* (1992) barometer, at the maximum preserved temperature.



Figure 6.3 (c) Hoisch's (1990) barometer produces consistent "peak" pressure estimates when compared with the Grt-Sil-Pl-Qtz barometers of Newton & Haselton (1981), Ganguly & Saxena (1984), and the Grt-Crd-Sil-Qtz calibrations of Nichols *et al.* (1992). However, such an estimate is thought to represent partial retrogression, from the maximum conditions experienced by rocks in the Gorman Crags region.

The *P*-*T* evolution of the significantly zoned garnet pelites from Mt Lanyon (LAN/19 & LAN/23) is described in detail below. In summary the maximum preserved conditions are estimated to have been 870°C and 6.6 kbar cooling on a shallow retrograde path to 550°C and 2.7 kbar. In comparison, the Hoisch (1990) formulation predicts a path of 805°C and 5.5 kbar, cooling to 450°C and 2 kbar, based on garnet core and rim pairs in specimen LAN/19 (Fig. 6.3d). These trajectories are remarkably similar; the Hoisch (1990)
formulation correctly identifying the retrograde path, probably because the Fe/Mg zonation in these garnets is so large, an unusual feature not found in other pelites from this region.



Figure 6.3 (d) Comparison of *P*-*T* estimations in specimen LAN/19, using the Grt-Sil-Pl-Qtz and Grt-Rt-Sil-Ilm (GRAIL) calibrations, with Hoisch's (1990) Grt-Bt-Pl-Qtz derivation. Circled area indicates the peak conditions estimated for specimen LAN/19, with a combination of thermobarometry, and phase relationships, described in section 6.4.2.3.



Figure 6.3 (d) Comparison of *P-T* estimations in specimen LAN/19, using the Grt-Sil-Pl-Qtz and Grt-Rt-Sil-Ilm (GRAIL) calibrations, with Hoisch's (1990) Grt-Bt-Pl-Qtz derivation. The GRAIL barometer produces erroneously high pressures because Ilm occurs as rims on Rt, and is not therefore in equilibrium. However, the Grt-Sil-Pl-Qtz barometers are comparable, in this specimen, with Hoisch's barometer.

The calculated  $\ln K_d$ s of the nPCM samples, for both the R1 and R2 calibrations used here, lie within, or slightly above, the range of data-set values quoted by Hoisch (1990): the reported ranges are  $3.61 \le R1 \le 6.62$ , and  $1.85 \le R2 \le 4.89$ . For example,

specimen	MB90/11	W90/5	LAN/19
$\ln K_d R1$	6.34	5.37	6.95
ln <i>K<sub>d</sub></i> R2	4.61	3.49	4.86

The erroneous pressure values estimated with the Hoisch (1990) barometer are therefore not a result of applying the calibrations outside their recommended compositional ranges.

In summary, the *P*-*T* paths derived using the Hoisch (1990) barometer are marginally steeper than paths from other calibrations. Where the Hoisch barometer indicates paths which are shallow, or entirely isobaric, a cooling trajectory can be interpreted with moderate confidence, however the magnitude of cooling and accuracy of the calculated pressures can usually only be used as an indication of the true trajectory. The Hoisch (1990) barometer is apparently only able to correctly predict *P*-*T* conditions and trajectories when the garnets preserve dramatic Fe/Mg zonation. The errors in estimated pressures may derive from the fact that the Hoisch calibrations were (a) empirically formulated with lower temperature rocks, and the slopes of these equilibria may not allow an accurate extrapolation to higher temperature rocks, & (b) that garnet and particularly biotite, are more prone to continual Fe/Mg exchange between other minerals (possibly cordierite and spinel) during cooling, than that which typically affects minerals in other exchange barometers.

## 6.3.2.1 System Grt-Opx-Pl-Qtz

The calibrations of Newton & Perkins (1982), Bohlen *et al.* (1983a), Perkins & Chipera (1985), Moecher *et al.* (1988) and Powell & Holland (1988) were applied to the system Grt-Opx-Pl-Qtz. As explained below the derivation of Harley (1984a), was not applied as it was found here, and in other studies, to be oversensitive to compositional variations underestimate pressures.

Excluding the Harley (1984a) barometer, the differences in these derivations results from the selection of different thermodynamic data, and in the choice of the activity models for garnet and plagioclase. Newton & Perkins (1982) employ an ideal pyrope-almandine garnet mixing model, combined with the Newton *et al.* (1980) plagioclase model, and an ideal two-site mixing model for orthopyroxene. Their selection of an ideal garnet mixing model has been supported by the recent thermodynamic modelling of Berman (1990) who derived a small deviation from ideal prp-alm mixing, biased slightly asymmetrically, with increased non-ideality for garnets around Mg 40.

The Harley (1984a) barometer, in contrast, is based upon the alumina solubility in orthopyroxene in equilibrium with garnet, however, is most sensitive to Fe/Mg resetting.

Fitzsimons (1991) in a comparative study of the Newton & Perkins (1982), Harley & Green (1982), Bohlen *et al.* (1983a), Ganguly & Saxena (1984), Harley (1984a), Moecher *et al.* (1988), Essene (1989) and Holland & Powell (1990) geobarometers, concludes that the Mg end-member derivation of Newton & Perkins (1982), Bohlen *et al.* (1983a) and the Fe end-member calibration of Essene (1989), are the most consistent and provide the best pressure constraints. The remaining barometers were rejected by Fitzsimons (1991) on the basis of spurious results, due to the large deviation from ideality in the prp-alm mixing model calculated by Ganguly & Saxena (1984), which was also employed by Essene (1989).

Carswell & Gibb (1987a) report that the Harley (1984a) barometer under-estimates pressures, quoting a disparity of at least 10% from known values, whilst Fitzsimons (1991) notes that the barometer is particularly sensitive to resetting of the exchange of Fe/Mg, upon cooling. The barometer is still usable, if a method described by Fitzsimons (pers. com. Jan. '92) in which reset mineral compositions are incrementally changed so that the calculated Fe/Mg exchange temperature approximates temperatures estimated independently, and these "reiterated mineral compositions" can then be used with Harley (1984a) to calculate a "peak" pressure (or vice versa: known pressure differentials can be reiteratively used to estimate temperatures, assuming that the pressure difference is only due to Fe/Mg exchange). However, in order to reduce the number of assumptions made during the estimation of peak

metamorphic conditions (which are already quite large), this calibration and reiterative method were not employed.

Figure 6.5 shows a comparison of the Harley (1984a) barometer with the more favoured derivations of Newton & Perkins (1982), Bohlen *et al.* (1983a) and Powell & Holland (1988). Harley's (1984a) calibration appears to be overly sensitive, relying solely on the Al content of Opx, thus pressure estimates, in this example vary from 6 kbar to negative values for rim estimates, at 800°C.

The specimen which depicts most clearly the difference between the Grt-Opx-Pl-Qtz calibrations is from the McKaskle Hills (72049), on the eastern side of the Lambert Glacier (Fig. 6.4). In this example, Moecher *et al*'s (1988) calibration over-estimates the maximum pressure, indicated best with Powell & Holland (1988) (Figs. 6.4a & b). The three other calibrations compare favourably with each other (Fig. 6.4c), although Perkins & Chipera (1985) displays the largest pressure variation, with the Fe end-member equilibria having the steepest and therefore most compositionally sensitive,  $\delta P / \delta T$ . Both Bohlen *et al.* (1983a) and Perkins & Newton (1982) provide good pressure constraints, with the former calibration proving to be the least sensitive to Fe/Mg differences between core, rim, and the symplectites. The compatibility of the three calibrations is also depicted in MB90/11, where core-rim conditions are strongly constrained by, and in agreement with changes in core-rim temperatures (Fig. 6.5).

The inference that Moecher *et al.* (1988) over-estimates pressures is demonstrated in W90/5, where pressures approximately 2.5 kbar higher than the Powell & Holland (1988) calibration are calculated at peak temperatures (Fig. 6.3b).

#### 6.3.2.2 System Grt-Pl-Sil-Qtz

The Grt-Pl-Sil-Qtz barometric calibrations of Newton & Haselton (1981), Ganguly & Saxena (1984) and Hodges & Spear (1982), were applied to appropriate aluminous assemblages. All three calibrations provide good pressure constraints in the compositions of the nPCM rocks. The Newton & Haselton (1981) calibration was applied the most frequently, as it appears to estimate the most consistent pressures; this derivation is slightly more sensitive to changes in Fe/Mg exchange, as it has a marginally steeper slope in P-T space, and therefore produces the greatest discrimination between core and rim pressure estimations (e.g. MB90/5 detailed below). Spear & Peacock (1990) report that the Ganguly & Saxena's (1984) derivation produces lower pressures for low grossular garnets, but pressures converge as grossular increases.



Figure 6.4 P-T diagram for McKaskle Hills (specimen M2), comparing the Grt-Opx-Pl-Qtz barometers of Newton & Perkins (1982), Bohlen et al. (1983a), Perkins & Chipera (1985), Moecher et al. (1988) and Powell & Holland (1988). (a) estimates for core and rim, with the interpreted path based on evidence combined from the three diagrams, (b) thermometer comparisons, & (c) continued on the following page.



Figure 6.4 *P-T* diagram for McKaskle Hills comparing the Grt-Opx-Pl-Qtz barometers (c) estimations for rim and adjacent analyses.



Figure 6.5 Comparison of the Grt-Opx-Pl-Qtz barometers in specimen MB90/11 demonstrating the close agreement between core and rim estimations with Newton & Perkins (1982), Powell & Holland (1988) and Bohlen *et al.* (1983a). The Harley (1984a) barometer however, is very sensitive to the Al content of coexisting Opx. Calculated core pressures are ~2 kbar higher than other calibrations in this specimen, with rim compositions producing unrealistic negative values, at 800°C.

# 6.3.2.3 System Grt-Crd-Sil-Qtz, Grt-Spl-Sil-Qtz, Spl-Crd-Sil-Qtz

The barometers and thermometers calibrated by Nichols *et al.* (1992) were applied to aluminous assemblages reported in the literature. As examined in Chapter 2, the Grt-Crd barometer reproduces experimental pressures better than  $\pm 1.5$  kbar, and in many cases is better than 0.5 kbar. Comparison with natural data is also good, but like all equilibria involving Crd, necessarily is partly dependent upon assumptions of fluid activities, which stabilize Crd.

The Grt-Spl barometer reproduces pressures of natural samples reported in the literature to better than  $\pm 1$  kbar (see Chapter 2).

Pressure calculations with the Spl-Crd barometer are the least precise, with an error on reported values of  $\pm 1.7$  kbar (Chapter 2). This is a result of the small experimental data base, the relatively small  $\Delta V$  of the reaction compared to garnet-cordierite, and the effect of fluid activity on cordierite stability.

# 6.3.2.4 System Grt-Cpx-Pl-Qtz

Newton & Perkins' (1982) calibration was the only geobarometer applied to rare Grt-Cpx assemblages, in specimen MB90/8. In this specimen grossular garnet  $(Gr_{0.87}Alm_{0.15}Py_{0.002})$  rims occur on clinopyroxene; the high grossular component of garnet would normally be considered to be outside the calibrations usual compositional range and would therefore deleteriously effect the calibration's accuracy, however, the retrograde pressure derived for this sample, is equivalent to pressures for nearby samples, within the claimed accuracies.

#### 6.3.2.5 System Ab-Jd-Qtz

The calibrations of Holland (1980) and Gasparik & Lindsley (1980), were applied, in the Ab-Jd-Qtz system to specimen FOX/18. The calculated pressures are variable, in particular Gasparik & Lindsley's (1980) barometer estimates unrealistically high pressures. The final peak pressure estimated for this specimen is only an indication of equilibrium conditions, but is consistent with adjacent rocks.

The errors and discrepancies in the albite-jadeite-quartz system, can in part be expected because of problems in the derivation of the barometers, particularly, in establishing the equilibrium of pyroxenes in experimental studies, due to the slow diffusion rates of Al in their lattices (Gasparik & Lindsley 1980). Secondly, the thermodynamic properties and complex quaternary solid solutions of the pyroxene end-members jadeite—diopside—Ca-

Tschermaks—Ca-Eskola, are not fully understood as most experimental studies have been restricted to binary solid solutions (Gasparik & Lindsley 1980).

# Τ

# 6.3.3 Selected thermometers, reasons for their discrimination

# 6.3.3.1 System Grt-Bt

Ferry & Spear's (1978) calibration was used exclusively to estimate Grt-Bt temperatures in pelitic and semi-pelitic assemblages. Although all Fe/Mg exchange thermometers suffer because of continued Fe/Mg exchange upon cooling so that calculated temperatures often do not accurately portray peak conditions, with biotite in particular subject to resetting, the Ferry & Spear (1978) calibration appears to produce the most consistent temperatures. Recognizing the potential problem of resetting, mineral pairs that were not immediately adjacent were selected to estimate conditions as near to peak temperatures as possible. Application of other Grt-Bt thermometers (e.g. Perchuk & Lavrent'eva 1983, Hodges & Spear, 1982) did not reduce the difference between Grt-Bt and Grt-Opx calculated temperatures, and therefore the Ferry & Spear (1978) calibration was consistently applied. In contrast, Chipera & Perkins (1988) favour the derivation of Perchuk & Lavrent'eva (1983) which they find provides the most accurate and precise temperature estimates in the English River subprovince, Ontario. They report that the Ferry & Spear (1978) calibration produces temperatures that are unrealistically high, for this region.

The Indares & Martignole (1985) calibration was designed to quantify the effects of Al<sup>VI</sup> and Ti substitution for Fe and Mg in biotite, and a derivation with a choice of either Ganguly & Saxena's (1984) or Hodges & Spear's (1982) garnet mixing models are possible in Spear & Peacock's (1990) computer programme. In order to assess the influence of Ti on the high Grt-Bt temperatures obtained with the Ferry & Spear (1978) calibration in LAN/19 and LAN/23 samples, temperatures were calculated for the same mineral pairs using the Indares & Martignole (1985) derivation. As these authors caution, the magnitude of the interaction parameter for Ti and Al<sup>VI</sup> substitution is dependent upon both assumptions regarding the actual substitution type and the Grt mixing model, with the maximum Ferry & Spear (1978) temperature reduced by  $\approx 100^{\circ}$ C with the Hodges & Spear (1982) Grt model and  $\approx 150^{\circ}$ C with the Ganguly & Saxena (1984) Grt model. Spear & Peacock (1990) similarly note the importance of the selected Grt mixing model on the estimated temperature,

and while they recognize some correction for Ti substitution is possibly necessary, they question the magnitude of the correction applied by Indares & Martignole's (1985) calibration. For this reason the Ferry and Spear (1978) calibration was applied to the Mt Lanyon samples without any activity correction for Ti substitution. The calculated values are probably maximum temperatures, considering that the activity corrections for the effects of Ti may be too large, however, Fe/Mg resetting will have partially lowered these estimates. The final Ferry & Spear (1978) temperature estimates for specimens LAN/19 & LAN/23 are within the quoted thermometric errors of peak temperatures calculated for other samples in the nPCM area, and this calibration is therefore preferred without correction.

# 6.3.3.2 System Grt-Opx

Three Grt-Opx calibrations, Harley (1984b), Lee & Ganguly (1988) and Sen & Bhattacharya (1984) are compared. Specimen 72049, from the McKaskle Hills (Fig. 6.4b) displays the comparison of these calibrations, with estimated temperatures for rim and core compositions depicted. The Harley (1984b) thermometer gives the lowest temperatures (in agreement with Carswell & Gibb's [1987a] conclusions) but is close to the Sen & Bhattacharya (1984) derivation. Lee & Ganguly's (1988) calibration gives the highest temperature estimates, and in other specimens not reproduced here, produces unreasonably high temperature estimates. The differences between the three thermometers increases with increasing calculated temperatures (Fig. 6.4b); exemplified by Harley (1984b) and Sen & Bhattacharya (1984) where rim temperatures are equivalent, but Harley's core estimates are lower than that of Sen & Bhattacharya by  $\approx 40^{\circ}$ C.

Harley's (1984b) thermometer is formulated with ideal garnet and orthopyroxene models, but non-ideality in garnet due to dilution with grossular, is allowed by an excess mixing term. Faulhaber & Raith's (1991) findings are in agreement with the conclusion reached here, that the improvement in accuracy of temperature estimates shown by Sen & Bhattacharya's (1984), over Harley (1984b), is due to the inclusion of a non-ideal garnet model in their thermometer.

In contrast, Fitzsimons (1991) comparison of Grt-Opx thermometers, suggests that the Harley (1984b) thermometer is "commonly reset" and that the Sen & Bhattacharya (1984) formulation produces "unreasonably high temperatures". As Fig. 6.4b clearly shows, all thermometers distinguish between core and rim compositions, and all produce a similar temperature difference between core and rim compositions. Of the three thermometers evaluated here it is unlikely that any one thermometer would suffer greater Fe/Mg exchange than another. Sen & Bhattacharya's (1984) thermometer is favoured here as it estimates the most consistent temperature values, a finding supported by Faulhaber & Raith (1991), while the under-estimation of temperatures by Harley (1984b) was reported as early as 1987 by Carswell & Gibb.

# 6.3.3.3 System Grt-Cpx

Both Ellis & Green (1979) and Powell's (1985) Grt-Cpx thermometers were utilized: these calibrations produce very similar temperature estimates. Carswell & Gibb (1987a), report typical differences of <15°C, and also note that the latter derivation probably produced the more accurate estimates below 1200°C for garnet lherzolites. However, a recent comparative study by Green & Adam (1991) suggests that the Ellis & Green (1979) formulation over-estimates temperatures at low pressures ( $\approx 10$  kbar), as the pressure correction and less significantly, the grossular garnet correction utilized by Ellis & Green, were incorrect at such pressures. It is suggested here however, that the deviations from ideality due to the calcic compositions to which the calibrations were applied, were calculated correctly, as the estimated temperatures are consistent with independently derived values.

#### 6.3.3.4 System Opx-Cpx

Bertrand & Mercier (1985), Gasparik (1984), Kretz's (1982) and Wells (1977) twopyroxene solvus thermometers were utilized for mafic compositions. However, as implied by Carswell & Gibb (1987a), the performance of high temperature thermometers at temperatures below 1100°C is not expected to be accurate. Moreover, they suggest that Kretz's (1982) calibration fortuitously reproduces experimental temperatures as it does not include a pressure correction term. When applied to granulite facies specimens, the best derivation appears to be that of Bertrand & Mercier (1985), a finding consistent with the evaluations for garnet lherzolites reported in Carswell & Gibb (1987b), and Carswell (1991), probably because this thermometer is calibrated in a larger component system and thus more closely approximates the compositions of the natural systems to which it is applied. The calibration of Wells (1977) is judged by Carswell & Gibb (1987a) to reproduce experimental temperature values the most accurately ( $\pm$ 50°C), for garnet lherzolite assemblages at pressures <37 kbar, although these compositions and equilibration conditions are far removed from those experienced by the rocks in this study. The Bertrand & Mercier (1985) two-pyroxene thermometer is thus favoured here.

#### 6.3.3.5 System Grt-Chl

Garnet-chlorite thermometry was applied to two specimens (BRO/15 & W90/2) using the Dickenson & Hewitt (1986) calibration, as well as the Laird (1989) modified version. Although comparisons are not necessarily meaningful with only a small number of specimens, the Grt-Chl temperatures are slightly lower than, but close to the Grt-Bt Ferry & Spear (1978) values, and similarly suffer from possible resetting during slow cooling, as Chl often only occurs immediately adjacent to garnet. Alternatively, the Grt-Chl estimates may reflect lower temperatures during the growth of retrograde chlorite.

6.4 Metamorphic synopsis, variations of P-T conditions and paths for the nPCM

## 6.4.1 Description of textures: Timing

The dominant fabric of the nPCM rocks represents a layer-parallel composite of progressively rotated foliations, variably developed, depending upon the lithology, and mineralogically equilibrated at peak metamorphic conditions. Sigmiodal inclusion trails of sillimanite, quartz, ilmenite and phlogopite within garnet porphyroblasts, and mineral lineations, interpreted as stretching lineations, are preserved evidence of high strain rotational (simple shear) deformation during peak, and near metamorphic peak conditions. These fabrics are fully described in Chapter 3.

Of particular relevance to the derivation of retrograde trajectories, is the recognition of relict magnesian cores (LAN/19 & 23), and zonation profiles in garnet porphyroblasts. The intricate and complex development of spinel generations, features which additionally constrain the peak metamorphic conditions, are combined with thermobarometric calculations of localized equilibria, to derive post-peak metamorphic trajectories, described below.

## 6.4.2 Introduction

Well defined pressure-temperature conditions described below for five separate localities in the northern Prince Charles Mountains provide an opportunity to examine the possible regional variations in the peak and retrograde metamorphic conditions experienced by this area of East Antarctica. The derivation of such paths necessitate a number of important assumptions requiring consideration, so that the results produced are meaningful; they are, (a) that core mineral compositions are unchanged from those established during peak conditions, (b) that the selected minerals used in thermobarometry were in equilibrium, (c) the thermodynamic system was effectively closed, on the scale of interest, to fluxes of components, (d) that rim mineral compositions were at least in local, grain to grain scale, equilibrium, and that this actually represents retrograde conditions, (e) the establishment and particular characteristics of a path between disparate rim and core conditions necessarily implies specific tectonic regimes, and implies that the rocks underwent a constantly changing continuum of conditions along their retrograde path, and in contrast do not reflect the superposition of entirely discrete metamorphic episodes.

Semi-pelitic, pelitic and garnet-orthopyroxene bearing granulite gneisses used to constrain the metamorphic evolution, were collected in five main areas of the northern Prince Charles Mountains (Fig. 6.1): these are labelled The Mt Béchervaise area which includes the nunataks Mt Béchervaise, Mt Dovers and the Hunt nunataks; The Gorman Crags area including the nunataks the Gorman Crags, Gorman Crags West, Wall Peak, Simon Ridge and Lensink Peak. The Mt Lanyon area, including Mt Lanyon and Mt Meredith. The O'Leary Ridges area that includes the O'Leary Ridges themselves, Taylor Platform and Brocklehurst Ridge. Finally the Fox Ridge mylonite locality along the southern portion of McLeod Massif, provided the most easterly P-T constraints from the nPCM in this study.

Specimens preserving the best examples of the retrograde P-T path from each locality are described in detail, and compared with two paths estimated for specimens located on the eastern side of the Lambert Glacier, from the Reinbolt Hills and the McKaskle Hills further north. The metamorphic evolution of the East Antarctic shield, from the Rauer Islands in the east to the Mawson coastline north of the PCM, is examined in context of the P-Ttrajectories calculated here and from those reported in the literature.

#### 6.4.2.1 Mt Béchervaise region

Mt Béchervaise and the surrounding nunataks Mt Dovers and the Hunt Nunataks, described here as the Mt Béchervaise region, comprise some of the most northerly outcrops of the Prince Charles Mountains, in the east-west trending Athos Ranges (Fig. 6.1).

#### Mt Béchervaise

#### Specimen MB90/8

This specimen, from which the most unambiguous P-T path for this region has been determined, sections a calcic boudin (10 by 25 cm across) lying within steeply dipping Grt-Opx bearing felsic gniesses, on the north facing cliffs of Mt Béchervaise.

The surrounding Grt-Opx felsic gneisses are moderately foliated, and contain pink, sieve textured, almandine garnets (core Alm<sub>0.59</sub>Py<sub>0.23</sub>Sp<sub>0.1</sub>Gr<sub>0.08</sub>) which appear to be in equilibrium with orthopyroxene ( $X_{Opx}^{Mg}$  =0.49) and anorthitic plagioclase (An<sub>0.81</sub>). Phlogopite occurs in the groundmass with quartz, but is preferentially associated with orthopyroxene.

Estimated preserved maximum conditions utilizing core-core analyses and the Grt-Opx calibration of Harley (1984b) are 750°C, compared with Sen & Bhattacharya (1984) of 775°C at a pressure of 4.5 kbar, from the Grt-Opx-Pl-Qtz derivations of Newton & Perkins 1982 and Powell & Holland 1988 (Fig. 6.3a).

The boundary of the zoned boudin is defined by a layer of sphene, which probably delimits the zone of inward Ti diffusion from biotite in the felsic gneisses, and outward Ca diffusion (plagioclase An<sub>0.97</sub>). A green layer rich in Cpx and anorthitic plagioclase (An<sub>0.98</sub>) occurs further toward the centre (Fig. 6.6); at the boudin's centre a brown layer of grossular garnet forms, on thin-section scale, an inter-meshed network rimming Cpx and anorthitic plagioclase (An<sub>0.99</sub>), and as discrete grains with calcite.

Thermobarometric calculations on the texturally later grossular garnet rims suggest Grt-Cpx temperatures of 600°C (Ellis & Green 1979, Powell 1985) and a pressure of 4.5 kbar at these temperatures (Newton & Perkins 1982, Powell & Holland 1988) (Fig. 6.3a). However as these garnet rims are dominantly grossular ( $Gr_{0.87}Alm_{0.15}Py_{0.002}$ ) and outside the recommended calibrations' compositional ranges, the estimated rim conditions are applied with caution. Despite these precautions, the interpreted isobaric cooling path is consistent with, and of equivalent magnitude to, paths derived from nearby Grt-Opx gneisses.

#### Specimen MB90/5

This specimen from Mt Béchervaise, is a coarse grained metapelite containing garnet porphyroblasts of up to 2.5 cm diameter, within coarse grained layers of anastomosing phlogopite and sillimanite. Cordierite occurs adjacent to garnet porphyroblasts and within the groundmass. The specimen has a weak gneissic foliation, predominantly defined by oriented phlogopite and sillimanite, but accentuated by thin leucocratic layers and zones between garnet porphyroblasts.

The coarser garnet porphyroblasts preserve snow-ball textures, indicating a sinistral (in the plane of this unoriented section) sense of rotation (Fig. 3.9d). The porphyroblasts predominantly contain inclusions of quartz, ilmenite; phlogopite and spinel appear to have developed in the final stages of rotation of the porphyroblasts and occupy fractures which are developed parallel to the internal sygmoidal foliation.

The porphyroblasts are zoned with rim  $X_{Grt}^{Mg}=0.18$  immediately adjacent to anastomosing phlogopite, although a rim value of  $X_{Grt}^{Mg}=0.23$ , not affected by late Fe/Mg resetting is more representative; core values are  $X_{Grt}^{Mg}=0.25$ , while grossular and spessartine contents do not vary significantly. These values were used to estimate a change in



Figure 6.6 Sketch depicting on the left, actual size of thin-section through the calc-silicate boudin, specimen MB90/8, and its boundary with the surrounding Grt-Opx groundmass (g.m.) gneisses. The boundary is defined by the change in ilmenite-bearing mineralogies within the Grt-Opx granulites, to the diffusion controlled formation of Sphene along the rim of the calc-silicate boudin. Enlargements (=100 x), right-hand side, illustrate the equilibrium of Grt-Opx-Bt assemblages within the enclosing gneisses, and the development of Grt-rims upon Cpx, characteristic of post-peak cooling.

equilibration conditions, assuming that the Fe/Mg zoning profile is a result of changing P-T conditions as the porphyroblast grew, and not the result of diffusional resetting. Applying the Grt-Pl-Sil-Qtz barometer of Newton & Haselton (1981) establishes a precise pressure decrease from core to rim of 1.7 kbar, with a core pressure of 3.2 kbar (at 675°C) and a rim pressure of 1.5 kbar at 600°C (Fig. 6.7b). The equilibration temperature of 675°C, is selected from the Grt-Crd thermometer (Grt core, Nichols *et al.* 1992), which indicates a maximum preserved pressure of 4.2 kbar (Fig. 6.7c), while garnet rim compositions suggest an equivalent decrease in pressure of 1.7 kbar, to 550°C and 2.5 kbar. Grt-Spl barometry (Nichols *et al.* 1992) applied to the texturally later spinel associated with biotite, provides a pressure estimate of 3 kbar and 570°C at the intersection of the Fe and Mg calibrations, conditions intermediate between those for the core and rim, and supporting the inference that spinel and biotite grew in the final stages of garnet rotation.

The maximum preserved conditions of 675°C and 4.2 kbar are consistent with low pressure and high temperature peak conditions for nearby specimens, with an equivalent shallow retrograde path, dominated by cooling.

#### Specimen MB90/11

This specimen has a proto-mylonitic fabric, with alternating layers dominated by pink almandine garnets, and light brown weathering layers rich in orthopyroxene. The dark coloured groundmass of fine grained quartz, plagioclase, K-feldspar, aligned phlogopite and sillimanite, also contains porphyroblasts of K-feldspar up to one cm long.

The garnets have sieve textures, dominated by inclusions of quartz, and are surrounded by phlogopite aligned parallel to the layering of the specimen. They show a small zonation, with cores typically having  $Alm_{0.67}Py_{0.26}Sp_{0.02}Gr_{0.06}$  and rims of  $Alm_{0.72}Py_{0.21}Sp_{0.02}Gr_{0.05}$ . Orthopyroxene is essentially unzoned with  $X_{Opx}^{Mg}$ =0.52.

The shape of the retrograde P-T path was derived using the Grt-Opx thermometers of Sen & Bhattacharya (1984) and Lee & Ganguly (1988), combined with the Grt-Pl-Opx-Qtz barometers of Newton & Perkins (1982), Bohlen *et al.* (1983a) and Powell & Holland (1988). A preserved maximum temperature of 800°C is supported by the intersection of the Sen & Bhattacharya (1984) thermometer with the barometers of Newton & Perkins (1982) and Bohlen *et al.* (1983a), at a pressure of 4.3 kbar (Fig. 6.7f).







The Lee & Ganguly (1988) calibration suggests peak temperatures some 50°C lower, within the error limits of both calibrations, however the intersection of two independently calibrated barometers and the Sen & Bhattacharya (1984) derivation provides strong evidence of temperatures of at least 800°C. Grt-Bt temperatures of 550°C from garnet core compositions



are reset (Ferry & Spear 1978). Rim conditions calculated by applying these calibrations are 550°C (Sen & Bhattacharya 1984) and 2.5 kbar (Newton & Perkins 1982, Bohlen *et al.* 1983a and Powell & Holland 1988). This path has a very shallow slope, and is predominantly a cooling trajectory at constant pressure.

#### Specimens MB90/4, MB90/7 & MB90/9

The *P-T* synopses of the specimens MB90/4, MB90/7 & MB90/9 are shown in Fig. 6.7a, d & e. The results are consistent with the Mt Béchervaise specimens discussed above, although, individually the rocks do not provide as good evidence for the changing *P-T* conditions. Both MB90/7 and MB90/9 preserve evidence of cooling from temperatures  $>650^{\circ}$ C to  $<550^{\circ}$ C

MB90/9 is an unusual gneiss composed almost exclusively of large garnet porphyroblasts, biotite, with a minor amount of sillimanite and quartz. The porphyroblasts contain an unusual amount of spinel inclusions, and uncharacteristically, no sillimanite inclusions. It is therefore inferred that the specimen is a relatively silica-poor composition. The estimated peak conditions of  $\approx 4.8$ , 665, are equivalent to the preserved conditions from other Mt Béchervaise samples.

### Mt Dovers and Hunt Nunataks

Pelitic and Grt bearing felsic gneisses from Mt Dovers and the Hunt Nunataks, the nearest outcrops to the east of Mt Béchervaise, give peak *P*-*T* estimates consistent with those for Mt Béchervaise, but trajectories are not as clearly defined. The specimens which retain the highest temperatures are D90/2 & D90/6 (Fig. 6.8b & e); Grt-Crd thermobarometry (Nichols *et al.* 1992) on a cordierite inclusion in D90/2, suggests peak conditions of 625°C and 4 kbar, while some Grt-Bt (Ferry & Spear 1978) thermometry retains similar temperatures ( $\approx$ 575°C), most is reset to below 500°C. Grt-Crd and Grt-Spl geothermobarometry (Nichols *et al.* 1992) applied to D90/6 with the Grt-Sil-Pl-Qtz calibrations of Newton & Haselton (1981) and Ganguly & Saxena (1984), indicates maximum preserved conditions of 660°C and 4 kbar.

Slightly more equivocal evidence in D90/1 (Fig. 6.8a), is interpreted to also reflect a shallow trajectory cooling path: peak pressures are estimated with Grt-Sil-Pl-Qtz barometers (Newton & Haselton, 1981, Ganguly & Saxena, 1984) combined with an assumed temperature from adjacent samples (D90/2 or D90/6).

Retrograde conditions are indicated by the coincidence of Grt-Crd and Grt-Spl values, using third generation spinels (Spl<sup>3</sup>), and Grt-Bt thermometry. Here a path passing from  $640^{\circ}$ C & 3 kbar, to  $525^{\circ}$ C & 3 kbar is suggested. However, extensive compositional

Figure 6.8 Estimated *P*-*T* conditions for Mt Dovers and Hunt Nunataks specimens, with peak conditions estimated from core compositions represented by dark hatched circles, and retrograde conditions indicated by light hatched circles. (a) Consistent peak preserved conditions for D90/1, are indicated by the Grt-Sil-Pl-Qtz calibrations, whilst the Grt-Crd and Grt-Spl assemblages show minor retrogression. The Hoisch (1990) calibration over-estimates pressures. (b) Peak conditions estimated with the Grt-Crd thermobarometer are comparable to those for D90/1, although Grt-Bt temperatures display considerable variation and resetting. (c) Mineralogical re-equilibration to low temperature and probably pressure conditions, is consistently shown in D90/3. (d) The Hoisch calibration probably overestimates pressures in D90/5, however, the Grt-Bt temperature is within the range of samples in this region. (e) A shallow retrograde path is depicted for D90/6, where peak conditions are calculated with the Grt-Crd thermobarometer, and retrograde P & T with the Grt-Sil-Pl-Qtz barometers and Grt-Spl<sup>3</sup> barometer. (f) Re-equilibrated mineralogies are displayed in the Hunt Nunataks specimen H90/1, with the only suggestion of an earlier higher grade history preserved as a core Grt-Bt temperature.





resetting is common in these outcrops (Figs. 6.8 c,d &h) and it is difficult to unambiguously determine the retrograde conditions.

### 6.4.2.2 Gorman Crags region

#### Wall Peak, W90/5

The best estimations of the variation in P-T conditions experienced in the Gorman Crags region, are made from the Wall Peak specimen W90/5, which sections a mylonitic contact between an Opx-Phl-Pl quartz-poor xenolith, within Grt-Opx bearing felsic gneisses. Both rock types are strongly deformed, and all structures within the xenolith are parallel to the foliation of the felsic gneisses. The xenolith (50 by 10 cm) forms the separated (boudinaged?) limb of a longer, folded xenolith. Mylonitization is most strongly developed between the two rock types (of differing rheologies) and probably occurred under upper amphibolite to lower granulite conditions, suggested by weakly undulose quartz and kinked feldspars.

Both Grt and Opx display weak Fe/Mg zonation with Grt cores of  $X_{Grt}^{Mg}$ =0.25 and rims of  $X_{Grt}^{Mg}$ =0.23, while Opx cores are  $X_{Opx}^{Mg}$ =0.52 and rims  $X_{Opx}^{Mg}$ =0.51 Using core-core

analyses with the Grt-Opx calibration of Sen & Bhattacharya (1984) provides a maximum preserved temperature of 700°C. Grt cores and distal phlogopites provide a partially reset temperature of 610°C. The pressure of equilibration was estimated with the Grt-Opx-Pl-Qtz calibrations of Powell & Holland (1988) (3.8 kbar at 700°C) and Moecher *et al.* (1988) (6.1 kbar at 700°C); the maximum preserved conditions for this sample are assumed to be represented by the median pressure of 5 kbar, at 700°C (Fig. 6.9c). These "peak" conditions compare favourably with those derived for a Grt-Opx bearing felsic gneiss (GOR90/17) from the nearby Gorman Crags.

The shape of the retrograde path was ascertained by calculating rim-rim Grt-Opx-Pl-Qtz pressures, with the same barometers (*op cit*), and estimating temperatures using the Ferry & Spear (1978) Grt-Bt thermometer with garnet core, rim and adjacent phlogopites. Figure 6.9 Pressure-temperature estimates using the indicated barometers and thermometers, for specimens in the Wall Peak region. (a) entirely re-equilibrated assemblage indicated by W90/2, (b) poorly constrained conditions, and apparently reset mineralogies in W90/3, and (c) the most strongly constrained trajectory from this region has a gentle slope consistent with other regional cooling trends.

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The Powell & Holland (1988) and Moecher *et al.* (1988) barometers indicate reequilibration for rim compositions at a pressure of 3.8 kbar at the Grt-Bt temperature of  $525^{\circ}$ C. However, it is possible that this temperature is too low, due to continual Fe/Mg exchange accentuated by continued deformation during mylonitization. Further, it is considered doubtful that Al exchange necessary for the growth of Grt and Opx, could continue to occur at such low temperatures, despite the mylonitizing event. If, however, these estimations precisely depict the direction of the retrograde *P-T* path, it must have been dominated by cooling rather than decompression.

Other specimens from the Gorman Crags region have less well defined P-Tconditions, but together provide supporting evidence for a shallow retrograde path established for W90/5. The most strongly constrained of these, is GOR90/17, a Grt-Opx bearing felsic gneiss. The preferred temperature estimate is 660°C (Sen & Bhattacharya 1984), at a pressure of 6 kbar (Fig. 6.10d) indicated by the Grt-Opx-Pl-Qtz barometers of Newton & Perkins (1982), Bohlen et al. (1983a) and Powell & Holland (1988). The pelitic samples GOR90/1 and GOR90/12 provide Grt-Sil-Pl-Qtz constraints with the barometric calibrations of Newton & Haselton (1981), Ganguly & Saxena (1984) which estimate pressures of 4.8 and 4 kbar (at 700°C), respectively. Grt-Bt thermometry (Ferry & Spear, 1978) has been reset in both specimens and Grt-Crd thermometry (Nichols et al. 1992) in GOR90/1, and therefore is not useful in constraining peak conditions. Grt-Spl barometry (Nichols et al. 1992) indicates an equilibrium pressure of 5.5 kbar at 700°C for GOR90/12, close to the Grt-Opx-Pl-Qtz values for GOR90/17. P-T estimates for the semi-pelitic Grt-Bt gneisses, GOR90/5 and GOR90/23 (Fig. 6.10b & e), are constrained only by Grt-Bt thermometry, and the Hoisch (1990) barometer. As described in section 6.3.1, the Hoisch (1990) calibration is not a reliable geobarometer for nPCM semi-pelitic rocks. However, the relatively flat cooling trajectory inferred for GOR90/5 (Fig. 6.10b) for core-rim compositions is similar to that obtained for W90/5.



Figure 6.10 *P*-*T* estimations for the Gorman Crags region. In these samples the trajectories are constrained by garnet zonations, however, retrograde re-equilibration is pervasive in many specimens e.g. (a), (c), (f), (g) & (h) with estimated T ≤550°C. Core Grt-Bt temperatures in excess of 650°C are preserved e.g. (b), (d), (h) & (i). At these temperatures, pressures of at least 4 to 5 kbar are indicated by the more reliable Grt-Pl-Sil-Qtz barometers (a) & (c), and Grt-Opx-Pl-Qtz calibrations (d). In samples containing restrictive mineralogies (b), (e), h) & (i), the less reliable calibration of Hoisch (1990) was applied, the results however, provide minimal constraints on the peak and retrograde conditions.





The specimens from Gorman Crags West, GW90/3 & GW90/4 are strongly reset to retrograde conditions (GW90/4  $\approx$  550°C & 3 kbar, Fig. 6.10g), commensurate with the late-stage deformational features, such as abundant boudinaged sillimanite separated by symplectitic Spl and Bt (e.g. Fig. 6.19i). The Lensink Peak samples (Fig. 6.10h & i) are poorly constrained with only Grt-Bt-Pl-Qtz assemblages available for geothermobarometry however, the Grt-Bt thermometry of Ferry & Spear (1978) suggests temperatures >750°C for S90/5 (Fig. 6.10h).

# 6.4.2.3 Mt Lanyon region

#### Mt Lanyon, LAN/23

The most compellingly constrained P-T path from Mt Lanyon was determined with a Grtrich pelitic gneiss LAN/23 and supported by evidence from a similar, although strongly deformed, nearby pelite LAN/19. LAN/23 is a medium grained, gneissic garnet-dominated pelitic gneiss, containing Ti-rich phlogopites, plagioclase, rutile, quartz and minor secondary, partially pinitized cordierite (Fig. 6.11) In contrast, LAN/19, is a strongly deformed pelitic gneiss, containing extremely attenuated garnet porphyroblasts, which along with sillimanite and biotite, define the gneissic foliation (Fig. 6.12). These specimens contain an unusual abundance of rutile, compared with many pelites in the nPCM; Ellis (1982) noted that the Napier Complex pelites are characterized by rutile as the Ti-accessory phase, where-as ilmenite and titaniferous biotite are common in Rayner Complex pelitic rocks.

The most diagnostic feature of these specimens is the unusual preservation of significant  $X_{Grt}^{Mg}$  zonation, with core values of 0.42 to rims of 0.19 (LAN/19) and 0.38 to 0.21 (LAN/23) (Fig. 6.13a & b).  $X_{Grt}^{Ca}$  values show little consistent variation, however  $X_{Grt}^{Mn}$ 

increases at the rims. Plagioclase inclusions in the central high Mg zone of the garnet porphyroblasts of LAN/23 are more calcic (An<sub>0.40</sub>) than plagioclase adjacent to the garnet rims (An<sub>0.32</sub>). However garnet does not display a zonation in  $X_{Grt}^{Ca}$  values around the more calcic inclusions (Fig. 6.11). In comparison, the groundmass plagioclase in LAN/19 is significantly more calcic with values around An<sub>0.69</sub>.

Figure 6.11 Textural and compositional features in the pelite LAN/23. Coarse grained (=4 mm diameter) garnet porphyroblast surrounded by partially pinitized cordierite (stippled), encompassed by and including, plagioclase and quartz. Sillimanite has lined hatching and Ilmenite is shaded black. Values of  $X_{Grt}^{Mg}$  (x 100) for a traverse through the porphyroblast are shown, as well as values of  $X_{Pl}^{Ca}$ ,  $X_{Crd}^{Mg}$ 

circled, and  $X_{Phl}^{Mg}$  (x 100) outside the garnet. The lower enlargements are of the three labelled plagioclase inclusions (stippled on inner rims) with values of  $X_{Pl}^{Ca}$  (x 100) and  $X_{Grt}^{Ca}$  (x 1000),

indicating no significant increase in the grossular content of the garnet towards the plagioclase inclusions. Note the higher anorthitic content of the inclusions compared with plagioclase outside the garnet porphyroblast.



Figure 6.12 Textural and compositional features in the pelite LAN/19. Extremely attenuated garnet porphyroblasts are surrounded by totally pinitized cordierite (stippled), within a groundmass of sillimanite (lined hatching), quartz, plagioclase and K-feldspar. Ilmenite is shaded black. Field of view is 10 mm wide. Garnet (94 analyses) is contoured for values of  $X_{Grt}^{Mg}$  (x 100).




Phlogopites in these specimens contain acicular rutiles, preferentially oriented along cleavage and crystal faces (Fig. 3.9h). Rims occasionally preserve symplectitic textures with intergrown vermicular quartz, which also occurs as thin veins within the phlogopite. These textures are interpreted to have formed by exsolution during cooling via the unbalanced reaction:

 $Ti-rich phl = Ti-poor phl + Rt + Qtz \qquad ...(6.1)$ 

an analogue of the reaction described by Forbes & Flower (1974), in which Titanphlogopite breaks down to a phlogopite solid solution, plus rutile.

In order to assess the Ti content of these phlogopites, selected idioblastic crystals were analyzed in both LAN/23 (50 points) and LAN/19 (32 points); the TiO<sub>2</sub> content of the integrated analyses is 6.7 wt% and 2.5 wt% respectively, with the phlogopites of LAN/23 showing higher TiO<sub>2</sub> values than usual granulite facies phlogopites. Forbes & Flower's (1974) experiments conducted on mantle composition Titan-phlogopites with around 10 wt% TiO<sub>2</sub>, were reportedly stabilized approximately 150°C higher than the pure phlogopite end-member. Titanium-rich phlogopites, which exsolved rutile and quartz upon cooling, are interpreted here as evidence of high metamorphic temperatures.

 $SiO_2$  and  $TiO_2$  values the 82 phlogopite analyses, are inversely correlated (Fig. 6.14) with a distinctive trend, defined mainly by analyses from LAN/23, towards 100% TiO<sub>2</sub>, confirming the visual identification of acicular rutile needles within phlogopites, and supporting an exsolution open-system type reaction (6.1).

The maximum preserved *P-T* conditions in LAN/23 are constrained by combining thermobarometry with phase relationships, delineated using calculated mineral isopleths. Applying the Grt-Bt thermometer of Ferry & Spear (1978) with garnet cores and the distal discrete phlogopites containing rutile and quartz exsolutions, provides a maximum preserved temperature range, at pressures of 6 to 7 kbar, of 820°C (Phl rim) to 900°C (Phl core). These are unusually high Grt-Bt temperatures, but are consistent with the textural interpretations of an early high temperature history. In section 6.3.3.1 Indares & Martignole's (1985) calibration which attempts to account for Ti and Al<sup>VI</sup> substitution was examined, with the conclusion that the magnitude of temperature correction was dependent upon the selection of the Grt mixing model and assumptions regarding the form of the actual substitution. It is recognized therefore, that these high Grt-Bt values represent maximum temperature estimates.

The peak pressure conditions experienced by this sample are constrained by combining Grt-Pl-Sil-Qtz barometry with calculated isopleths for cordierite and spinel in equilibrium with the garnet core  $(X_{Grt}^{Mg} = 0.38)$ , using the Nichols *et al.* (1992) data (Fig. 6.15a).



Figure 6.13 (a) Longitudinal zoning profile, from rim to rim, through an extremely elongate garnet porphyroblast in specimen LAN/19, (b) similar profile across an equant porphyroblast typical of garnets in LAN/23.



Figure 6.14 Weight percent SiO<sub>2</sub> & TiO<sub>2</sub> values from phlogopites in the Mt Lanyon specimens LAN/19 & LAN/23. A negative correlation is established dominantly from LAN/23 values, with a clear trend towards 100% TiO<sub>2</sub> reflecting partial or edge analyses of included rutile needles.

Figure 6.15 *P-T* constraints for LAN/23, (a) the Grt, Grt-Spl, Grt-Crd & Spl-Crd fields are depicted, calculated for a core Grt (Mg N° 38) with Nichols *et al.* (1992) and applying the recommended errorbars therein. The preferred maximum conditions circled, supported by Grt-Sil-Pl-Qtz barometry (b), lie within the error limits of the Spl field in (a), while the retrograde path must just pass into the Crd field.

The anhydrous cordierite isopleth defines the lower stability field of garnet in equilibrium with sillimanite and quartz, to 6.8 kbar, at the maximum calculated temperature of 900°C (Ferry & Spear 1978). LAN/23 contains small amounts of altered cordierite providing strong supporting evidence for the positioning of this isopleth with an equivalent peak estimate of 860±50°C and 6.6±0.6 kbar (Nichols *et al.* 1992).

The rock is spinel absent, so the spinel isopleth defines a minimum peak pressure of 9.1 kbar, along the maximum temperature isopleth of Ferry & Spear (1978), below which garnet and spinel are calculated to be stable in this rock. The pressures indicated by the



spinel isopleth are the minimum possible for these compositions, as the spinel was assumed to contain no Zn or  $Fe^{3+}$ , both components which would if present, increase the stability field of the garnet-spinel field with respect to the garnet field (Nichols *et al.* 1992).

Newton & Haselton's (1981) Grt-Pl-Sil-Qtz barometer was used with garnet rim and adjacent plagioclase, as well as garnet core and plagioclase inclusion pairs, to establish any change in pressure conditions during garnet growth. Their calibration is, however, relatively insensitive to small variations in anorthitic component. Ganguly & Saxena's (1984) Grt-Pl-Sil-Qtz calibration applied to these mineral pairs reveals a core pressure of 6.6 kbar (at 870°C), and rim conditions of 1.7 kbar at 550°C (Fig. 6.15b).

A consideration of the error bars on each of the constructed isopleths further constrains the peak conditions. The calculated errors on the anhydrous cordierite isopleth are  $\pm 0.6$  kbar, and those on the spinel isopleth are  $\pm 0.95$  kbar (Nichols *et al.* 1992). The errors on Ganguly & Saxena's (1984) barometer are  $\pm 1$  kbar, while a temperature error of  $\pm 50^{\circ}$ C was used for the Ferry & Spear (1978) formulation, on a median core-rim temperature of 870°C. The preferred maximum preserved conditions, congruent with the following lines of evidence, lying within the error bars of the spinel isopleth, consistent with the Ganguly & Saxena (1984) and Newton & Haselton (1981) core pressures, and with the cordierite isopleth, are 6.6 kbar and 870°C (Fig. 6.15a).

The retrograde trajectory must be shallower than the calculated spinel isopleth, as spinel is absent from these pelites. Further the path probably only just crosses into the cordierite stability field, as it occurs in minor amounts in LAN/23 and is absent from LAN/19. As the volume of cordierite produced is predominantly a function of both the *P-T* conditions and a function of fluid activities, assuming the correct potential bulk rock compositions, partial re-hydration, even with very low water activities, will cause the breakdown of garnet by promoting the stability of cordierite. Therefore, the absence of cordierite and its scarcity in LAN/23, may be caused by localized variations in fluid activities, or may as is preferred in this case, reflect a shallow retrograde trajectory just passing into the cordierite stability field. Pinitization of most of the cordierite around garnet, and the narrow rims of pinite around garnet are commensurate with partial re-hydration, however the introduction of vapour causing the pinitization of cordierite, may have occurred much latter than the formation of cordierite.

Reaction rims of ilmenite on rutile provide further evidence of the retrograde evolution of these pelites, however they may have formed independently through one, or a combination of reactions. The possible reactions to consider are

> $Grt + 3 Rt = 3 Ilm + Sil + 2 Qtz \qquad ...(6.2)$ 9 Grt + 15 Rt + 3 Sil = 6 Crd + 15 Ilm \qquad ...(6.3)

> > 150



$$6 \text{ Grt} + 12 \text{ Rt} = 3 \text{ Crd} + 12 \text{ Ilm} + 3 \text{ Qtz} \qquad ...(6.4)$$
  

$$4 \text{ Sil} + 5 \text{ Qtz} + 2 \text{ Grt} = 3 \text{ Crd} \qquad ...(6.5)$$

In order to assess the conditions at which these reactions occurred it is necessary to assume that the reaction or reactions, preceded from either the garnet core composition, or occurred latter from a rim, or near rim composition.

Reaction rims of ilmenite on rutile in these pelites suggests the retrograde crossing of the 'GRAIL' reaction (6.2) calibrated by Bohlen *et al.* (1983b). Using Grt rim compositions with rutile rims to estimate the pressure conditions at which this reaction occurred, produces pressures of 8.5 kbar (at 870°C), using the Berman (1988) database. Clearly ilmenite is not in equilibrium with the garnet rims; garnet core and ilmenite pairs however, indicate a pressure of 5 kbar (at 870°C), and this isopleth is crossed along the preferred shallow path at 3.3 kbar and around 600°C. These calculations therefore suggest that ilmenite grew relatively early in the retrograde history.

The Crd only producing reaction (6.5), calculated with core compositions, indicates equilibrium at  $\approx 9$  kbar, at peak temperatures. If Crd had formed when this high pressure decompression occurred, and assuming that this is the only specimen preserving this part of the *P*-*T* path, then the composition of Grt that the ilmenite would have had the opportunity to grow from would have been more Fe-rich than a Mg 38 garnet core. Conversely, if rim garnet compositions are used for this reaction, a pressure of 6.8 kbar is attained.

A synopsis of these lines of evidence is as follows: the Crd reaction (6.5) produces reasonable P if Grt-rim compositions are used in the calculation, that is, Crd must have grown late and is not in equilibrium with core Grt compositions. In contrast, reaction 6.2 produces reasonable P if a core Grt composition is assumed, implying that the ilmenite rims formed early in the retrograde history. Calculated pressures decrease with increasing almandine-Grt (rimward from core), but increase with increasing activity of H<sub>2</sub>O: in contrast reaction 6.2 estimates higher pressures with increasingly more Fe-rich Grt.

For comparison the internally consistent data-base of Holland & Powell (1990), applied with core compositions, derives comparable pressures at a lower suggested temperature (750°C), of 6.0 kbar for reaction 6.5, and 7.6 kbar for reaction 6.2.

The rim conditions provided by applying the Grt-Pl-Sil-Qtz calibrations of Newton & Haselton (1981) and Ganguly & Saxena (1984) are very low, 1.7 kbar at 550°C. Given the possible 1 kbar error on this value, retrograde conditions of about 2.7 kbar are plausible and much more consistent with the petrographic evidence of the rarity of cordierite, which is expected if the retrograde path was shallow; where-as if the path had been steeper, a much greater proportion of the cooling history would have occurred in the cordierite fields.



In summary, these significantly zoned garnet pelites preserve strong evidence of high temperature (870°C) and moderate pressure (6.6 kbar) conditions, succeeded by a relatively shallow cooling path to conditions of 550°C and 2.7 kbar.

#### Other Mt Lanyon specimens.

Two other specimens (LAN/1 & LAN/2), a pelitic rock similar to LAN/19, and a Grt-Bt felsic gneiss, provide minimal, but consistent *P-T* controls. Textures preserved in LAN/1 are analogous to those in LAN/19: the garnet porphyroblasts are elongate, and have narrow rims of totally pinitized cordierite. The specimen contains abundant ilmenite, however, unlike LAN/19 does not contain plagioclase or rutile. The garnets are considerably more Ferrich than either LAN/19 or LAN/23, with a rim-core  $\chi_{Grt}^{Mg}$  variation of 0.22 to 0.28,

compared with a variation of 0.19 to 0.41 (LAN/19). The lack of rutile and anorthitic plagioclase, and the preservation of Fe-rich Grt is significant, and provides evidence to infer the reaction of

Alm + 3 Rt = 3 Ilm + Sil + 2 Qtz ...(6.6)

as the rock passed into lower temperatures and pressures. In preference to the reaction

Grt + 2 Rt = 2 Ilm + An + Qtz ...(6.7)

implying that the peak garnets did not contain a significant grossular component.

Grt-Bt thermometry (Ferry & Spear 1978) on LAN/1 (Fig. 6.16a), demonstrates compositional resetting of Fe/Mg between these mineral pairs, and estimates temperatures between 450-550°C, equivalent to the retrograde conditions established for LAN/19 & LAN/23. Thermometry applied to Grt-Bt pairs in LAN/2 detected the preservation of near peak temperatures ( $\approx 750^{\circ}$ C), as well as retrograde temperatures down to 550°C (Fig. 6.16b).

Although the P-T conditions for LAN90/10 are poorly constrained, the specimen deserves a brief description as these estimates are useful in defining the retrograde trajectory with respect to mylonitic deformation. The mylonitic specimen is an extremely strongly deformed calc-silicate composition rock, containing porphyroclasts predominantly of Carich amphibole, diopside and sphene (rimming ilmenite), within an anastomosing fine grained groundmass of quartz, K-feldspar, biotite, anorthitic plagioclase and minor calcite. The internally consistent data-base programme of Holland & Powell (1990) was applied to this sample, and it derives an average P-T from six independent sets of reactions, of  $4 \pm 5$  kbar at 550°C (Fig. 6.16d). While the standard deviation on the average pressure is very

Figure 6.16 Pressure-temperature diagrams for Mt Lanyon and Mt Meredith specimens. (a) The only constraints in LAN/1 are Grt-Bt temperatures which are reset. (b) LAN/2 retains Grt-Bt compositions relevant to near-peak temperatures, although considerble scatter towards low temperatures demonstrates partial Fe/Mg exchange with cooling. (c) The Hoisch formulation estimates an equivalent *P-T* trajectory, for LAN/19, to that carefully established for LAN/23 (above). (d) The Powell & Holland data produce a poorly constrained *P-T* estimate for the mylonitic specimen LAN90/10, however, deformation appears to have occurred post-peak conditions. (e) & (f) The *P-T* paths established for Mt Meredith specimens, using the Hoisch (1990) derivation have similar gradients to the paths independently constrained, although absolute pressures are poorly constrained.





large and by itself provides no useful constraint, the result suggests the following: (a) the selected mineral compositions may not be in equilibrium, although this does not appear to be the case as the diagnostic standard deviations on each mineral are in the order of 5 kbar, i.e. no single phase produces the large standard deviation on the estimated pressure intersection, (b) the mineral data may be poorly constrained in calcic compositions, (c) the system of reactions may have relatively small values of  $\delta V cf$ .  $\delta S$ , so that they have steep gradients in *P-T* space and therefore provide poor pressure constraints, and (d) mylonitization occurred at relatively low temperatures, and although virtually unconstrained by this data, at low pressures, conditions which fall within the calculated retrograde trajectory.

### Mt Meredith

Two samples from Mt Meredith, MER/10 and MER/11, indicate *P-T* paths consistent with those from the Mt Lanyon samples, however as they are derived with the Hoisch (1990) barometer, the absolute pressure values are not as well defined. Both specimens are Grt-Bt bearing felsic gneisses, in which the Fe-rich ( $\chi_{Grt}^{Mg}$  =0.10-0.15) garnet porphyroblasts have

partially reacted to biotite. Similar temperatures are estimated for these samples, with the Ferry & Spear (1978) Grt-Bt thermometer calculating core values of  $715^{\circ}$ C &  $700^{\circ}$ C, and rims of  $580^{\circ}$ C &  $575^{\circ}$ C, for MER/10 and MER/11 respectively. However, the absolute pressure values estimated with Hoisch's calibration (Fig. 6.16e & f), are not accurate, and the slightly steeper cooling paths derived for Mt Meredith are therefore not as reliable as the paths described for adjacent Mt Lanyon outcrops. Taking these pre-cautions into consideration, the combined textural and thermobarometric evidence is reliable enough to assert that Mt Meredith trajectories are dominated by cooling, consistent with paths for the nPCM in general.

# 6.4.2.4 The O'Leary Ridges area

The O'Leary Ridges area includes the O'Leary Ridges, Taylor Platform and Brocklehurst Ridge. The best constrained P-T paths were derived from Brocklehurst Ridge with two pelitic rocks (BRO/11 & BRO/12), whose constituent minerals allow the application of Grt-Crd, Grt-Spl and Crd-Spl thermobarometry, as well as the Grt-Pl-Sil-Qtz barometry of Newton & Haselton (1981). Peak temperatures are indicated for this area, to have been at least 745°C (Ferry & Spear 1978, BRO/11), and maximum pressures are suggested to have been at least 4 kbar using the barometer of Newton & Haselton (1981), for peak conditions in BRO/12. Temperatures of at least 780°C are estimated using the Berman (1988) data for the reaction:

 $2 \text{ Wo} + \text{An} = \beta \text{Qtz} + \text{Grs} \qquad \dots (6.8)$ 

displayed in a calc-silicate boudin (BRO/6), with fine grossular rims on wollastonite ( $X_{CO_2}$  estimations and textures are described in section 6.6). The conditions estimated by the Nichols *et al* (1992) thermobarometry, for Grt cores with either Spl or Crd, are relatively low; temperatures are less than 650°C, and equilibrium pressures less than 4 kbar (Fig. 6.17a &b). Garnet cores are therefore not considered to be in equilibrium with cordierite or spinel, and garnet rims were used to estimate the conditions during the retrograde growth of these minerals. These conditions are calculated to be surprisingly low, around 550°C and 2 to 3 kbar for both pelites, however this result is determined with the internally consistent Grt-Crd and Crd-Spl thermometers, and additionally the Grt-Spl barometer.

The constraints on the peak equilibrium conditions assessed from Grt-Bt bearing felsic gneisses, BRO/15 and OL90/4 (Fig. 6.17 c & d), are minimal: interestingly, however, Grt-Chl thermometry (BRO/15), estimates similar temperatures to the Grt-Bt calibration.

In summary, the *P*-*T* trajectory for this region has a shallow gradient, although the calculated retrograde conditions may be too low, especially the suggested pressure, and conceivably have been adversely affected by continual cation exchange enhanced by slow cooling rates.

#### 6.4.2.5 The Fox Ridge locality

Fox Ridge occurs as an approximately east-west striking ridge on the southern portion of McLeod Massif, in the north-east of the nPCM (Fig. 6.1). Outcrop at the eastern end of the ridge is dominated by strongly deformed felsic gneisses which retain K-feldspar phenocrysts (2-3 cm) and occasional mafic xenoliths. Along the crest of the ridge a mylonite of 1 metre thickness strikes at 083° and dips 80° N, and cross cuts the earlier foliation of the felsic gneisses. This mylonite appears to be just one of many anastomosing shear zones, with a large, poorly exposed mylonitic zone on the southward facing slopes away from Fox Ridge, revealed by scattered outcrops and loose mylonitic fragments occurring across 200 m of strike.

A sub-vertical, dominant lineation characterizes the mylonitic zone with doubly plunging folds demonstrating high strain, accompanied by progressive rotational deformation; on micro-scales, rotation of porphyroclasts, strongly recrystallized and anastomosing fabrics (Fig. 3.11e), typical of moderate to high grade mylonitic deformation, are interpreted here to suggest post peak-metamorphic movement (see also Chapter 3).

Thermobarometric data from a pelitic gneiss (FOX10), a garnet felsic gneiss (FOX/14) and a mafic gneiss (FOX/18), specimens not strongly affected by the mylonitic deformation,

Figure 6.17 Pressure-temperature estimations for specimens of the Brocklehurst Ridge and O'Leary Ridges region. (a) & (b) *P-T* trajectories constrained by Grt-Crd, Crd-Spl & Grt-Spl<sup>1</sup> thermobarometry, with additional constraints of Grt-Bt temperatures in (a), and Grt-Pl-Sil-Qtz pressure in (b). The Hoisch derivation apparently over-estimates pressures in (c) & (d), however, Grt-Bt and Grt-Chl thermometry retain near peak temperatures in (c).

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were combined to infer a *P-T* trajectory for the Fox Ridge area. Maximum temperatures preserved in these rocks were calculated with the Opx-Cpx thermometry of Bertrand & Mercier (1985) in the mafic specimen, 733°C, and a Grt-Bt temperature of 710°C (Ferry & Spear 1978) for the felsic rock (Fig. 6.18c & b). Grt-Bt temperatures of less than 400°C have been reset in the pelite, possibly accentuated by deformation (Fig. 6.18a). Evidence of the retrograde cooling to approximately 550°C is suggested by the Opx-Cpx Kretz (1982) thermometry (FOX/18), as well as the Grt-Bt Ferry & Spear (1978) rim temperature of 595°C in the felsic gneiss (FOX/14).

Peak pressures recorded by these specimens are between  $\approx 5$  kbar (Hoisch 1990, FOX/10) and 6.1 kbar (Newton & Haselton 1981, FOX/10), and although the pressure is not as well constrained for FOX/18, it lies within this range at 6 kbar. Retrograde pressures, are interpreted for FOX/14 from the intersection of the Hoisch (1990) barometer on rim compositions, with rim Grt-Bt temperatures at  $\approx 3$  kbar; if this path is precise, an isobaric trajectory is suggested. Similarly, the intersection of the Albite-Jadeite-Qtz calibrations of Holland (1980) and Gasparik & Lindsley (1980), and the lower Opx-Cpx temperatures, indicates a shallow retrograde path to 4.5 kbar at 550°C in specimen FOX/18.

Figure 6.18 *P-T* paths for specimens from the Fox Ridge locality, (a) the strongest constraints in FOX/10 are placed by the Grt-Sil-Pl-Qtz barometer, (b) poorly constrained, although consistent path indicated by the Hoisch (1990) barometer for FOX/14, and (c) the better defined trajectory for this region, from FOX/18, indicates predominantly cooling with some decrease in pressure.



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Summarizing the thermobarometric evidence in these three specimens suggests that the peak preserved conditions in the Fox Ridge region were 720°C and 6 kbar, followed by a relatively flat cooling path to 550°C and 4.5 kbar.

### 6.5 Spinel morphologies, their mode and conditions of formation

6.5.1 Spinel textures and compositional variations

Hercynitic-gannitic spinels of variable composition, with three distinct textural morphologies occur as minor phases in the pelitic rocks. The morphology interpreted to represent the earliest formed, labelled Spl<sup>1</sup>, occurs as rounded inclusions within sillimanite (Fig. 6.20d & f), and rarely within plagioclase. The second type, Spl<sup>2</sup> (Fig. 6.19e), a groundmass spinel, sometimes associated with ilmenite. Spl<sup>3</sup>, interpreted to have grown synkinematically (with respect to post-peak deformation) occurs as symplectitic intergrowths with biotite (± ilmenite) (Fig. 6.20i) and occasionally cordierite (Fig. 6.19g), or between boudinaged sillimanite (Fig. 6.19h & i). The retrogressive growth of delicate spinel symplectites, Spl<sup>3</sup>, within the necks of boudinaged, coarse grained sillimanite, is congruent with contemporaneous deformation and retrogression. This latter deformational episode was probably a discrete event, as in some specimens the fabric developed between boudins, at a high angle to the dominant foliation, is inter-connected with other boudin necks or anastomoses with the main fabric around large porphyroblasts of garnet. These textural interpretations are similar to those reached by Morand (1988), who describe syntectonic retrogression concomitant with the development of retrogressive muscovite in boudin necks of andalusite, in a granitic aureole, New South Wales.

The compositional distinctions between each spinel variety are complex, and differ from rock to rock within the same region. Effectively, the reactions and local equilibria must be considered for individual spinels and adjacent grains, in order to understand the conditions, and development of compositional variations during the retrogressive growth of the second and third generation spinels.

## 6.5.2 Interpretation of the retrograde growth of spinel

Seven specimens, preserving different textural and compositional varieties of spinels, are discussed here to demonstrate the complexities of the retrograde partial re-equilibration, these are D90/1, GOR90/12, GW90/3, GW90/4, MB90/4, MB90/7 & MB90/9, and are selected from two separate regions, the Mt Béchervaise area in the north, and the Gorman Crags region in the south.

Figure 6.19 Detailed thin-section enlargements of nPCM specimens:

(a) D90/1 (ring 9) Spl<sup>3</sup> enclosed by biotite (stippled), and sillimanite (lined), in apparent equilibrium with ilmenite (black), adjacent to two garnet porphyroblasts.

(b) D90/1 (ring 8) Spl<sup>3</sup> within a pressure-halo, in a fracture separating a garnet porphyroblast. Spinel is in equilibrium with biotite (stippled), sillimanite (lined) and quartz.

(c) D90/1 (ring 10) Spl<sup>3</sup> adjacent to garnet, sillimanite, ilmenite and biotite, with near-by quartz.

(d) GOR90/12 (ring 7) Spl<sup>1</sup> inclusions within sillimanite, adjacent to garnet and ilmenite.

(e) GOR90/12 (ring 2)  $Spl^2$  adjacent to a garnet porphyroblast, sillimanite and biotite, with near-by K-feldspar and ilmenite.

(f) GOR90/12 (ring 5) Spl<sup>1</sup> inclusions within sillimanite, and Spl<sup>1</sup> partly included by sillimanite and also surrounded by ilmenite (black). Note also quartz inclusion suggesting Spl + Qtz equilibrium during prograde(?) metamorphic conditions.

(g) GOR90/12 (ring 3) Spl<sup>3</sup> adjacent to garnet, and surrounded by biotite plus partly pinitized cordierite (dotted).

(h) MB90/7 (ring 2a) spinel which with textural criteria alone, appears to be a  $Spl^3$ , but compositionally has high Cr implying that it grew in equilibrium with an early assemblage. This spinel probably originated as a  $Spl^1$ , was included within sillimanite which was boudinaged in one of the latest deformations; the boudinage-fracture propagated from the inclusion site, a likely zone of weakness, and the necked area, under slightly less compressional stress, allowed the growth of cordierite (dotted), probably from the break-down of garnet (bottom of picture), ilmenite and minor biotite.

(i) Intricate symplectitic  $Spl^3$  and biotite, with minor ilmenite, developed at the neck between boudinaged sillimanite, in GW90/3 (ring 2).



















D90/1 contains spinel inclusions (Spl<sup>1</sup>), that like most early generation spinels, have higher Cr/Zn ratios than the other texturally distinct spinels in this rock (Fig. 6.20a graph Zn/Cr). Specimen D90/1, from Mt Dovers, contains a xenoblastic Spl<sup>1</sup> inclusion, in recrystallized K-feldspar and quartz, which preserves a variation in Cr along its length, but has an almost constant Zn content, of around 11 wt%. This suggests that the diffusional rates of Cr, compared with Zn, are vanishingly slow within the spinel lattice, a remarkable conclusion given that Spl<sup>1</sup> inclusions are interpreted to have grown close to peak conditions, of at least 750°C, over a duration in the order of tens of millions of years (e.g. Ruppel *et al.* 1988, model uplift occurring over 30 million years: Sandiford 1989, models a perturbed geotherm for  $\approx$ 75 million years).

Spinels from Mt Béchervaise samples are plotted in Fig. 6.20b, in most examples they conform to the principle that early spinels contain more Cr, than later generations. A notable exception is that of MB90/9, where Spl<sup>2</sup> are more Cr-rich than the Spl<sup>1</sup> which are included within garnet porphyroblasts. It is unlikely that the spinels within the garnets formed later than the groundmass spinels; the most reasonable explanation for higher Cr in Spl<sup>2</sup> is partial consumption of spinel, leaving the remaining spinel richer in Zn and Cr (as Cr preferentially partitions into spinel).

Figure 6.20c depicts the variable Zn/Cr ratios of spinels from the Gorman Crags region. The most significant specimen is GOR90/12, in which three generations of spinels are present. Spl<sup>1</sup> contain variable quantities of Zn, and Cr, but are characterized by Cr values greater than 1wt%. Spl<sup>2</sup> have discernibly lower Cr values than Spl<sup>1</sup>, with many intermediate between Spl<sup>1</sup> and Spl<sup>3</sup>. Third generation spinels are significantly depleted in Cr, but contain moderately high proportions of Zn.

In order to constrain the retrograde growth of later generation spinels, isopleths for D90/1 were constructed with Berman's (1988) programme (Fig. 6.21). Spinel consuming reactions are important, for relatively shallow retrograde paths:

Spl + Crd = Prp + 2 Sil(6.9)	
9 Spl + 5 Kfs + 3 Crd + 5 H <sub>2</sub> O = 5 Phl + 15 Sil	(6.10)
$3 \text{ Spl} + 15 \text{ Prp} + 10 \text{ Kfs} + 10 \text{ H}_2\text{O} = 9 \text{ Crd} + 10 \text{ Phl}$	(6.11)
$6 \text{ Spl} + 3 \text{ Prp} + 5 \text{ Kfs} + 5 \text{ H}_2\text{O} = 5 \text{ Phl} + 9 \text{ Sil}$	(6.12)

The retrograde paths for much of the nPCM are dominated by shallow cooling trends, gradients which are sub-parallel to reaction (6.9). The formation of late spinel suggests that at least in part, the retrograde path is steeper than the reaction:

 $Prp + 2 Sil = Spl + Crd \qquad ...(6.13)$ 





Figure 6.20 Graphical comparison of wt% ZnO versus wt% Cr<sub>2</sub>O<sub>3</sub> for three spinel generations from pelitic gneisses of the nPCM. Spinel generations are sequentially numbered with a superscript, whilst the second number indicates the estimated pressure in kbar, using the calibrations of Nichols *et al.* (1992). Note that where Spl is not demonstably in equilibrium with Grt, as well as Qtz & Sil, or where Spl is isolated from these minerals, the estimated pressures will not reflect the equilibration pressure. (a) selected spinels from the Mt Dovers region; note the variation of Cr in Spl<sup>1</sup>, and the range of Zn in Spl<sup>3</sup>. Calculated pressures with Spl<sup>3</sup> from specimen D90/1 display considerable variation, primarily due to mineralogical and chemical isolation during retrogressive, disequilibrium growth. (b) spinels from Mt Béchervaise, and (c) spinels from the Gorman Crags region. In samples GOR90/12 & GW90/3 all three spinel generations are represented. Spl<sup>1</sup> retain high Cr, while Spl<sup>2</sup> & Spl<sup>3</sup> retain similar chemistries with <1wt% Cr, and variable Zn.



Figure 6.21 Isopleths for specimen D90/1, calculated using the data of Berman (1988) with core compositions, and assuming an a<sub>H2O</sub>=0.1. Spinel forming reactions are only significant for P-T trajectories steeper than the Prp + 2 Sil = Spl + Crd isopleth, whilst for paths dominated by cooling, spinel consuming reactions are predicted to be important.

This equilibrium is probably most important in controlling the formation of Spl<sup>2</sup>, immediately after peak conditions, and where Grt, Sil and Qtz are adjacent, for the locallized growth of Spl<sup>3</sup>, during late-stage retrogression. The inclusion of Spl<sup>1</sup> in sillimanite and garnet with occasional cordierite inclusions (e.g. specimen D90/2 and reported by Thost & Hensen 1992), suggests the prograde crossing of reaction 6.13. Although the reaction concievably could also be crossed on essentially isobaric cooling paths. Such paths however, necessitate very high temperature maximums, and shallower gradients than are generally estimated for nPCM specimens.

The position of reaction 6.13's analogue, reaction 6.9, controls the effective loss of Cr from the system, as it is taken-up by Spl<sup>1</sup>, thereby preventing it becoming a component of later spinel generations. The prograde path is constrained to be steeper than the slope of this reaction ( $\delta P/\delta T$  slope  $\approx 30^{\circ}$ ), but its actual position in *P*-*T* space is dependent upon the abundance of additional components in the system, such as Zn, Cr, Fe<sup>3+</sup>, which stabilize spinel and spinel-bearing assemblages to lower temperatures and higher pressures (Nichols *et al.* 1992).

The formation of Spl<sup>3</sup>, cordierite and biotite with or without ilmenite, symplectites within boudin necks of sillimanite (Fig. 6.19i) can be understood in terms of an intricate combination of reactions, controlled by both P & T but as demonstrated below, dominantly the local activity of sillimanite. Deformation producing the sillimanite boudins, probably also contributes to the initiation of these reactions which may otherwise remain metastable. To visualize the influence of sillimanite's activity on symplectite formation, log activity sillimanite versus log activity pyrope isopleth diagrams were constructed utilizing the Berman (1988) data. Figure 6.22a is drawn for the retrograde conditions established for D90/1 ( $\approx 600^{\circ}$ C, 4 kbar), and using rim compositions to calculate phases' activities. The most conspicuous feature of this diagram are steep garnet, K-feldspar and sillimanite breakdown reactions. The most Fe-rich garnets breakdown with K-feldspar, upon the addition of water-bearing fluid, as follows:

for high 
$$a_{Sil}$$
 9 Prp + 5 Kfs + 3 Sil + 5 H<sub>2</sub>O = 6 Crd + 5 Phl ...(6.14)  
for lower  $a_{Sil}$  Prp + Kfs + H<sub>2</sub>O = Sil + 2 Qtz + Phl ...(6.15)

Where local grain scale areas effectively react with more magnesian garnet, the quartz absent garnet breakdown reaction produces Spl<sup>3</sup>:

$$Prp + 2 Sil = Spl^3 + Crd$$
 ...(6.16)

Figure 6.22 Log aSil Vs Log aPrp pseudosections, calculated with the Berman (1988) data, for rim compositions of specimen D90/1, assuming aH2O=0.5, at the estimated retrograde conditions of 600°C & 4 kbar. (a) garnet breakdown reactions are dependent upon the activity of Prp and the local activity of Sil, and (b) pseudosection for quartz absent assemblages applicable where reactants effectively isolate local areas from quartz.


Here an explanation of the variable abundance of Zn in Spl<sup>3</sup> can be demonstrated to be controlled by the growth or consumption of spinel, in these local inter-boudin neck areas. Where Spl<sup>3</sup> is demonstrably growing it will preserve a low wt% Cr, as most Cr was partitioned into early growing spinels and thence effectively removed from the system and latter reactions. Local areas growing a relatively large volume of spinel compared with cordierite, or phlogopite, will have lower proportions of Zn, than Spl<sup>3</sup> which are latter themselves partly consumed, thereby increasing the percentage of zinc.

Figure 6.22b is a log activity sillimanite versus log activity pyrope isopleth diagram constructed with equivalent data, but for quartz absent assemblages. Here ilmenite and rutile bearing reactions, which were metastable in the presence of quartz, are stable, although only for very low activities of sillimanite. Common to Figures 6.9a and b are the garnet breakdown reactions (15 & 17): producing cordierite and phlogopite, and cordierite and spinel. The quartz absent reaction grid (Fig. 6.22b) is useful to consider only for localized inter-boudin conditions, once these grain-scale regions are effectively removed from contact with quartz, by the growth of biotite, cordierite and spinel. The extremely low mobility of Al<sub>2</sub>O<sub>3</sub>, particularly along the retrograde path, combined with the enclosure of the sillimanite-boudin faces with biotite, ensures a very low activity of sillimanite (and also Qtz) within these areas, ensuring the formation of minor ilmenite via:

4 Prp + 5 Alm + 3 Sil + 15 Rt = 6 Crd + 15 Ilm ...(6.17)

The reactions therefore follow a sequence primarily controlled by the local activity of sillimanite and quartz, and can usefully be visualized in terms of radially decreasing volumes of local equilibration, contracting inward with decreasing temperature. Retrograde reactions proceeding from near peak metamorphic conditions, where sillimanite is stable (activity  $\approx 1$ ), react Prp, Kfs and Sil with introduced hydrous fluids, to produce Crd and Phl intergrowths. The formation of phlogopite may remove, locally, the small volumes of fluid introduced during retrogression, and enhance the quartz absent garnet plus sillimanite breakdown, which is responsible for the growth of Spl<sup>3</sup>. Within the inter-boudin necks, the growth of biotite, cordierite and Spl<sup>3</sup>, reduce the activity of sillimanite principally by physical isolation, thus allowing the further growth of cordierite and minor ilmenite.

Evidence for fluid infiltration is additionally supported by the growth of fine-grained biotite (usually with minor ilmenite), cross-cutting and replacing garnet rims, or cordierite upon garnet rims. Such fluids were at least therefore, partly hydrous, and evidence of higher ferric values in second generation spinels (e.g. MB90/9, Fig. 6.20b), implies that they grew in a more oxidized state, than prograde conditions, in this sample. In most pelites however, Spl<sup>1</sup>, Spl<sup>2</sup> and Spl<sup>3</sup> have low ferric ion contents.

# 6.6 The role of fluids during the metamorphic evolution of the nPCM6.6.1 Introduction

An assessment and quantification of the role and nature of fluids participating in peak and retrograde metamorphism, and their probable inter-lithological variations, was not one of the major emphases of this research. The particularly important influence which hydrous and carbon-dioxide bearing fluids exert on the stability relationships of calc-silicates, and hydrous phases in pelitic lithologies, has however, been the one of the centres of research interest (Bertrand *et al.* 1991, Bickle & Baker 1990, Hiroi *et al.* 1987, Lamb & Valley 1988, McPhail *et al.* 1990 and Valley *et al.* 1990), and some preliminary interpretations from nPCM rocks deserve attention here.

Studies of the composition of fluids during peak and post-peak metamorphism, and in the investigations of dehydration melting, necessarily assume that fluids are composed of mixtures of a relatively small number of possible species, which usually only include  $CO_2$ and  $H_2O$ , at differing  $fO_2$  conditions (e.g. Wolf & Wyllie 1991). In some areas additional species such as  $CH_4$ ,  $SO_4^{2-}$ ,  $Cl^-$ ,  $F^-$  and  $NH_4^+$  are investigated (e.g. Poulson & Ohmoto 1989). Quantitative evidence of fluid compositions is provided here, assuming fluid mixtures of  $CO_2$  and  $H_2O$ .

Local mineralogical equilibria combined with possible spatial fluid compositional variations must be significant, over an area as large as the nPCM, and estimations of fluid compositions are therefore relevant only to the areas of investigation.

# 6.6.2 Qualitative evidence of fluid compositions

Qualitative evidence of fluid compositions is provided by the following mineralogical evidence. The southerly facing cliff exposure of Mt Lanyon (Appendix 1) is dominated by marbles and felsic-gneisses, separated, at the eastern end of the cliff, by a steeply dipping fault. Calcic-amphibole porphyroblasts with calcite developed in pressure shadows, occur within the strongly sheared adjacent felsic gneisses, consistent with the local mobilization of CO<sub>2</sub>-bearing fluids, channelled along the fault plane. At the same locality, and within these felsic gneisses, pyrrhotite-dominant pods (LAN/39A & LAN/40), which appear to have been subjected to peak metamorphic conditions, provide evidence of local sulphur-rich fluids, probably at an early stage in the area's history. Further qualitative evidence of late fluid migration, associated with minor faults, for example those on Taylor Platform which cross-cut the Permian aged dykes, are in places, associated with brecciated platey calcite, intergrown with later microcrystalline quartz, with an ultimate stage of crystalline quartz infilling vugs (e.g. LAN/48).

# 6.6.3 Quantitative evidence of fluid compositions

#### 6.6.3.1 Oxygen fugacities

Evidence of reduced conditions during near-peak, and demonstrably post-peak metamorphism is provided by estimating the ferric iron ratios of successive spinel generations (section 6.5.2), thereby estimating the equilibration  $fO_2$  conditions (e.g. Ballhaus *et al.* 1991) and consequently constraining the possible composition of the fluid. Reduced  $fO_2$  conditions are also supported by the occurrence of graphite pods (2 to 3 cm<sup>3</sup>) in some pelitic gneisses (e.g. D90/4).

#### 6.6.3.2 Fluid compositions constrained by calc-silicates

Evidence of fluid compositions, constrained by mineral equilibria, is provided by the preservation of distinctive reaction zonations, in calc-silicates and marbles from one region in particular, and includes the outcrops of the O'Leary Ridges (specimens OL90/5 & OL90/7), Brocklehurst Ridge (BRO/6) and Taylor Platform (TP/14).

Specimen BRO/6, from Brocklehurst Ridge, passes from the surrounding calcicamphibole gneisses, through the rim and towards the centre of a calc-silicate boudin, dominated by grossular garnet, early clinopyroxene ( $Cpx^1$ ), and anorthitic plagioclase. Parallel with the boudin's margin and adjacent to the green calcic-amphiboles, is a layer of acicular ilmenite grains, however, further towards the centre, sphene becomes the dominant Ti-bearing phase. Within the centre of the boudin, grossular garnet forms thin rims on wollastonite, and in places  $Cpx^1$ . Indicating the crossing of the reaction,

$$An + 2 Wo = \beta Qtz + Grs \qquad \dots (6.18)$$

from temperatures of at least  $\approx 780^{\circ}$ C, estimated with the Berman (1988) data. Grossular garnet porphyroblasts are surrounded by vermicular intergrowths of clinopyroxene (Cpx<sup>2</sup>) within an anorthitic groundmass, implying the garnet breakdown reactions:

$$Fe_{3}Al_{2}Si_{3}O_{12} + 4 CaCO_{3} + SiO_{2} = 3 CaFeSi_{2}O_{6} + CaAl_{2}SiO_{8} + CO_{2} \qquad ...(6.19)$$
  
Alm + 4 Cal + Qtz = 3 Cpx + An + CO<sub>2</sub> ...(6.20)

and 
$$Ca_3Al_2Si_3O_{12} + 2CO_2 = CaAl_2SiO_8 + 2CaCO_3 + 2SiO_2$$
 ...(6.21)  
Grs + 2CO\_2 = An + 2Cal + 2Qtz ...(6.22)

Figure 6.23a displays the breakdown reactions of grossular garnet porphyroblasts and wollastonite, on an isobaric, temperature versus  $X_{CO2}$  section. Central portions of the boudin probably experienced moderately CO<sub>2</sub>-rich vapour, with a maximum permissible value indicated by these equilibria of 0.45. However, the mineralogical evidence of ilmenite

Figure 6.23 Temperature  $Vs X_{CO2}$  sections at 5 kbar, based upon the data of Berman (1988): reactants on the high temperature side of the reactions are written on the left-hand side. (a) The development of grossular rims on wollastonite in specimen BRO/6, indicates the crossing of the An + 2 Wo =  $\beta$ Qtz + Grs reaction, at 780°C; the maximum permissible  $X_{CO2}$  for the centre of the boudin is thus 0.45. Reaction 1: Grs + 3 Hm + 3 Wo + 3 CO<sub>2</sub> = 3 Spn + 3 Cal + Alm, reaction 2: 4 Grs + 3 Hm + 6  $CO_2$  = 3 Spn + 6 Cal + 3 An + Alm.

(b) Isobaric pseudosection for specimen OL90/5, with the reaction controlling the stability field of zoisite, dotted along its lower margin, and indicating for temperatures > 550°C, an  $X_{CO2}$  < 0.1. Reaction 1: 2 Zo + CO<sub>2</sub> = Cal + 3 An + H<sub>2</sub>O, reaction 2: Spl + 9 Di + 11 An + 6 H<sub>2</sub>O = 2 Tr + 8 Zo, reaction 3: 5 Di + 9 An + 4 H<sub>2</sub>O = 6 Zo + Tr + 2 Qtz, reaction 4: 3 Spl + 27 Di + 7 H<sub>2</sub>O + 11 CO<sub>2</sub> = 11 Cal + 6 Tr + 2 Zo, reaction 5: 3 Tr + 10 Zo + 26 CO<sub>2</sub> = 15 Spl + 54  $\beta$ Qtz + 26 Cal + 8 H<sub>2</sub>O, reaction 6: 5 An + Tr + 7 CO<sub>2</sub> = 5 Spl + 18  $\beta$ Qtz + 7 Cal + H<sub>2</sub>O, & reaction 7: 3 Spl + 8  $\beta$ Qtz + 7 Di + 2 H<sub>2</sub>O = 3 An + 2 Tr.



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adjacent to the calcic-amphibole rim, with sphene closer (approximately 5 mm) towards the centre of the boudin, demonstrates the extremely localized influence of the CO<sub>2</sub>-fluids, since the sphene-stable fields pass into the ilmenite-stable regions, at low  $X_{CO_2}$ 's < 0.1 for T  $\approx$  780°C (Fig. 6.23a reactions 1 & 2). Mobilization occurs over similar scales in the Mt Béchervaise calc-silicate boudin, MB90/8, within orthopyroxene-bearing felsic gneisses, where the transition from sphene to ilmenite occurs in 2-3 mm.

The anorthite plus wollastonite breakdown reaction, however places no minimum constraints on the value of  $X_{CO_2}$ . The equilibration  $X_{CO_2}$  experienced during peak conditions may have been «0.45, and the change from ilmenite-dominant to sphene mineralogies, could alternatively be produced by diffusional gradients of CaO and TiO<sub>2</sub>.

Fluid compositions are well constrained in the Cpx-An-Cal rich boudin from the O'Leary Ridges, OL90/5. The boudin in surrounded by a thin rim of calcic-amphibole, and lies within olivine-bearing marbles discussed below (OL90/7). The most significant features of the Cpx-boudin, are porphyroblastic spinels, partly altered to chloritic mica, groundmass zoisite, and occasional grains of chalcopyrite. At near peak metamorphic temperatures, zoisite and spinel-bearing assemblages are only stable at  $X_{CO2}$ 's < 0.1 (Fig. 6.23b): when temperatures fall below  $\approx 550^{\circ}$ C, zoisite is stabilized over an expanding range of  $X_{CO2}$ , however, spinel is not stable at these conditions. These low  $X_{CO2}$  conditions are consistent with those obtained for the near-by outcrops of Brocklehurst Ridge.

Olivine-bearing marbles (OL90/7) hosting the calc-silicate boudin, preserve interesting cooling reaction textures, which are however, only weakly sensitive to changes in fluid compositions. In zones where the marble is immediately adjacent to the boudin, the forsteritic olivines (Fo 0.93) react with Cpx via:

 $Fo + Di + CO_2 = Cal + 3 En$  ...(6.23)

The Berman (1988) data place this reaction between 650 and 450°C (Fig. 6.24a), for reasonable fluid composition estimates.

A calc-silicate boudin, from Taylor Platform (TP/14), preserves an interesting mineralogy with rare reaction textures, however, the equilibria by which these are formed are also insensitive to the relative abundance of  $CO_2$  in metamorphic fluids, at the considered temperatures and pressures. The boudin is composed predominantly of pale-green (in hand-specimen) diopsidic clinopyroxene, calcite, anorthitic plagioclase, and minor quartz. The interesting textures consist of partly resorbed spinels, associated with minor corundum, within moats of calcite, that are themselves surrounded by a rim of plagioclase intergrown with clinopyroxene which is oriented radially away from the central spinel. Figure 6.24b

Figure 6.24 (a) Temperature Vs X<sub>CO2</sub> section at 5 kbar, based upon the data of Berman (1988), for the olivine-bearing marble specimen OL90/7. While the crossing of the reaction, Fo + Di + CO<sub>2</sub> = Cal + 3 En, evidences substantial cooling, the reaction is not particularly sensitive to variations in X<sub>CO2</sub>.
(b) Pressure Vs temperature pseudosection for specimen TP/14. The sequential crossing of the reactions explaining the development of the Spl + Cor textures, moated by Cal. Reaction 1: An + Di + 2CO<sub>2</sub> = Spl + 4 βQtz + 2 Cal.

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Figure 6.25 A schematic for the sequential formation of Spl + Cor, moated by Cal in specimen TP/14. (a) an early assemblage of anorthitic plagioclase and spinel, reacts upon cooling to corundum and diopsidic clinopyroxene (b), with further cooling the anorthite reacts to calcite, quartz and corundum (c), continued cooling promotes the final reaction of corundum, diopside and carbon-dioxide to partially reform spinel, quartz and additional moats of calcite (d).

displays isopleths for the equilibria responsible for the formation of these textures. The sequential development of Spl + Cor moated by calcite, is shown schematically in Fig. 6.25, corresponding to crossing of these equilibria upon cooling: an early assemblage containing anorthitic plagioclase and spinel reacts as follows,

An + Spl = Di + 2 Cor ...(6.24)

plagioclase breaks down further to produce Cor, Cal and Qtz,

$$An + CO_2 = Cor + Cal + 2 \beta Qtz \qquad \dots (6.25)$$
  
$$Cor + Di + CO_2 = Spl + Cal + 2 \beta Qtz \qquad \dots (6.26)$$

Analogous Spl + Cor textures are reported by Buick & Holland (1991), who infer the crossing of a similar, although Qtz-absent reaction, during cooling.

#### 6.6.4 Summary

The values of  $X_{CO_2}$  for the calc-silicates investigated here, are relatively low, <0.1, and where some evidence exists for a partly CO<sub>2</sub>-saturated fluid phase (BRO/6), mineralogical criteria remonstrate that mobilization was effective over very short distances ( $\approx 5$  mm). Ferric iron ratios in peak and post-peak spinels, are suggestive of low  $f_{O_2}$  conditions. Leucocratic melt segregations, in both macroscopic, but also microscopic, layer-scales, would have effectively partitioned all available hydrous vapour. This combined evidence, implies that peak assemblages were not subjected to extensive CO<sub>2</sub>, H<sub>2</sub>O or O<sub>2</sub> fluid flushing during equilibration.

There is however good evidence of the interaction of fluids both before and after peak conditions; the occurrence of metamorphosed pyrrhotite pods, garnet breakdown to cordierite and late-stage biotite and fluids channelled during faulting. It is hypothesized therefore, that fluids had a significant role during the early part of the metamorphic history, during crustal dehydration. As the crust approached peak temperatures partial melting caused the local formation of migmatites (preserved in meta-pelitic lithologies) and fluid remaining at these conditions was immediately partitioned into the melt phase. The equilibrated assemblages preserving the peak metamorphic conditions, thus experienced essentially fluid free conditions, although calc-silicates possibly experienced very localized  $CO_2$ -rich environments.

Post-dating peak conditions, the reintroduction of minor volumes of partly hydrous fluids is evidenced by the partial breakdown of garnet to biotite and pinite. Cordierite, in many cases itself replaced by pinite, grew from the partial retrogression of garnet, but this did not significantly affect the mineralogy established during peak equilibration. The minor rim-replacement of Grt by Crd however, suggests that either the specimens just passed into



the Crd-stability field, or that the assemblages were effectively anhydrous. A conclusion supported by the preservation of Grt and delicate (i.e. easily reacted) Spl mineralogies.

Very much later, post-Permian,  $CO_2$ ,  $H_2O$  and  $SiO_2$ -rich fluids were channelled along minor fault surfaces, and formed quartz-calcite intergrowths in veins.

#### 6.7 The formation of acicular sillimanite inclusions in garnet

Acicular aluminosilicate needles included within garnet porphyroblasts feature in many pelitic rocks from the nPCM, and in other metamorphic terranes, for example many amphibolitic, and granulitic regions (Anmatjira Range central Australia, Vernon 1989). Understanding their development, and defining the probable conditions of formation, even in a qualitative manner, provides further information on the metamorphic trajectory experienced by these rocks, and allows comparisons of these conditions. As well an implicit comparison of the diffusional rates of components in garnets, arrived at in this study, leads to a possible explanation of the preserved zonations in garnets.

Fine sillimanite needles, coarse sillimanite, ilmenite, quartz, occasionally spinel and plagioclase are the most common phases included within garnet porphyroblasts in the nPCM. The coarser grained sillimanite unlike the finer grained mineralogical equivalents, invariably lies parallel to the anastomosing foliation, where-as fine sillimanite needles have a large proportion without an obvious systemmatic orientation, although some are usually sub-parallel to the surrounding foliation. The densities of acicular sillimanites decreases in accordance with the proximity to quartz and coarse grained sillimanite inclusions (e.g. LAN/1), and with increasing Mg-number of the host garnets (e.g. LAN/19 & 23)

Pigage (1982) applied linear regression techniques to model the two-stage breakdown of garnet and staurolite, with rutile required initially, to produce sillimanite-bearing assemblages at Azure Lake, British Columbia. However, these reactions also produce muscovite, a reactant phase not apparently involved in the formation of sillimanite in the nPCM.

The disposition of acicular sillimanites implies that sillimanite grew contemporaneously with the formation of almandine garnet, either by diffusional growth, from the most magnesian garnet, that nucleation occurred on pre-existing coarser grained sillimanites if they were available, and that the relative diffusion rates of Al in garnet is much less than that of other components. The Fe/Mg zonation in samples from Mt Lanyon (LAN/19 & 23) reflects the processes of post-peak cation diffusion, where Mg has diffused rimward through originally homogeneous garnets, and there, has become a contributing component of reactant phases such as biotite, cordierite and spinel in similar composition rocks. In many nPCM specimens this diffusional homogenization has proceeded to



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completion, and no high temperature or pressure magnesian-rich cores remain. Significantly, almandine garnets, for example those from FOX/14, rarely contain acicular sillimanite, supporting the importance of pyrope breakdown in the development of acicular sillimanite.

Essentially, pyrope rich garnets, acting in response to decreasing temperature and decreasing  $a_{Sil}$ , breakdown to form quartz, sillimanite, and a magnesian-bearing phase, for example phlogopite, (Fig. 6.26a) i.e.,

$$Prp + Kfs + H_2O = Sil + 2 Qtz + Phl \qquad ...(6.27)$$
  
or 3 Prp + 6 Spl + 5 Kfs + 5 H\_2O = 9 Sil + 5 Phl \qquad ...(6.28)

The reactions are dependant upon the  $a_{Sil}$ , where the formation of sillimanite is favoured for low  $a_{Sil}$ . Figure 6.26a is calculated with the core garnet compositions (Mg N<sup>2</sup> 42) of specimen LAN/19, whereas Figure 6.26b, effectively an inset of 6.27a, is calculated for rim garnet compositions, signifying that the formation of acicular sillimanites occurs with the reaction of pyrope-rich garnet, and at high temperatures.

The local activity of silica, during the breakdown of pyrope-rich garnet is also important for the formation of acicular sillimanites. Specimen MB90/9 provides an example of a relatively sillimanite and quartz-poor assemblage, where spinel inclusions within coarse garnet porphyroblasts are common, and uncharacteristically, there are no sillimanite inclusions within the garnets.

Figure 6.26 Temperature Vs log  $a_{Sil}$  pseudosections, calculated at 7 kbar, with the data of Berman (1988), for specimen LAN/19. (a) isopleths relevant to core compositions, depicting the reaction of pyrope garnet, at high temperatures, to form sillimanite, and (b) equivalent isopleths, calculated for rim compositions. Reactions, assemblages written on the left hand side are stable on the high temperature side, 1: 3 Prp + 5 Kfs + 6 Spl + 5 H<sub>2</sub>O = 9 Sil + 5 Phl, reaction 2: 3 Crd = 4 Sil + 5  $\beta$ Qtz + 2 Prp, and reaction 3: Crd + Spl = 2 Sil + Prp.



Presumably, the pyrope-rich garnets reacted with sillimanite in the quartz absent reaction, at relatively high activities of Sil (Fig. 6.26a):

9 Sil + 2 Prp + 15 Ilm = 5 Alm + 6 Spl + 15 Rt ...(6.29) thereby consuming early sillimanite and producing the preserved spinel inclusions.

The relative diffusional rates in garnet are in approximate decreasing rates, Fe = Mg > Si > Al. Suggested by Carmichael (1969), who cites samples which demonstrate the relative immobility of Al, compared with other elements. The diffusivity of Al may be increased, however, with accompanying deformation, demonstrated by the resultant growth of fibrolitic sillimanite (Vernon & Flood 1977). Upon cooling the excess Mg removed from pyrope breakdown, diffuses rimward relatively rapidly, but Si and Al may not have time enough to diffuse to the rim. This phenomena, termed incongruent dissolution by Carmichael (1969), is equivalent to the inferred process described by Pinet & Smith (1985) to explain the presence of rutile inclusions having exsolved from Ti-rich eclogitic garnets. Si nucleates on pre-existing quartz inclusions, and Al will also follow the same phenomena, but is more strongly limited by its diffusional rate, therefore as its effective diffusional radius is less, excess Al will preferentially combine with Si to nucleate acicular sillimanites within garnet. The latter conclusion is commensurate with the findings of Foster (1982) whose estimates based upon chemical potential gradients and thermodynamic diffusional rates, suggest that sillimanite is the major Al sink in sillimanite-bearing segregations.

In contrast, garnets with abundant Spl inclusions (e.g. MB90/9) probably represents the prograde growth within Si poor assemblages, supported by minor Sil in the groundmass; this phenomena is therefore a prograde growth, not retrograde diffusional reequilibration as the Sil inclusions.

#### 6.8 Discussion

#### 6.8.1 Spatial variation of P-T trajectories in the nPCM

P-T trajectories plotted on Figure 6.27 were calculated with consistent thermometers and barometers, and have similar shallow gradients. The post-peak metamorphic history of the nPCM is therefore dominated by cooling with minimal decompression.

Reconnaissance mapping and sampling, suggested to early geologists, that the metamorphic grade decreased from the most northern to the southern nPCM outcrops (Tingey 1972). However, as depicted in Figure 6.27, the recorded ranges of temperatures over the region are almost constant (the lower temperatures may in part be caused by the same blocking kinetics, preventing Fe/Mg exchange to temperatures below  $\approx 550^{\circ}$ C). In contrast, the maximum preserved pressures vary significantly from eastern outcrops, where









pressures are highest, to the most western yet examined, where the lowest pressures were recorded.

# 6.8.2 Comparison with eastern Lambert Glacier paths

## 6.8.2.1 Reinbolt Hills

A well constrained P-T path, described in Chapter 4 and in Nichols & Berry (1991), established the change in metamorphic conditions from 800°C & 7 kbar, to 690°C & 5 kbar, for the Proterozoic aged granulites (Grew & Manton 1977) of the Reinbolt Hills. This path closely matches the slopes of decompressional paths established for the Proterozoic Rauer Group granulites and the Larsemann Hills (Nichols & Berry, 1991), although it has a slightly shallower slope, even when considering the possible errors in the geothermobarometric evaluations (*cf* Figs. 6.29a, c & d). The magnitude of both pressure and temperature change is consistent with those changes estimated by Harley (1988) for the Proterozoic Rauer Group granulites.

The P-T path of granulites from the Reinbolt Hills is particularly important in assessing the variations in trajectories of granulites for this region of East Antarctica, as the Reinbolt Hills are one of the closest outcrops to the Prince Charles Mountains, but are separated by a large physiographical structure, the world's longest glacier, the Lambert. This north-south trending feature, lies parallel to the Beaver Lake Graben filled with greater than 2500 m of Permian aged Amery Group sediments, subdivided into the basal Radok Conglomerate, middle level deltaic sequences of sandstones, the Panorama Point beds, which are overlain by the Bainmedart Coal Measures (McKelvey & Stephenson, 1990), and have an upper Late Permian to Triassic aged sequence called the Flagstone Bench Formation (Fielding & Webb, 1992). The Beaver Lake Graben and possibly the Lambert Graben, are considered to have been connected to the Son-Mahanadi Graben in northeast India, forming an extensive linear Permian braided fluviatile drainage system (Webb & Fielding, 1992), however, it is not clear if this graben feature developed in the early Permian, or if it was accentuated by Permian extensional tectonism (evidenced by alkaline and ultrabasic magmatism during late Mesozoic times, Andronikov, 1990), along a pre-existing Precambrian structure. Preliminary apatite fission track analysis supports the hypothesis of aborted rifting and some uplift during the Early Cretaceous (Arne, 1992). It has been further suggested by Kent (1991) that the development of the continuous Son-Mahanadi-Lambert Graben drainage system, resulting from uplift and crustal extension, provides prior evidence of the underplating of mafic magmas (here the Kerguelen-Heard plume), which evidence themselves as the Cretaceous alkalic, mafic and continental tholeiitic magmatism, in this region of Gondwana.

Figure 6.28 Comparison of P-T trajectories derived in the nPCM, with regions of East Antarctica, and the Yilgarn Craton, Trajectories in **bold** are pre-1100 Ma paths, many with either Archaean ages (quoted in Ma, where dating exists) or are assigned to the Archaean by relative chronology; paths in thin lines are Proterozoic; dotted paths are constrained only by the juxtaposition of the rocks in which they occur; dashed paths are inferred, or poorly constrained. (a) P-T paths calculated for the nPCM, equivalent to Fig 6.28 and included to facilitate direct comparison. (b) In **bold**, an undated but probably Archaean trajectory derived for Søstrene Island by Thost et al. 1991, followed by Proterozoic retrogression indicated in the adjacent Bolingen Islands (Motoyoshi et al. 1991), (c) Archaean (3300-2830 Ma) trajectory in **bold**, for Mather Peninsula (Rauer Islands) mafic boudins and layers (Harley 1991). Paths Nº 1 & 2 Proterozoic trajectories for the Rauer Islands (Harley, 1988 and Fitzsimons & Harley, 1991, respectively), path Nº 3 for the Brattstrand Bluffs, Fitzsimons & Harley (1991). (d) Decompressional path followed by cooling, for the Larsemann Hills, and rectangle indicates P-Tconditions for Hamm Peak, in the Munro Kerr Mountains (further west), Stüwe & Powell (1989), (e) Upper angular path established by Passchier et al. (1990) for the Vestfold Hills, lower curved trajectory by Seitz (1991). (f) In bold, Archaean isobaric cooling from 3050 to 2500 Ma (Harley 1985a), post-dated by Proterozoic decompression (Harley 1985b), and curved trajectory inferred by Motoyoshi (1990) for the Proterozoic (1100-700 Ma) Lützow-Holm Bay Complex. (g) Intricate paths established by Muhling (1990), for the Archaean, and Proterozoic evolution of the northern Yilgarn Craton. If a Precambrian structure existed, P-T paths on either side may preserve different retrograde paths, quantification of which, may define the structure itself.



When compared with the *P*-*T* paths established for the PCM rocks, the Reinbolt Hills' path records higher maximum pressures by around 1 kbar (than easterly PCM areas), and preserves decompression of 2 kbar, similar but slightly greater than the PCM rocks. The cooling experienced synchronously with decompression for the Reinbolt Hills rocks ( $\approx 110^{\circ}$ C), is slightly less than recorded for most nPCM samples around 150-200°C, producing the steeper gradient. Significantly the maximum pressures of the Reinbolt Hills are intermediate between those from the nPCM and from the McKaskle Hills supporting the hypothesis that there was a gradual change in preserved conditions from the east to the west, rather than a discontinuous change in paths across the now, Lambert Graben.

#### 6.8.2.2 McKaskle Hills

A decompressional P-T history described in Chapter 5, is derived for the McKaskle Hills, which lie within a north-south trending belt of nunataks, along the eastern side of the Lambert Glacier, north of Jennings Promontory and the Reinbolt Hills. The decompressive episode recorded by the symplectitic growth of orthopyroxene + plagioclase + spinel, from garnet, in mafic gneisses (e.g. M2, 72049), has a gradient comparable with the path experienced by the Reinbolt Hills (Fig. 6.28a), although preserved temperatures and pressures are greater. The decompressive phase experienced by the McKaskle Hills gneisses, apparently synchronously with the Reinbolt Hills, is correlated with the preserved cooling episode in the Prince Charles Mountains.

## 6.8.2.3 Brattsrand Bluffs

Approximately 15 square kilometres of Proterozoic outcrop along a 70 km segment of coastline, between the Rauer Islands and the Larsemann Hills, are referred to as the Brattstrand Bluffs by Fitzsimons & Harley (1991) who describe regional correlatives and an interpreted *P-T* path for this area. They estimate that peak metamorphic conditions of 850°C & 6 kbar were proceeded by a decompressive episode (Fig. 6.28c), evidenced by spinel-cordierite symplectites (equivalent to those described by Nichols & Berry 1991), to pressures of 3-4 kbar. Fitzsimons & Harley (1991) correlate this decompression with the decompressive episode in the Rauer Islands, and the Larsemann Hills; differentiating basement for the higher pressure Rauer Group, an interleaved basement-cover sequence for the moderate pressure Brattstrand Bluffs, and a cover sequence for the lower pressure Larsemann Hills. The three regions lie on an equivalent *P-T* trajectory, and cool nearly isobarically, post-decompression, until probable exhumation during an event  $\approx 500$  Ma (Fitzsimons & Harley, 1991).

The P-T path preserved in the Brattstrand Bluff granulites is therefore comparable with the decompressional path described for the Reinbolt Hills, and like paths on the eastern side of the Lambert Glacier, retains characteristics of decompression, rather than isobaric cooling common to the Prince Charles Mountains.

### 6.8.2.4 Bolingen and Søstrene Islands

Thost *et al.* 1991, describe very similar changes in *P*-*T* conditions to the Archaean mafic layers from Mather Peninsula, Rauer Islands, with the superposition of an undated but probably Archaean high *P*-*T* metamorphism (980°C,  $\approx$ 10 kbar), by a Proterozoic M2 event of 850°C &  $\approx$ 7 kbar, for garnet-bearing mafic granulites from Søstrene Island, about 100 km west of the Rauer Group (Fig. 6.28b). Further retrogression is indicated for calc-silicate granulites from the nearby Bolingen Islands, which record a retrograde path from 760°C & 6 kbar, to 450°C & <3 kbar (Motoyoshi *et al.* 1991).

The Proterozoic retrograde path determined in the Bolingen Islands (Motoyoshi *et al.* 1991) has a relatively shallow gradient equivalent to paths from the Prince Charles Mountains, and is significantly shallower than the Proterozoic decompressional episodes reported for the Rauer Group (Harley & Fitzsimons, 1991), Reinbolt Hills and adjacent Larsemann Hills (Stüwe *et al.* 1989).

#### 6.8.2.5 Larsemann Hills

Stüwe & Powell (1989) describe the Proterozoic *P*-*T* evolution of low pressure granulites from the Larsemann Hills, where an early metamorphism at conditions of 750°C &  $\approx$ 4.5 kbar is indicated by assemblages of Grt-Sil-Spl-Crd-Qtz-Pl in pelitic gneisses. They establish an essentially isothermal decompression of 1-1.5 kbar preceding these conditions (Fig. 6.28d), which they correlate with the equivalent decompressional events recorded in the Rauer Group and other areas of Pyrdz Bay. They propose an under-accretion of crustal magma beneath the Larsemann Hills region, in preference to a crustal thickening model which they claim is in direct conflict with the observed early assemblages of Spl + Qtz in pelitic rocks, and their calculations show such collisional paths would require values of thermal conductivity and heat flux outside the range for normal continental crust. Following decompression, the gneisses cooled essentially isobarically.

The maximum pressures recorded by the Larsemann Hill rocks ( $\approx 4.5$  kbar) are constrained by the occurrence of early Spl + Qtz assemblages, however, these estimations base upon mineral associations, do not account for the influence of ZnO in spinel, stabilizing spinel and spinel-bearing assemblages to higher pressures and lower temperatures (Nichols *et al.* 1992). Although ZnO was not analyzed in the reported spinel compositions (Stüwe &

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Powell 1989), their low totals, and the abundance of ZnO in many Antarctic pelites, lends some support to the contention that these spinels contain ZnO, which would increase estimates of their equilibration pressures.

The slope of the Larsemann Hills path is similar to that estimated by Harley (1988) for Proterozoic decompression in the Rauer Group, and for the Reinbolt Hills, but commences at shallower crustal levels (Figs. 6.29d, c & a). A decompressional phase followed by an indeterminate amount of isobaric cooling documented for the Larsemann Hills, is comparable with the suggestion of Clarke *et al.* (1989) that a decompressional episode occurred before isobaric cooling for rocks along the MacRobertson Land coastline. Similarly, near isobaric cooling presented for the northern Prince Charles Mountains, is consistent with a regional, sporadically preserved, cooling episode, for a large sector of the Rayner Complex of East Antarctica.

Possibly the isothermal and isobaric phases are preserving essentially the same tectonic event, albeit from different crustal levels: where the crustal fragments were already at shallow levels, the paths preserved are shallow, in contrast, steeper decompressional trajectories record the isostatic rise of continental crust. This however, implies that geothermal gradients differed significantly between the western and eastern areas. Such a contrast may be developed by magmatic underplating in the western area causing thermal equilibration at shallower levels, and the amelioration of their earlier history.

## 6.8.2.6 Rauer Islands

Recently, exceptionally high Mg mafic granulite xenoliths and boudinaged entrained layers have been described (Harley 1991) which preserve mineralogical and compositional thermobarometric evidence of exceptionally high temperatures, around 980°C, comparable with regionally metamorphosed rocks from Enderby Land. Isotopic dating of the host orthogneisses, Mather Peninsula Rauer Islands, containing the extended layers reveals Archaean ages (3300 & 2830 Ma, U-Pb on zircon, Kinny & Black 1990), suggesting to Harley (1991) that these high temperatures represent metamorphic conditions during an Archaean event, and that Proterozoic tectonic events of lower grade, incorporated these lithologies but did not cause mineralogical resetting: an Archaean decompression from 12-13 kbar to 8 kbar occurred at temperatures of 900-1000°C, while decompression in the Proterozoic occurred from 7-8 kbar to 4-5 kbar at 700-800°C (Harley 1988, Fig. 6.28c).

#### 6.8.2.7 Vestfold Hills

The *P-T* path described by Passchier *et al.* (1990), joins the Archaean (2501-2526 Ma Black *et al.* 1991) granulite facies metamorphism of the Mossel Gneiss in the Vestfold Hills at

conditions of  $\approx 1000^{\circ}$ C & 10 kbar, to the emplacement of dykes 1800 Ma old at 700°C & 7.5 kbar, followed by a decompression of 5 kbar concomitant with cooling to 500°C, evidenced by the generation of pseudotachylytes. Reburial occurred before the Proterozoic (1100 Ma) metamorphism at  $\approx 600^{\circ}$ C & 6-7 kbar, and the rocks then cooled and decompressed (Fig. 6.28e). The unusual and intricate shape is based on evidence of successive generations of pseudotachylytes, both before and after the Proterozoic amphibolite-granulite facies metamorphic episode.

The recent studies of Seitz (1991) have derived lower than previously estimated emplacement pressures for a suite of early ( $\approx 2350$  Ma) high-Mg tholeiitic dykes, at conditions around 3-5 kbars (although emplacement may have been as low as 1-2 kbars), prevaricating from the work of Passchier *et al.* (1990) by implying a significantly earlier decompressional event.

The Archaean part of this path commences at high pressures and temperatures, like the suggested Archaean paths of Ellis (1980), Ellis et al. (1980), and Harley (1985a), for the Napier Complex of Enderby Land. However the path depicts an overall decompressional character, prior to the Proterozoic metamorphism, and in this respect is markedly different from the isobaric cooling paths of Enderby Land; major decompression in the Vestfolds, indicated by the first generation pseudotachylytes, (Passchier et al. 1990) and high-Mg tholeiitic dykes (Seitz 1991), predates the Proterozoic metamorphism whereas, in Enderby Land decompression is synchronous with the Proterozoic Rayner orogeny (Harley, 1985b). The Enderby Land and Vestfold Hills paths, although both of Archaean age, are only similar in a qualitative manner: both areas experienced unusually high temperature and pressure metamorphism, and both regions preserve evidence of significant decompressive episodes, however, the Enderby Land rocks are characterised by isobaric cooling, a feature not reported for the Vestfold Hills gneisses. Black et al. (1991) chronologically differentiate between the Rauer Islands and the Vestfold Hills although they report some similarities, with Archaean rocks of the Napier Complex, Enderby Land, and some chronological affinities with the southern Prince Charles Mountains.

While Proterozoic decompression in Enderby Land is of similar magnitude to decompression recorded in the Reinbolt Hills (Nichols & Berry 1991), Rauer Islands (Harley 1988, Harley & Fitzsimons 1991), and Søstrene Island (Thost *et al.* 1991), the decompressional event described by Passchier *et al.* (1990), and Seitz (1991), which otherwise may be considered to be a correlative of this decompressive phase, pre-dates the 1100 Ma metamorphism and therefore must record a different tectonic event.

In summary, the preserved changes in P-T conditions for rocks of the Vestfold Hills, are not similar to the decompressive phase attributed to post-peak Proterozoic tectonism in

the Rauer Group, Søstrene Island, Reinbolt Hills, McKaskle Hills or Prince Charles Mountains.

#### 6.8.3 Comparisons with paths of the MacRobertson coast

Clarke *et al.* (1989) describe retrograde mineral textures for reworked Proterozoic metapelitic gneisses exposed along the MacRobertson and East Kemp Land coastline, which qualitatively indicate an isobaric cooling, possibly with a very minor pressure increase. They note that the elucidation of an isobaric cooling component does not preclude early decompression.

#### 6.8.4 Comparisons with Enderby Land paths

Ellis (1980) and Ellis *et al* (1980), describe osumilite breakdown reactions and textures forming during isobaric cooling preceding peak metamorphic conditions of 8-10 kbar & 900-980°C, for Archaean metapelitic rocks of Enderby Land. They suggest that the preservation of these exceptionally high regional metamorphic temperatures is probably a result of tectonic stability facilitating slow cooling, before tectonic uplift, where in many other areas, uplift probably occurs at temperatures where reaction kinetics remove all evidence of a former high *P-T* metamorphism. Harley (1985a) quantifies this retrogression in the Tula Mountains, Enderby Land, with M1 (3050 Ma) at 950°C & 6-8 kbar, cooling isobarically over  $\approx$ 500 Ma, to 600-700°C & 4-8 kbar (Fig. 6.28f). Proterozoic shear zones record further evidence of the tectonism in this region, with shear zones (Casey Bay) preserving decompression from 700°C & 8 kbar to 650°C & <5.5 kbar, attributed to the Rayner orogeny (Harley, 1985b).

#### 6.8.5 Comparisons with paths of Sri Lanka & eastern India

Reconstructions of Gondwana (e.g. Fedorov *et al.* 1982, Grew 1982, Yoshida *et al.* 1990a) juxtapose the east coast of India and Sri Lanka with the Lützow-Holm Bay area of Enderby Land, and align the comparable features of the Permian Son-Mahanadi Graben (in NE India) with the Permian Antarctica feature, Radok Lake, in the Prince Charles Mountains, further to the east (Fig. 6.29). Correlations between Sri Lanka and Lützow-Holm Bay are supported by similar mineral assemblages in these regions (Motoyoshi 1990,



Dasgupta et al. 1991), and comparable structural trends and similar P-T-t histories (Hiroi et al. 1983, Motoyoshi et al. 1989, and Yoshida et al. 1990a).

# 6.8.6 Comparisons with Western Australian granulites The Yilgarn Craton

An intricate *P*-*T*-*t* path elucidated for Mukalo Creek (Muhling 1990), lies within the Archaean cratonic Yilgarn Block (Fig. 6.30) and is an area of the Proterozoic reworked Narryer Gneiss Complex Western Australia. Although the Yilgarn Craton and the Mukalo Creek area in particular, are a large distance away from the Prince Charles Mountains, the Yilgarn Craton is the closest, large Archaean remnant to the Vestfold Hills in many Gondwana reconstructions (e.g. Fedorov *et al.* 1982, Grew 1982, Yoshida & Kizaki 1983), and this particular *P*-*T*-*t* path is chronologically well constrained, providing evidence of both isobaric and decompressional tectonism (Fig. 6.28g). The features however, of the paths described for the Vestfold Hills (Passchier *et al.* 1990, Seitz 1991), section 6.8.2.7, suggest early high temperature granulite facies metamorphism (T > 950°C), significantly higher than the Mukalo Creek area (T  $\approx 800^{\circ}$ C, Muhling 1990). Further the recent research of Seitz (1991) demonstrates that decompression in the Vestfold Hills had occurred by 2501-2526 Ma, markedly disparate from the Yilgarn Block where decompression to  $\approx 4$  kbar had occurred by 1600 Ma.

The Enderby land paths (Harley, 1985a & 1985b) display similar high pressure and temperature peak conditions, although Enderby Land temperatures are significantly higher than the Yilgarn region, however both regions are characterized by Archaean isobaric cooling, with the Mukalo Creek area interpreted to display two isobaric cooling episodes. The main decompressive episode in Enderby Land is attributed to Proterozoic tectonism (1100 Ma) affecting a large area of East Antarctica (Harley 1985b), whereas a possible correlative, the decompressive phase of the Yilgarn region had occurred by 1600 Ma (Muhling 1990).

The Proterozoic decompressional phase in the Yilgarn Craton, the most likely segment of the *P*-*T* path to be comparable with paths from the Prince Charles Mountains and Eastern Lambert Glacier, is comparable with decompression in the Reinbolt Hills, in magnitude and absolute values, however, decompression occurred significantly earlier in the Yilgarn than in the Reinbolt Hills (absolute dating of the decompression there, however, is poorly constrained, but post-dates the  $\approx 1100$  Ma metamorphism).

In summary, the Archaean Yilgarn Craton displays qualitative similarities with the Archaean Enderby Land P-T paths, (early high peak metamorphism, Archaean isobaric cooling) and the Proterozoic decompressional episode affecting Enderby Land and the


Figure 6.30 Geological provinces of western and northern Australia, after Clarke (1991), depicting the juxtaposition of the Albany Fraser Province along the southern and south-eastern margins of the Archaean Yilgarn Craton, and the Leeuwin Block on the south-western edge of the Yilgarn Craton. An intricate P-T-t path established by Muhling (1990) for Narryer Gneiss Complex rocks, is from the Mukalo Creek area, in the north of the Yilgarn Craton.

Eastern Lambert Glacier region, however quantitative chronological differences are significant, and comparison of these paths is useful only in the recognition and understanding of probable analogous tectonic processes.

#### Albany-Fraser Orogen

Orogenesis in the Albany-Fraser region, along the southeast of the Yilgarn Craton (Fig. 6.31), culminated around 1300-1100 Ma (Myers 1990). Myers subdivides the orogen into a high-grade crustal component composed of deformed tectonic slices (Biranup Complex), juxtaposed with less deformed gneisses and granites (Nornalup Complex), and suggests that the southwestern extension of the orogen probably continues in Antarctica.

Pressure-temperature estimates for this region are based upon the relatively early geothermobarometric calibrations of two pyroxene, plagioclase, quartz  $\pm$  olivine granulites. Pressures of equilibration in the range of 8-10 kbar, at temperatures around 800°C are suggested by Wilson (1976). However, there was no recognition of variation in metamorphic conditions, either with time, or from the differing tectonic units.

While chronological and structural comparisons confirm a connection with Antarctic granulites, P-T paths for the Fraser Ranges are not sufficiently constrained for definitive conclusions.

#### The Leeuwin Block

Wilde & Murphy (1990) describe the Late Proterozoic ( $\approx$ 570 Ma) gneissic granulites from the Leeuwin Block, Western Australia, which outcrop on the western most margin of the Yilgarn Craton (Fig. 6.30). Although unable to derive a *P*-*T* path, Wilde & Murphy (1990) estimate a temperature of equilibration for mafic and felsic gneisses of  $\approx$ 690°C, and compare this with the work of Harris *et al.* (1982) on low pressure granulites of southern India that were metamorphosed at 700°C & 5±1 kbar. They postulate that the development of these Late Proterozoic granulites occurred in a tensional regime, during the initiation of rifting (between India, Australia and Antarctica) as early as 570 Ma. While variations of *P*-*T* conditions with time are not well constrained by this research, this provides supportive evidence that cratonization and granulite facies metamorphism continued to occur at least in Western Australia, but possibly in other regions of Gondwana, as late as 570 Ma.

#### 6.8.7 Comparisons with other nPCM paths

# 6.8.7.1 The Athos and Porthos Ranges

The recent studies of Thost & Hensen (1992) place P-T path constraints on the northern outcrops, the Porthos and Athos Ranges, in the nPCM. They use Grt-Opx-Pl-Qtz,

Grt-Sil-Pl-Qtz and Grt-Sil-Rt-IIm geothermobarometry to establish peak metamorphic conditions of  $750\pm50^{\circ}$ C &  $6\pm1$  kbar (Fig. 6.31); micro-textures in mafic and calc-silicate gneisses provide evidence of essentially isobaric cooling, post-dating peak conditions. These features are consistent with the *P*-*T* paths reported above.

Thost & Hensen (1992) however, interpret an anticlockwise shaped P-T trajectory, which they base on the following equivocal evidence. Coarse grained garnets within metapelitic gneisses contain inclusions of cordierite and sillimanite, which they interpret as implying significant heating during burial, within the sillimanite stability field. The reaction of Crd to Grt, Sil and Qtz has a shallow slope in P-T space, and they suggest this was crossed from low to high pressures, at high temperatures.

The preservation of sillimanite inclusions within garnet porphyroblasts does not provide strong evidence for initial heating at low pressures, since the metamorphosis of kyanite to sillimanite, would occur within a relatively short time period, at peak temperatures. Pelites from many areas where clockwise shaped *P*-*T* paths are inferred, do not preserve kyanite within porphyroblasts, or within their groundmasses, even though their expected paths must have travelled through the kyanite-stable field. Kyanite is usually only preserved in pelites where rapid decompression occurs, or the rocks did not experience temperatures greater than  $\approx 675-700^{\circ}$ C in the sillimanite field.

Cordierite inclusions within garnets do suggest the crossing of the Crd to Grt reaction, this is not however, discriminatory and predicted clockwise as well as anticlockwise trajectories, will foreseeably cross this reaction and produce identical textures.

The Mt Béchervaise region, within the Athos Range, contains samples where near isobaric cooling at pressures  $\approx 4$  to 5 kbar is well constrained (e.g. Figs. 6.3a & 6.6f). It is probable that the maximum preserved pressures represent re-equilibration at temperatures of 750 to 800°C, and that the rocks may have experienced considerably higher pressures during their clockwise trajectories. If however, they underwent heating at shallow depths, along an anticlockwise path, the estimated perturbation of the geotherm would necessarily have been extremely large, requiring extensive magma underplating.

P-T paths examined over a wide area of the nPCM, and including outcrops along the eastern Lambert Glacier, define a continuum (section 6.9) which is inconsistent with an anticlockwise shaped path.

#### 6.8.7.2 The Nemesis Glacier region

Examining the *P*-*T* histories of seven granulitic gneisses from the Amery Peaks/Nemesis Glacier region, nPCM, Fitzsimons (1991) prefers the derived peak conditions of 800°C & 6.5 kbar, from a range of core values between 750-800°C & 6.0-6.5 kbar. The rim estimates



Figure 6.31 Comparison of the *P*-*T* paths established for gneisses of the nPCM. Seven paths for the Nemesis Glacier area (from Fitzsimons, 1991) have equivalent gradients to paths derived here, for the nearby Fox Ridge locality, although the Nemesis paths preserve higher peak temperatures. The anticlockwise *P*-*T* trajectory, interpreted for rocks in the northerly Athos and Porthos Ranges, by Thost & Hensen (1992), contrasts with the inferred shape of the paths presented here (e.g. Fig. 6.27). Their anticlockwise trajectory is interpreted from the following lines of evidence discussed further in the text; a, Crd and Sil inclusions in garnet porphyroblasts, b, peak conditions constrained by thermobarometry, and c, reaction textures indicating essentially post-peak isobaric cooling.

from zoned minerals vary between 600-750°C & 4.5-6.0 kbar (Fig. 6.31). These samples therefore are characterized by shallow to nearly isobaric cooling post-dating the preserved metamorphic peak, and have consistent magnitudes (although in some specimens greater peak temperatures) to paths from the Fox Ridge area, and comparable gradients with nPCM trajectories established here.

#### 6.8.7.3 The Radok Lake area

Quantitative pressure-temperature estimates have not been established for gneisses near Radok Lake, an area less than 10 km south-east of Fox Ridge. However, McKelvey & Stephenson (1990) have described the granulite facies mineralogies of Grt-Opx-Bt-Pl orthogneisses, as well as calc-silicates preserving retrograde reaction of scapolite to Pl, grossular Grt and Cal, and an aluminous assemblage containing Grt-Sil-Crd-Pl-Bt-Qtz. The attainment of Grt + Crd assemblages was interpreted by McKelvey & Stephenson (1990) to infer relatively low pressure peak granulite facies conditions, and they suggest that retrograde mineralogies formed at amphibolite facies P & T.

These assemblages and inferred metamorphic conditions are not definitive, however the breakdown of scapolite implies some retrograde component of cooling, from probable low to moderate peak conditions evidenced by the presence of Grt-Crd-Sil. A retrograde path fulfilling these requirements is consistent with the paths established for nearby, and nPCM, outcrops.

# 6.9 The overall picture: are there meaningful tectonic implications?6.9.1 Proviso

The P-T-(t) paths assembled and discussed above, summarize a large volume of data collected by many researchers over a very large area, analyzed with different microprobe equipment, derived with different calibrations and different assemblages, while representing the fragmentally recorded, crustal evolution which occurred over a protracted time scale. Of particular importance here, is the proviso that P-T trajectories established for different tectonic units, although now juxtaposed, do not necessarily provide a single history of the tectonism of a region: the units may be of different ages and therefore not coeval, or from different structural levels. Any tectonic processes promulgated from the preserved P-T paths must therefore remonstrate against the paucity of definitive chronological constraints in East Antarctica.

#### 6.9.2 Discussion

In the western Archaean region of Enderby Land, approximately 500 Ma of isobaric cooling, is well documented, from  $\approx$ 3050 Ma (Harley 1985a). Similar aged, and probably comparable isobaric cooling is interpreted for the Yilgarn Craton and is reported by Muhling (1990), although the low temperature event of the isobaric segment of this path is not as well defined. The similar aged (3300-2830 Ma) mafic entrained layers in the Rauer Islands (Harley & Fitzsimons 1991), record a dissonant path with a predominantly decompressional *P-T* evolution, comparable with the path derived by Thost *et al.* (1991) for the presumably Archaean mafic layers in Søstrene Island. The Vestfold Hills preserve an early ( $\approx$ 2500 Ma) decompressional episode, based upon the work of Seitz (1991), suggesting a different tectonism to either the Archaean Rauer Group or Søstrene Island, and the Yilgarn Cratonic area.

While intricate and disparate trajectories are preserved for the Archaean remnants of Gondwana (Pangaea), the affects of Proterozoic tectonism are ubiquitous over much of East Antarctica, and possibly the Yilgarn Craton, and broadly appear to reflect similar tectonic processes. In the Eastern Lambert Glacier region, including the Reinbolt Hills, McKaskle Hills, Brattstrand Bluffs, Larsemann Hills, Rauer Group and Vestfold Hills, *P-T* trajectories retain early, relatively steep slopes, and are interpreted to result from Proterozoic decompression immediately post-dating peak Proterozoic metamorphic conditions. Shallow trajectories are also a feature of the post-peak Proterozoic metamorphism, notably in the Prince Charles Mountains, Bolingen Island, east Kemp Land coast, with cooling paths also reported post decompression in the Larsemann Hills and Yilgarn craton.

A consistent decrease in pressure, with similar ranges of prograde to retrograde temperatures, from the easterly Fox Ridge locality to westerly Mt Béchervaise and Gorman crags regions in the nPCM, appears to preserve an oblique crustal section, with originally deeper levels now exposed in the east. Such an idea is supported by the higher pressure, steeper gradient paths along the East Lambert Glacier, which increase in pressure from the Reinbolt Hills towards the more northerly McKaskle Hills. So although outcrops on either side of the Lambert Graben do preserve paths of different gradients, the pattern of P-T paths when considered from the west PCM to the northerly McKaskle Hills nunataks appears to change systematically, with a decrease in the maximum preserved pressures from the McKaskle Hills, to the westerly PCM outcrops, Mt Béchervaise and Gorman Crags. This evidence suggests that there has no been no large vertical component of movement on the Lambert Graben structure, that is since graben development, nor post-dating the establishment of the systematic pressure variation.

In comparing the Eastern Lambert Glacier P-T paths with those from the nPCM a poignant observation supporting the hypothesis of a continuous crustal section, became apparent. Comparable decompressional paths, for example, the Reinbolt Hills and the Proterozoic Rauer Island paths, terminate at temperatures around 700°C. In comparison rocks following isobaric, or those dominated by shallow cooling trends (e.g. those in the Prince Charles Mountains), cool to temperatures in the order of 450-550°C. These exceptionally low temperatures, as suggested above, may be recording the kinetic blocking of Fe/Mg exchange upon which many thermometers are based and therefore not a true metamorphic event, rather a thermal relaxation. Nevertheless thermal relaxation is as likely to post-date both trajectories, and a 150-250°C dichotomy between the lowest preserved temperatures for decompressional versus isobaric paths is significant. The observations are at variance with the effects of varying cooling rates where slower cooling with resultant lower preserved temperatures would be predicted for deeper level crust, exposed by decompression. The observation of lower preserved temperatures from shallower crust, however is consistent with the premise that decompression and isobaric cooling were synchronous, reflecting different responses to the same tectonic process, and that deformation contemporaneous with waning metamorphic conditions accentuated the growth of late stage minerals (cf. Knipe 1989), for example, symplectitic Spl<sup>3</sup> + Crd + Phl between boudinaged sillimanite. The shallower, westerly rocks behaved in a brittle manner with the formation of boudinage and fracturing after D<sub>3</sub> deformation, while the deeper level easterly rocks, remaining at depth during deformation, either continued to deform in a ductile manner, or were not strained to the same degree, and therefore did not develop the lower temperature minerals upon cooling. Both westerly and easterly regions presumably followed similar paths to the then stable geotherm.

An alternative to the favoured continuous crustal section hypothesis, is the suggestion that decompression proceeded an isobaric cooling episode, that is, distinct tectonic events occurred resulting in two separable, but now joined, trajectories. A decompressional phase in the Larsemann Hills, correlated here with the decompression in the Reinbolt Hills, Rauer Islands and shallow cooling in the nPCMs, was followed by reported isobaric cooling (Stüwe & Powell 1989). Similarly, Clarke *et al.* (1989) report isobaric cooling for the east Kemp Land coastline and note that the elucidation of this trajectory does not preclude earlier decompression. The latter path was not quantified and it is therefore difficult to debate the full significance of their findings; however, the separate 'paths' described by Stüwe & Powell (1989) are also, and more saliently, explained by a single path of intermediate gradient, crossing the decompressional Spl + Ilm and Spl + Rt, as well as isobaric Grt + Bt + Ilm forming, reactions (Stüwe & Powell 1989, Fig. 6). The unusual preservation of strongly zoned garnets from Mt Lanyon (nPCM, samples LAN/19 & 23), and the derivation of high peak metamorphic temperatures, provided promising initial encouraged for support of the two stage, decompressional-isobaric trajectory. However, detailed study of the phase relationships and possible stability fields, combined with geothermometry on core-inclusions, and rim assemblages, strongly constrained a constant, shallow *P-T* slope, equivalent to other nPCM areas.

Applying the adage of 'Occam's Razor', the simpler, and less equivocal hypothesis, that of an oblique crustal section, is favoured.

#### 6.10 Conclusions

#### 6.10.1 Reliable geothermobarometers

Conclusions about the accuracy of geothermobarometers and their application with various compositional assemblages in East Antarctica, are here summarized.

1. Pressure-temperature trajectories derived using the Hoisch (1990) thermobarometer are marginally steeper than paths from other calibrations. Where the Hoisch barometer indicates paths which are shallow, or entirely isobaric, a cooling trajectory can be interpreted with moderate confidence, however the magnitude of cooling and accuracy of the calculated pressures can usually only be used as an indication of the true trajectory. The Hoisch (1990) barometer is apparently only able to correctly predict P-T conditions and trajectories when the garnets preserve dramatic Fe/Mg zonation. The errors in estimated pressures may derive from the fact that the Hoisch calibrations were (a) empirically formulated with lower temperature rocks, and the slopes of these equilibria may not allow an accurate extrapolation to higher temperature rocks, & (b) that garnet and particularly biotite, are more prone to continual Fe/Mg exchange between other minerals (possibly cordierite and spinel) during cooling, than that which typically affects minerals in other exchange barometers. Hoisch's derivation, when applied recognizing these precautions, provides an indication of the probable P-T slope, in Grt-Bt-Pl-Qtz assemblages which suffer a paucity of suitable calibrations.

2. Bohlen *et al.* (1983a) and Perkins & Newton (1982) geobarometers provide the most consistent pressure constraints in the Grt-Opx-Pl-Qtz system, with the former calibration being the least sensitive to Fe/Mg exchange. The internally consistent computer programme by Powell & Holland (1988), and Holland & Powell (1990), produces good pressure and temperature values in this system. The assertion of Carswell & Gibb (1987a), that the Moecher *et al.* (1988) formulation over-estimates pressures, is supported by this

comparative study. Harley's (1984a) barometric formulation was found to be unsatisfactory in estimating pressures, being overly sensitive to resetting of Fe/Mg upon cooling.

3. In Grt-Sil-Pl-Qtz assemblages, the calibrations of Newton & Haselton (1981), Ganguly & Saxena (1984) and Hodges & Spear (1982) provide good pressure constraints. The former barometer provides the clearest distinction between Grt core and rim compositions, and was therefore useful in establishing P-T trajectories in samples with zoned garnets.

4. The internally consistent thermobarometers of Nichols *et al.* (1992) furnishes useful pressure constraints in aluminous granulites; the system Grt-Crd-Sil-Qtz suffers the least resetting, has the smallest estimated calibrational errors, and therefore provides the most accurate peak pressures and temperatures. The barometric calibration of the Grt-Spl-Sil-Qtz system is particularly useful for estimating the conditions during the formation of various spinel generations, where they are in demonstrable equilibrium with Sil and Qtz.

5. Newton & Perkins' (1982) derivation in the Grt-Cpx-Pl-Qtz system estimates comparable pressures with other barometers applied to adjacent samples.

6. The albite-jadiete-quartz system, calibrated by Holland (1980) and Gasparik & Lindsley (1980) to estimate pressures, appear to suffer from calibrational problems due to (a) attainment of equilibrium in their experiments, caused by the slow diffusional rate of Al, and (b) complex quaternary solid solutions that are inadequately assessed using simple binary systems; these barometers were therefore applied with caution, and are able only to bracket the possible peak pressures of the nPCM granulites.

7. Ferry & Spear's (1978) Grt-Bt thermometric calibration calculated temperature values which most closely match those estimated using Grt-Opx thermometry, and this early derivation was systematically applied throughout the nPCM specimens. The Indares & Matignole (1985) thermometer, designed to negate the over-estimation of temperatures caused by Ti substitution in Phlogopite, was found to be too dependent upon the selection of the Grt mixing-model. The magnitude of the correction applied by their thermometer is thus brought into question, and therefore this calibration was not used.

8. Thermometers in the Grt-Opx system were evaluated with the conclusion that Sen & Bhattacharya's (1984) calibration produces the most consistent temperatures, in

agreement with Faulhaber & Raith (1991). Harley's (1984b) Grt-Opx thermometer produces lower temperatures than other formulations. It is concluded that this is an inherent calibrational discrepancy.

9. In the few Grt-Cpx bearing specimens, both Ellis & Green's (1979) and Powell's (1985) thermometers were used, both producing equivalent, and consistent values.

10. Bertrand & Mercier's (1985) two pyroxene solvus thermometer consistently reproduces the most consistent temperatures when applied to mafic composition granulites, consistent with the conclusion reached by Carswell & Gibb (1987b).

11. Grt-Chl thermometry using the calibration of Dickenson & Hewitt (1986), and the Laird (1989) modified version, estimates temperature values comparable with the Grt-Bt thermometer of Ferry & Spear (1978), however this finding is suggestive only, as it is based upon a limited number of comparisons.

12. The two internally consistent programmes, GEO-CALC by Berman (1988), and THERMOCALC by Powell & Holland (1988), and Holland & Powell (1990), were applied to assemblages where there are few single-assemblage calibrations, or to depict pseudosections ( $\log_a Vs \log_a$ ). Both programmes provide useful *P*,*T*,*X* and  $\log_a$  information about assemblages, with pressure and temperature values converging in well defined experimental systems.

# 6.10.2 *P*-*T* evolution of the northern Prince Charles Mountains

Pressure-temperature trajectories derived for regions in the nPCM are graphically summarized in Figure 6.27.

1. All the northern PCM trajectories have similar gradients, dominated by cooling, post-peak metamorphic conditions. Eastern Lambert Glacier paths are similar, although, statistically steeper, and preserve higher pressure and temperature peak conditions.

2. Comparative analysis of established P-T paths for the East Antarctic region, and Gondwana continental-fragments, is hindered by reliable age constraints; some features are however, common throughout the region.

(a) peak Archaean conditions are characteristically high temperature and pressure events, and are usually followed by isobaric cooling of substantial duration.

(b) a Proterozoic event, characterized by the re-establishment of geothermal conditions, and post-dating the formation of the preserved peak metamorphic assemblages, is a widespread feature. This synchronous(?) tectonic episode retains predominantly a decompressional component, in many East Antarctic areas, for example the East Lambert Glacier paths, the Larsemann Hills and Rauer Island trajectories.

(c) the strongest evidence correlating this decompressional event with the paths dominated by cooling, experienced by the nPCM rocks, is the observation that their gradients follow a continuum, changing from the steepest in the east to the shallowest, and lowest pressures, in the west. Preliminary radiometric age dating also supports this correlation.

(d) these conclusions implicitly support the hypothesis that a continuous Proterozoic crustal section is exposed from the Rauer Islands to the western nPCM, and that this probably experienced synchronous changes of metamorphic conditions; the differences in preserved P-T paths reflect the level of crust from which the rocks are exposed.

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# Chapter 7

# TECTONIC MODELS FOR THE LAMBERT GLACIER REGION

# 7.1 Introduction

The pressure-temperature trajectories and structural evolution, of the McKaskle Hills, Reinbolt Hills, and nPCM regions, presented in Chapters 3, 4, 5 and 6, provide data which forms the basis of the interpreted tectonic models discussed below. The estimated P-Tpaths represent partial, post-peak segments of the metamorphic evolution of the respective areas, whilst the structural observations constrain the relative timing of metamorphism, with respect to deformation.

*P*-*T* paths are usually depicted on a pressure versus temperature plane, conventionally, with abscissa and ordinate values increasing from the lower left, towards upper right. The *P*-*T* trajectories described by rocks, are assumed to commence at the origin, and thence follow usually simplified, rounded, anticlockwise or clockwise loops, which terminate at the diagram's origin. The prograde metamorphic conditions of rocks which have reached granulite facies are usually the least well constrained, as pervasive mineral re-equilibration occurs rapidly, in terms of geological time-scales, at temperatures  $\geq 750^{\circ}$ C (e.g. Cygan & Lasaga 1985). Although relatively small segments of the *P*-*T* trajectories are preserved, their relative positions and gradients have been presented as discriminatory evidence for varying tectonic environments (e.g. Harley 1989). However, there is some controversy regarding the definitiveness of the vortice-direction of *P*-*T* loops; for example Bohlen (1991) states that presently there is insufficient knowledge to determine specific tectonic settings from a *P*-*T*-*t* path, and that dextrorotatory and lævorotatory paths are "possible in the same tectonic setting". Similarly, Jamieson (1991) finds that unique tectonic solutions are usually not justifiable with the resolution of the available metamorphic data.

Re-equilibration of mineral compositions with cooling, is a phenomena recognized to potentially reduce the values of the calculated peak conditions, and the concept has been extended by Frost & Chacko (1989), who infer that thermobarometric estimations will consistently under-estimate true-peak conditions, because of the comparatively low blocking-temperatures of mineral exchange equilibria. Although, their caveat is ameliorated by the similarity of P-T estimations from phase-relationship data and thermobarometry (Bohlen 1991), re-equilibration by intra- and intergranular cation diffusion is accepted as a process accentuated by slow cooling rates, and is particularly important in fine-grained

mineralogies. In one recently reported example, distortion of the retrograde path by intragranular diffusion, was shown to be appreciable where cooling rates are less than 10°C/Ma, or when garnet grains have diameters <1 mm (Florence & Spear 1991).

In the following sections paths characterized by cooling histories, with little or no pressure decrease, are referred to as 'isobaric cooling paths', whereas, those with large pressure changes and corresponding small temperature decreases, are termed 'isothermal decompression' (Harley 1989). The characteristics of these trajectories are summarized below.

#### 7.1.1 Characteristics of isothermal decompression paths

Pressure-temperature trajectories with steep gradients, have been explained as post metamorphic-peak trajectories, preserved during the isostatic re-equilibration of overthickened continental crust, usually without the addition of magmatic heat sources. Alternatively such paths may be produced in extensional tectonic settings, provided that additional magmatic heat is added during crustal thinning. Harley (1989) suggests that extensional exhumation may be relevant where relatively low maximum pressures are calculated (2-5 kbars), but asserts that decompression from higher peak pressures (4-12 kbars) usually occurs in tectonically thickened crustal regions.

Harley (1989) compares decompressional paths calculated with the erosional parameters derived by England & Thompson (1984). Allowing for a range of possible parameters, for example the variants (1) paths resulting from simply doubling the thickness of continental crust, or (2) those produced after thrusting of the continental crust at depths of 30 km. Although the calculated paths differ, the differences are not significant enough to discriminate between the two major tectonic settings. Harley (1989) suggests that isothermal decompression paths are characterized by low thermal conductivities and high basal heat fluxes that result in high surficial heat flows.

Analogous steep P-T trajectories are calculated by Ridley (1989) for terranes initially thickened by thrusting, and extended by low-angle, normal-displacement fault zones.

#### 7.1.2 Characteristics of isobaric cooling paths

Trajectories preserving isobaric, or near isobaric cooling, are interpreted to have developed in crustal terranes, essentially in isostatic equilibrium, and therefore are the preserved segments of post-metamorphic peak, cooling. Harley (1989) describes five possible tectonic processes reported in the literature, which may be responsible for the formation of such paths. The possibilities he discusses are (a) the accretion of magma beneath continental terranes (from Wells 1980, Bohlen 1987), (b) extension of continental crust, with external heat sources (from Sandiford & Powell 1986), or without additional magmatic heat (from Thompson & England 1984, Sandiford & Powell 1986), (c) compressional thickening of thinned continental crust (from Vielzeuf & Kornprobst 1984), (d) extensional collapse of overthickened crust (England & Thompson 1986, Sonder *et al.* 1987, & Sandiford 1989), & (e) cooling experienced by the lower crustal rocks, in overthickened terranes, which may accompany erosional uplift (from England & Thompson 1984, Ellis 1987).

# 7.2 Requirements of the tectonic model

Any tectonic model for this part of East Antarctica, and in particular, the Lambert Glacier region, must explain a number of critical observations, discussed in the previous chapters; these include:

(a) The envisaged tectonic environment must include mechanisms capable of ensuring that large regions undergo similar metamorphic and structural processes. Specifically, the model must provide an explanation of the high-grade metamorphic conditions which occurred synchronous with, high-strain deformations, during, as presently understood, Late Proterozoic times.

(b) The tectonic model should also explain the metamorphic-pressure gradient, observed from the northern East Lambert Glacier (ELG) region, including the McKaskle and Reinbolt Hills, to outcrops in the southern and western northern Prince Charles Mountains, the Gorman Crags, a distance of approximately 335 km (Fig. 7.1). In Chapter 6 it was demonstrated that the maximum calculated pressures vary from 8 kbars in the ELG, to 4.5 kbar in the west nPCM. However, the maximum preserved temperatures do not show such a marked change; in the east, 'peak' temperatures are estimated to be 850°C, whilst those in the west are around 750°C. Typically the conditions experienced by the western area, would be categorized as low pressure and high temperature granulite-facies metamorphism, usually interpreted to result from unusually high geothermal gradients. However, the conditions experienced by more easterly regions fall within the range of normal calculated geothermal gradients for regions instantaneously or homogeneously over-thickened (England & Thompson 1986). It was concluded in Chapter 6, that the eastern to western exposures represent the remnants of a continuous crustal section, which experienced synchronous changes of metamorphic conditions. If this interpretation is correct, the estimated geothermal gradients may have varied significantly across the region, during metamorphism.

(c) The model should also account for the top-block towards south and southeast, direction of early thrusting, and later, but still at high-grade, folding deformations.



(d) Consistent northwest block-up movements are ascertained for second generation mylonites, and these vertical crustal movements may be related to the exhumation, or partial uplift, of the high-grade terrane.

(e) Third generation mylonites, commonly associated with pegmatites which are emplaced along sub-horizontal shear-planes, record consistent easterly shear senses, from localities in the east, to those in the west. The abundance of pegmatite associated with the fault planes, and the degree of drag-fold deformation of the associated gneisses, decreases from the west towards the east. Such a change may indicate of a gradual decrease in the temperature experienced by the gneisses immediately prior to  $MY_3$  faulting. The nature and cause of the easterly movement may also be related to the final exhumation of the terrane.

(f) The model must address the apparent disparity between the approximately NNW-SSE regional stress regime, inferred by the development of the ENE to WSW gneissic trend, early southerly and southeasterly directed  $MY_1$  mylonites and regionally EW trending F<sub>3</sub>-folds, whilst the metamorphic conditions display the greatest pressure variation in eastwest directions.

# 7.3 Formulation of the favoured model

In order to develop a tectonic model for the East Lambert Glacier region, the major phases of orogenesis are separated into the burial, metamorphic and exhumation episodes.

#### 7.3.1 The burial phase

An early north northwesterly to south and southeasterly directed compressional axis, with a southeasterly to easterly  $MY_1$  mylonitization, is recognized. This, and later deformations influenced by this stress orientation, including the development of F<sub>3</sub> folds, occurred at granulite facies conditions, as a result of the crust thickening, in a progressive rotational strain regime. As there were no pre-granulite facies fabrics recognized, it is unclear whether the early deformational axis was related to the tectonic processes responsible for the burial of the terrane, or if the axis represents the stress orientation of entirely post-burial deformations. The Himalaya however, provide a possible modern analogue of the physical processes and resultant structures to the Lambert Glacier region. In particular, thrust faults, developed with perpendicular orientations to the India-Asia collisional axis (e.g. Treloar *et al.* 1992), if analogous with the major Lambert Glacier structures, would indicate that tectonic inhumation of the terrane was related to a southerly to southeasterly compressional axis.

# 7.3.2 Peak and retrograde metamorphic conditions

The highest temperatures and pressures preserved vary throughout the Lambert Glacier region, and this is interpreted to result from an interplay of at least four factors. The first, a potential problem for any geothermobarometric estimates, is that the estimation of a 'peak' or maximum preserved pressure, is dependent upon a chosen temperature, that may be lower than the actual peak temperature, because of continued cation diffusion which occurs during cooling from the thermal maximum. Secondly, partial re-equilibration is considered to have a greater effect in regions subjected to slower uplift concomitant with slower cooling. That is, the maximum temperatures preserved in paths from the western region may reflect slower cooling, rather than markedly lower metamorphic conditions. Evidence for this assertion is the occurrence of Grt-Opx bearing felsic gneisses in regions where thermometry indicates maximum preserved temperatures of <750°C, for example the Wall Peak area (e.g. specimen W90/5). Similarly, strongly zoned garnets in pelitic gneisses from Mt Lanyon, indicate large degrees of re-equilibration, and that cores were originally in equilibrium at high-grade metamorphic conditions (e.g. specimens LAN/19 & LAN/23).

A third factor, and suggested here to be one of the most important, is that the preserved peak pressures are assumed to have equilibrated at different crustal depths, so that a gradation in pressures is considered to be representative of varying degrees of crustal uplift. Finally, it is accepted that as only a relatively small proportion of the *P*-*T* segments are preserved, and have probable error bars in the order of  $\pm 1$  kbar and  $\pm 50^{\circ}$ C, some of the recorded inter-region variation may be exaggerated.

It is considered that peak preserved conditions are directly attributable to crustal thickening, produced during continent-continent collision (discussed below).

# 7.3.3 Exhumation processes

It is suggested here, that the exhumation process, or combination of processes, resulted in the formation of the retrograde decompressional (sections 4.4.2 & 5.2.1) and cooling trajectories (section 6.8) variably preserved throughout this region of East Antarctica. This interpretation contrasts with that of Stüwe & Powell (1989) and Stüwe & Hand (1992), who suggest that corona textures developed in response to a second and unrelated metamorphic event, much later than the pervasive high-grade conditions, possibly around 500 Ma ago. Absolute radiometric age dating of the coronas, preferably with isotopic systems not influenced by resetting, is required to resolve this debate.

The favoured interpretation that exhumation soon after peak metamorphic conditions, was responsible for the development of the corona and zoning features, is supported here by amalgamating the structural evolution, critical field relationships, with the estimated metamorphic history. The gneissic layering,  $MY_1$  mylonites, and early folding episodes, which formed at high-grade, are truncated by the upright second generation mylonites,  $MY_2$ . These mylonites are characterized by lower granulite to upper amphibolite facies assemblages, and are therefore considered to have formed relatively soon after the preserved metamorphic peak. They have NE-SW strikes and demonstrate relative NW block-up motions, consistent with the S to SE directed, early compressional axis.  $MY_2$  mylonites may be related to the initial stages of exhumation.

The MY<sub>3</sub> mylonites, which truncate and post-date MY<sub>2</sub>, indicate a consistent easterly tectonic movement direction, across the nPCM and the ELG region, but their metamorphic grades, constrained mainly by their association with abundant pegmatites and low-grade amphibolite facies assemblages, suggests that they developed at a later stage than the initial exhumation event. Here it is postulated that they are related to the 500 Ma event, by their lower grades, mineralogical association with granitic magmatism known to be of a 500 Ma age in the Sandefjord Bay region (Landing Bluff Adamellite, Sheraton & Black 1988), and field relationships with basaltic dykes (section 3.8.2).

This model has a number of internal consistencies. The early stress regime, inferred from MY<sub>1</sub>, also from F<sub>3</sub> fold orientations, and which was possibly responsible for the formation of MY<sub>2</sub> mylonites, appears to have had a consistent S to SE compressional axis. Further, the movement sense of MY<sub>3</sub> mylonites, estimated to have developed much later, around 500 Ma, also has an average easterly tectonic movement direction.

Although this model is almost certainly a gross over-simplification of the stresses, and thermal history of the terrane, it provides a plausible development of tectonism in the region. One of the notable features of the model, is the consistent, stress regime, which can be compared with the possibly analogous Himalayas, where the collisional directed stress orientation was finally also responsible for their exhumation.

#### 7.4 Schematic model

The favoured hypothetical tectonic model, based on the structural data, and metamorphic trajectories, is shown in Fig. 7.2. The model has four main phases, beginning presumably in post-Archaean times (Nd model ages of nPCM rocks are  $1793\pm346$  Ma, Hensen *et al.* 1992), with shallow, south to south-eastward subduction of an inferred continental crustal fragment, which was possibly an amalgamation of the Indian and Australian plates. The inferred convergence direction is assumed to be perpendicular to the strike of early mylonites, and the strike of the gneissic fabric.

The second stage of the model corresponds to the maximum preserved metamorphic conditions, which are attributable to crustal overthickening during crustal-collision,

Figure 7.2 Schematic map, depicting the favoured tectonic model of the Lambert Glacier region's evolution, with adjacent pressure-temperature diagrams depicting the inferred contemporaneous trajectory changes. (a) Continent-continent collision, in post-Archaean times, occurs along an east-west trending boundary, at which time the more northward continental-mass is shallowly-subducted. Pressures experienced by the subducted crust rise rapidly, and reach maximum values prior to maximum temperatures. (b) Continuation of collision. The lower continental-crust experiences extremely highstrain deformation as it wedges further beneath the upper crust. Layer-parallel F<sub>2</sub> sheath folds (labelled '2') with coaxial high-grade mineral-stretching lineations develop parallel to the south, to southeastward tectonic movement. MY1 mylonitic thrusts are common, and some develop with back-thrust geometries. The lower crust experiences maximum temperature values. (c) Crustal-collision velocities presumably have decreased by this stage. Possibly the Archaean rigid cratonic blocks, the Vestfold Hills and Enderby Land, were transported southerly on the colliding plate. F3 tight folds (labelled '3') fold the gneissosity, about ENE to WSW axial planes, but F3 fold axes are coaxial with F2 folds, that is sub-parallel to the tectonic movement direction. At approximately 1000 Ma the maximum preserved temperatures and pressures are recorded, and it is from these values that the retrograde cooling and decompressional paths are recorded; earlier higher grade conditions were totally reequilibrated. As subduction of the lower crustal fragment is restrained by the southern Prince Charles Mountains Archaean-craton (stippled), the compressional axis rotates anticlockwise, producing subvertical MY<sub>2</sub> mylonites (NW block-up movements) with continued shortening, and open F<sub>4</sub> folds (labelled '4'). Cooling dominates the nPCM P-T trajectories, but further decompression occurs along the eastern Lambert Glacier region, an area not affected by the 'locking' influence of the sPCM cratonic block. (d) Probably around 500 Ma, when crustal collision had presumably ceased, shallowly dipping third generation mylonites frequently associated with pegmatites, truncated earlier structures, and have consistent eastward tectonic movements. Episodes of basaltic magmatism, some related to Late Carboniferous - Permian (~280 Ma) EW crustal-extension, and minor NS striking wrench faults, were subordinate deformations and are not depicted.

The distance between Enderby Land and the Vestfold Hills is approximately 1000 km.



≈500 Ma



analogous to the tectonic scenario of the Himalayan region. In the East Lambert Glacier region the three Archaean, cratonic blocks, the Napier Complex, the Vestfold Hills and the southern PCM, are suggested to have behaved as rigid blocks, probably causing strike-slip convergent plate motions along their boundaries (Fig. 7.2b). In this respect also, the tectonism is analogous with the Himalayan region, which has been modelled as a collision between a rigid indentor (India), and the deformed Asian continent (e.g. Tapponnier *et al.* 1982 & Treloar *et al.* 1992). During this major phase of tectonism in the ELG region, the formation of the high-strain structural features, the early MY<sub>1</sub> mylonites, some with back-thrust geometries (e.g. Mt Lanyon), high-strain sheath  $F_2$ -folds, coaxial mineral-stretching lineations, and the coaxial  $F_3$  folding responsible for the orientation of most of the gneissic layering, occurred during high-grade metamorphic conditions.

Uplift is suggested to have been initiated by vertical crustal movements, preserved as  $MY_2$  mylonitic zones, under the influence of continued NW to SE directed crustal compression, and possibly due to the wedging-movement of the crustal fragment beneath the nPCM complex. Significant northwest block-up movement occurred during this tectonic episode (Fig. 7.2c), possibly in the order of one to two kbar for the entire ELG region.

It is postulated that some rotation of the compressional vector occurred during the latter stages of this crustal episode, evidenced initially by the NE-SW trend of MY<sub>2</sub> mylonites, and secondly, by the axial-plane orientation of macroscopic F<sub>4</sub> folds, which produce great-circle girdles of the earlier fold axes and mineral lineations. It is possible that the collision had become 'locked' at this stage, being impeded by extensive crustal thickening, resulting in an anticlockwise rotation of the compressional axis, towards a SE orientation. This concept is extended to explain the additional decompression (possibly a further 1 to 2 kbar) then experienced by the eastern region, which continued to experience uplift as it was not restrained by the 'locking' mechanism affecting the nPCM area. Crust along the eastern region was not hindered by an Archaean cratonic mass, and was therefore able to continue to undergo uplift. In this way, the crustal section effectively pivoted around a fictitious horizontal axis, to the west of the nPCM, so that progressively greater amounts of uplift are recorded in an easterly direction. The ELG regions then cooled relatively rapidly, compared with the nPCM and they do not record pervasive high-strain deformations that post-date the decompressional phase. For example, delicate symplectitic fabrics are preserved in the Reinbolt Hills pelites, and from the McKaskle Hills Grt-bearing mafic gneiss.

As a comparison, Coward & Butler (1985), infer that approximately 470 km of the Indian plate had been subducted and shortened by a combination of ductile shearing, recumbent folding, and back thrusting (Treloar *et al.* 1989) beneath Kohistan. Thickened



crust acted as a mechanical impediment to the northward propagation of the collision, and caused rotation of the Indian plate, resulting in the development of easterly crustal movement of northern regions (Treloar *et al.* 1992).

Whilst the eastern domain had cooled sufficiently so that pervasive deformations were then more difficult to preserve, the western nPCM region remained under a compressional regime, and cooled more slowly. The resultant trajectories are therefore shallower, and the rocks were able to preserve greater amounts of post, or near metamorphic peak, deformation. For example sigmoidal garnets although, not common, are a feature of the nPCM pelites, whilst were not observed in any of the ELG metapelites.

The ultimate stage of pervasive deformation, is recorded as an easterly transport direction along shallow third generation mylonites. Critical field relationships described in Chapter 3, suggest that MY<sub>3</sub> mylonitization occurred approximately  $\geq$ 500 Ma. If these chronologic postulations are correct, MY<sub>3</sub> mylonites were produced during an entirely separate tectonic event. This is the favoured hypothesis. An appealing speculative extrapolation of this idea, is that rotation of the compressional axis, postulated to have commenced as the collisional zone was 'locked' (Fig. 7.2c), had rotated further anticlockwise, during the 500 Ma interval, between stages 3 and 4 (Fig. 7.2d), however, the estimated duration of this interval suggests that it was an unrelated tectonic episode.

The mineralogies and southeastern block-up shear-sense interpreted from greenschist facies retrograde shear-zones that truncate  $MY_3$ -mylonites, located at Wall Peak and Mt Lanyon, indicate that they significantly post-date the third generation (?)500 Ma mylonites. However, they do not provide sufficient data to further constrain the tectonic model.

Basaltic intrusives and a young lava flow (49.1-51.8 Ma, Tingey 1976), have a wide range of reported ages, that is  $504\pm20$  for an alkaline olivine basalt,  $246\pm6$  for a calcalkaline basalt (Sheraton 1983), for an alkaline picrite 145-150 (Laiba *et al.* 1987), and an alnöite  $108-110\pm3$  Ma (Sheraton 1983). The alkaline-picritic phase of the basaltic-magmatism has been related to a late Mesozoic crustal extension event throughout the Gondwana continents, Andronikov (1990). He however, suggests that the data is insufficiently conclusive to correlate this magmatism definitely with the alkaline-ultrabasic magmatism recorded in the other Gondwana continental fragments, especially Africa. Sheraton (1983) noted that Cretaceous lamprophyres "of virtually identical age and geological setting" to those of the nPCM, were reported from eastern India by Sarkar *et al.* (1980), and this association may be related to the Gondwana rifting episode.

Apatite fission-track analysis, interpreted by Arne (1992), suggests that the terrane underwent significant cooling in the Early Cretaceous, which may have been related to exhumation of several kilometres of crustal material. Although the amount of crustal uplift,

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associated with the cooling, is not clearly defined, the timing of cooling suggests an association with asymmetric rifting along the Lambert Graben, possibly contemporaneous with the initiation of Gondwana breakup (Arne 1992).

These Palaeo-Mesozoic extensional events are therefore probably related to the ultimate significant uplift of the terrane, which was certainly exposed during Permo-Triassic times, in the east Radok Lake region.

#### 7.4.1 Provisoes

Derivation of a tectonic model for the Lambert Glacier region, necessarily relies on a comparison of either observed or inferred modern tectonic processes, with those interpreted for this region. Such a comparative analysis relies on the assumption that modern day processes are essentially equivalent in style, and structure, to those operating in the Late Proterozoic. Such an assumption is upheld by the views reported by Thompson & Richter *et al.* (1984), who use thermobarometric evidence from Archaean cratonic regions, to infer that these regions underwent comparable P & T to rocks now in the Himalaya. They therefore conclude that crustal dynamics have not changed significantly since the Archaean.

Another of the critical assumptions inherent in these interpretations is that the estimated P-T trajectories reflect a single evolution of the metamorphic conditions of the region, rather than successive but unrelated, metamorphic episodes. Whilst this assumption is supported by the relative lack of pervasive, lower-grade over-printing equilibrium assemblages, the lack of definitive chronological constraints, adds a degree of uncertainty to these interpretations. Accurate geochronological estimations are thus required of not only the retrograde path, but also of the timing of peak conditions.

#### 7.5 Extrapolation of the model: Gondwana's reconstruction

Gondwana reconstructions, at least since the 1970s, have usually portrayed the juxtaposition of the Enderby Land-Mawson coast of Antarctica with the east coast of India, aligned by the Son-Mahanadi, Lambert and Radok Lake Grabens (Fig. 7.3). Australia is usually correlated with the Antarctic coastline, further east, whilst Sri Lanka lies to the west of Enderby Land. The near-perfect fit of the east coast of South America with the west coast of Africa was recognized by Snider, at least as early as 1859, and these continents have more recently been considered to adjoin with Madagascar and the western Antarctic extremity (Fig. 7.3).

Yoshida *et al.* (1990a) suggest in their detailed reconstruction of Sri Lanka, India and Antarctica, that the structural trend of the Late Proterozoic gneissic fabric, can be traced through Sri Lanka, around the southern margin of Enderby Land, and appears continuous with the trend of the fabric of the Prince Charles Mountains and east Lambert Glacier

Figure 7.3 Reconstruction of the Gondwana continents, adapted from McWilliams (1981), Craddock (1975), and Nairn (1973) depicting the distribution of the known Archaean cratons of East Antarctica, relative to the stylized shield or Archaean cratonic areas of Australia, India, Africa and South America. The trends of Proterozoic and Cambrian structures or gneissosities are represented by fine lines, while stippling indicates the Ethiopian volcanic plateau.

A: Arabian, A-F: Albany-Fraser, B: Brazilian, C: Congo, E: Enderby Land, G: Gawler, Mt Painter & Willyama terranes in Australia, G: Guyana, I: Indian, K: Kalahari, N: Amadeus basin, Arunta, Kimberly, McArthur, Mt Isa, Pine Creek, P: Pilbara, S: São Francisco, sPCM: southern Prince Charles Mountains, V: Vestfold Hills, W: West African, Y: Yilgarn.

outcrops. Such an orientation is also sub-parallel with the gneissic fabric, in southern India, which trends towards, and merges with that of Sri Lanka. Additional supporting evidence for their reconstruction, is provided by the similarity of Archaean structural trends, in the Archaean cratons south of Madras, and in Enderby Land, that are broadly consistent with the orientation of the granulitic fabric in the Vestfold Hills (refer also to Fig. 6.29).

As depicted on Figures 7.3 & 7.4 the Proterozoic aged structural trend is inferred to extend from the eastern side of the Vestfold Hills, and appears to continue along the Antarctic coast, to the southern and eastern margin of the Archaean Yilgarn craton. The Albany-Fraser Orogen culminated around 1300-1100 Ma (Myers 1990) (see also section 6.8.6). Whilst definitive correlations are not yet possible as chronological, structural and *P*-T-t path data are presently poorly constrained, it is plausible that the tectonic processes responsible for the development of the early structural fabrics, in the Lambert Glacier region, also produced the equivalent gneissosities in the Albany-Fraser Orogen.

The mobile Proterozoic reworking zone has recently been postulated by Hoffman (1991) and Moores (1991), to extend, in an arcuate zone around Antarctica to include the Grenville orogen, along the eastern margin of Canada. Such an extrapolation however, is beyond the scope of the tectonic model devised here.





Also shown on Figure 7.3 adapted from McWilliams (1981), is the possible convergence of the Albany-Fraser structural trend with that of the Paterson Orogeny, which extends from the northern margin of the Pilbara Craton, to the Musgrave Block (see also Fig. 6.31). The chronological studies of Black *et al.* (1983), reported by Goscombe (1992a), indicate that a pervasive fabric developed in the Strangways Orogenic Belt (after James & Ding 1988), around ≈1800 Ma, but was overprinted ≈1500-1400 Ma, during Proterozoic reworking. These Proterozoic dates are older than those of the Albany-Fraser Orogen, and older than that in the Lambert Glacier region. The actual junction area is not exposed, and extension of the correlation, beyond the Albany-Fraser Orogen appears conjectural.

In developing a plausible tectonic model for the Lambert Glacier granulites, it is therefore necessary to consider its probable Late Proterozoic linear extent. However, the boundaries of this orogen are at the best, poorly defined, in contrast to modern analogues where tectonic boundaries are often well defined. Furthermore the lack of precise chronology on the formation of structures, fabrics and P-T trajectories is variably and often incompletely constrained, in the regions which were possibly interconnected. Given these restrictions it is hazardous to construct an intricate tectonic model for this area, especially when one considers the complexities of modern convergent regions (e.g. the Himalaya, the Australian-New Guinean convergence), for which there is abundant plate motion data, including earthquake epicentre analysis.

Like these modern convergent regions, it is also feasible that Proterozoic convergence was diachronous across the orogen. The available chronology, dating the approximate time of formation of the early pervasive gneissosity appears to follow a diachronous change, from Central Australia to eastern Africa. For example, in the NE Strangways Ranges, Australia, pervasive (D<sub>2</sub>-D<sub>3</sub>) foliation development is suggested to have occurred at ≈1500-1400 Ma (Goscombe1992b), the Albany-Fraser Orogen is dated at ≈1300-1100 Ma (Myers 1990), and in the Lambert Glacier region the early fabric is thought to have developed ≈1000 Ma (Sheraton 1983). There is currently some controversy regarding the timing of metamorphism of gneisses from Sri Lanka that have Archaean and Late Proterozoic derivation ages ≈2500-2600 and 1800-1000 Ma (Kagami *et al.* 1990). They calculate a Cambrian age for granulite facies metamorphism ≈500-400 Ma (*ib. id.*). In contrast Yoshida *et al.* (1990b) suggest that the pervasive gneissosity developed around 1100 Ma. To the east of Sri Lanka (Fig. 7.3), the age of the gneissosity which cuts through the Archaean cratons in southern Africa, is reported to be ≈500 Ma (Nairn 1973).



Figure 7.4 Schematic Gondwana reconstruction, depicting Proterozoic to Cambrian aged gneissic granulite terranes (stippled), separating Archaean cratons (black). The timing of the formation of the pervasive gneissic foliation is referenced and decreases from the right to left. Arrows indicate the estimated compressional axes, with a S to SE tectonic transport direction estimated for the nPCM (Chapter 3), whilst Goscombe (1992b) estimates a W transport direction for the Strangways Ranges, Australia. Nomenclature of cratons explained in Fig. 7.3.

The ages range from 1500-1400, 1300-1100, to  $\approx$ 1000 Ma, in the Lambert Glacier region. The range in ages appears too large to consider that the Proterozoic reworking represents a single event, if the maximum values are used, i.e. 1500-1400 to 1000 Ma. However, if a conservative error of ±100 Ma is applied, then the range in values can be reduced to 200 Ma, that is 1400-100 to 1000+100 Ma.

Summarizing this argument: whilst the compressional axis in central Australia calculated by Goscombe (1992b), and that determined for the Lambert Glacier region (Chapter 3), appear to be similar, the present chronological precision is not sufficient to definitively correlate the structural Proterozoic reworking events. A variant of the argument, that reworking may have evolved through time, from central Australia, through the Albany-Fraser region, to the Lambert Glacier region of Antarctica, appears to be an elegant, but conjectural hypothesis, requiring a prolonged tectonic evolution of at least 200 Ma, and possibly as long as 500 Ma.

# 7.6 Alternative models

Alternatives to the favoured tectonic model must satisfy the requirements listed in section 7.2. The crustal thickening requirement may be satisfied by early thrusting (e.g. Ridley 1989), in a shortening regime, with ELG regions experiencing deeper levels of thickening. The alternative model differs from the favoured model since the maximum preserved pressures are interpreted to represent the maximum pressure conditions of the rocks. Where as, explicit in the favoured model, is the assumption that both eastern and western regions were subjected to approximately equal pressure conditions, but the lower recorded conditions in the west were the result of slower cooling and uplift rates, caused by 'locking' of the compressional axis.

If the maximum conditions of the regions were originally significantly different, the mechanisms responsible for their retrograde paths may also have been different. Additional heat is required to increase the high geothermal gradients for the western region, but is not necessary to explain the eastern decompressional trajectories. Magmatic underplating or plutonism are plausible heat sources, where as delamination of the thermal-boundary layer, another mechanism for adding heat to the base of the crust (Sandiford 1989), is usually predicted to increase geothermal gradients over an extensive area, and would therefore have affected both regions. Plutonism, evidenced by the occurrence of syn-kinematic charnockites, occurs in both eastern and western regions, and therefore can not be employed as the sole source of additional heating. Magmatic underplating has been proposed to explain the low pressure-high temperature paths observed in the Larsemann Hills (Stüwe & Powell 1989). At least 450 Ma of basaltic activity is recorded as dykes, sills and an extrusive lava, in the nPCM, which provides some evidence for an underplating theory, and hence additional heat, for the western region.

The alternative model is complicated by the difficulty in explaining (a) why the maximum conditions preserved in the west are less than those in the east, & (b) requiring an additional heat source for the western region in order to explain the shallower cooling trajectories.

In summary, this alternative model requires an amalgamation of effectively different tectonic processes to produce the P-T path variations in the eastern and western areas. Initially the two regions were buried, possibly by thrusting in a shortening tectonic regime; the eastern region underwent relatively rapid uplift, possibly because the over-thickened crust was unstable and underwent extensional collapse (Nichols & Berry 1991), while magmatic underplating raised geothermal gradients in the shallower, nPCM region.

Another, third possibility is that both eastern and western regions experienced essentially comparable initial conditions, but that magma was underplated only in the

western region. This may have raised western geothermal gradients sufficiently to reequilibrate mineralogies, and remove most evidence of the earlier part of the P-T trajectory.

Thost & Hensen (in press) interpret mineral inclusions in garnet, as evidence of a very low pressure, but high temperature, anticlockwise prograde paths. As described in Chapter 6, the evidence provided is equivocal. Further, it is difficult to explain extremely high-strain deformational features that formed contemporaneously with high-grade metamorphic conditions, for example weakly zoned sigmoidal garnets, early mylonites, sheath-folds, at relatively low pressure conditions.

The crustal thickening models favoured here, are considered to follow clockwise P-T paths.

#### 7.7 Conclusions: the favoured model and extrapolations

The merits of the favoured model are derived from its ability to account for the development of structures within the Lambert Glacier area, and further, the model allows extrapolation of these mechanisms, to the larger, regional 'Gondwana-scale' tectonics, without necessitating additional assumptions. As cautioned above however, such an extrapolation is conjectural, although provides a focus for further research.

Specifically the model explains the formation of the early, pervasive, high-strain features, extremely high strain mylonites zones ( $MY_1$ ), and  $F_2$  sheath folds, which developed parallel to, or within the high metamorphic grade gneissosity. These structural features are best explained by a clockwise rotating trajectory, incorporated into this model, where high-strain occur during the peak metamorphic conditions.

A change in the compressional axis, from S to SE directed, occurred after the development of  $F_2$  and  $F_3$  folding, and is constrained by the strike of high amphibolite, to low-granulite grades of MY<sub>2</sub> mylonites. Continuation of compressional stress, albeit with a new orientation, is consistent with a Himalayan regime where escape zones develop in response to overthickening of the crust in the path of convergence. The high-grades of MY<sub>2</sub>, but slightly lower than peak conditions, suggests that these mylonites record the initiation of uplift of the nPCM.

The consistent right-lateral shear geometry portrayed by  $MY_3$  structures over the entire Lambert Glacier region, is interpreted to have resulted from an easterly directed transport  $\approx 500$  Ma ago and is unrelated to the early history of the region.

In conclusion, the favoured tectonic model provides an eloquent explanation of the early high-strain and high-grade deformation features of the Lambert Glacier region, and additionally incorporates the locking of crustal-movement, analogous with the Himalaya, by which the gradational and variable degrees of uplift or cooling, can be understood.

It is accepted that the favoured model is a non-unique solution, and alternative interpretations may be equally valid, however the available constraints are not yet adequate to discuss their merits.

# Chapter 8

# SUMMARY

S ignificant findings resulting from this study, are summarized here.

The experimental investigation of the modification of the stability-field of spinel in equilibrium with garnet or cordierite, with excess quartz and sillimanite (Chapter 2), was related to the stabilizing influence of zinc, which preferentially partitions into spinel at conditions applicable to granulite facies rocks of East Antarctica and other regions. This relationship was thermodynamically modelled using SVD, to quantify the Fe and Mg pressure-sensitive equilibria: Grt-Spl-Sil-Qtz, Grt-Crd-Sil-Qtz, Spl-Crd-Sil-Qtz, as well as the thermometric exchange equilibria, Grt-Crd-Sil-Qtz and Spl-Crd-Sil-Qtz.

The structural features of the East Antarctic regions, the Reinbolt Hills and the northern Prince Charles Mountains, described in Chapter 3, are dominated by early high strain deformational episodes, during which the gneissosity was transposed, in many areas suffered layer-parallel extension, and was deformed by at least three, and four (in the nPCM) identifiable, fold-styles. The parallelism of mineral-stretching lineations and fold axes, is interpreted to result from high strain, accompanying the early structural phase, during which early-formed structures were progressively rotated into the orientation of tectonic movement. Sub-horizontally, northward dipping, fault zones at Mt Lanyon and Mt Meredith, with inferred south-eastward and eastward reverse movements, are interpreted as early mylonitic thrust zones (MY<sub>1</sub>). There are no metamorphic-grade distinctions between mineralogical fabrics associated with the gneissic layering, MY<sub>1</sub> mylonites (in the nPCM), or with the early fold generations which deform the layering, as all features were apparently produced during peak granulite-facies conditions. In many regions, later deformation has rotated the orientation of early mineral-stretching lineations into generally steeper plunging orientations, with both easterly and westerly trends.

Coaxial  $F_2$  and  $F_3$  folds responsible for the orientation of much of the gneissic layering, were produced synchronously with peak metamorphic conditions, and during a continuation of the northwest-southeast directed stress regime, which is first recognizable, by the development of MY<sub>1</sub> thrusting. Later F<sub>4</sub> folds, macroscopically significant at Wall Peak and at Mt Béchervaise, are suggested to have formed in response to a compressionalstress axis directed in an east-westerly orientation, during the waning stages of metamorphism.

In the nPCM region, second generation mylonites,  $MY_2$ , formed after peak metamorphism at low granulite to upper amphibolite conditions, and are characterised by sub-vertical dips, and northeasterly-southwesterly strikes. They consistently depict reverse movement, and except for one specimen from Mt Lanyon (LAN90/10), they have a northwest block up, relative to southeast block shear sense. It is feasible that  $MY_2$  mylonites were produced in response to sub-vertical crustal movements, responsible for crustal exhumation that is recorded in the metamorphic cooling and decompressional trajectories throughout the northern Prince Charles Mountains and Eastern Lambert Glacier region. Alternatively they record crustal movements during the diminution of metamorphic conditions.

Once substantial uplift had occurred, and the crust had cooled significantly,  $MY_3$  mylonitization occurred, probably around 500 million years ago. They may have been related to additional crustal heating evidenced by the localized production of granitic-pegmatitic magmas, which are frequently emplaced along  $MY_3$ 's fault zones. They consistently depict right-lateral, eastward movement shear-sense.

In summary, the approximately east-west orientation of the northern Prince Charles Mountains and the Reinbolt Hills' structures, together with consistent north towards southeast interpreted early thrusting directions, followed by relative northwest block up movements, and an ultimate episode of easterly, right-lateral shear movement, are features consistent with a northwest to southeast compressional regime, which accompanied metamorphism from peak granulite to retrograde amphibolite, and finally greenschist facies conditions.

A decompressional *P*-*T* path established for the Reinbolt Hills (Chapter 4), which passes through the equilibration conditions of 800°C and 7 kbar, and crosses 3 independent retrograde reactions that produce Crd, Spl and Ilm, terminates at 690°C and 5 kbar. The trajectory's magnitude and gradient, are consistent with the preferred trajectory of the McKaskle Hills which passes from the preserved peak conditions of 850°C and 8 kbar to 700°C & 4 kbar. This path is most strongly constrained by Grt-Opx-Pl-Qtz barometry combined with Grt-Opx, two pyroxene thermometry, while minimum retrograde conditions are determined from Mag-Hc solvus temperatures.

The comparative study of spinel solid-solutions with Opx intergrowths in specimens M2 and M3, provides evidence for the localized equilibrium chemistries, and importantly provides constraints on the P-T evolution of the McKaskle Hills. These reaction
and corona textures are best explained by the breakdown of andraditic garnet, under quartz saturated, and quartz under-saturated equilibrium conditions. The alternate explanation that oxygen fluxing produced the magnetite solid-solutions, is not compatible with the detailed interpretation of textures and mineral chemistry.

A comparative study of the accuracy of geothermobarometers, when applied to a compositional range of East Antarctic lithologies, and presented at the beginning of Chapter 6, resulted in the following conclusions.

1. Whereas *P*-*T* trajectories derived with the Hoisch (1990) thermobarometer are marginally steeper than those calculated independently, where a shallow or isobaric path is indicated, a cooling trajectory can be interpreted with moderate confidence. The Hoisch (1990) barometer, however both over and under-estimates pressures, possibly because (a) it was empirically formulated with lower temperature rocks, and the slopes of these equilibria may not allow an accurate extrapolation to higher temperature rocks, & (b) that garnet and particularly biotite, are more prone to continual Fe/Mg exchange between other minerals during cooling, than that which typically affects minerals in other exchange barometers. Hoisch's derivation, when applied recognizing these precautions, provides an indication of the probable P-T slope, in Grt-Bt-Pl-Qtz assemblages which suffer a paucity of suitable calibrations.

2. Bohlen *et al.* (1983a) and Perkins & Newton (1982) geobarometers provide the most consistent pressure constraints in the Grt-Opx-Pl-Qtz system, with the former calibration being the least sensitive to Fe/Mg exchange. The internally consistent computer programme by Powell & Holland (1988), and Holland & Powell (1990), produces good pressure and temperature values in this system. The assertion of Carswell & Gibb (1987a), that the Moecher *et al.* (1988) formulation over-estimates pressures, is supported by this comparative study. Harley's (1984a) barometric formulation was found to be unsatisfactory in estimating pressures, being overly sensitive to both small changes in the alumina content of orthopyroxene as well as resetting of Fe/Mg upon cooling.

3. In Grt-Sil-Pl-Qtz assemblages, the calibrations of Newton & Haselton (1981), Ganguly & Saxena (1984) and Hodges & Spear (1982) provide good pressure constraints. The former barometer provides the clearest distinction between Grt core and rim compositions, and was therefore useful in establishing P-T trajectories in samples with zoned garnets. 4. The internally consistent thermobarometers of Nichols *et al.* (1992) furnish useful pressure constraints in aluminous granulites; the system Grt-Crd-Sil-Qtz suffers the least resetting, further has the smallest estimated calibrational errors, and therefore provides the most accurate peak pressure and temperature determinations. The barometric calibration of the Grt-Spl-Sil-Qtz system is particularly useful for estimating the conditions during the formation of various spinel generations, where they are in demonstrable equilibrium with Sil and Qtz.

5. Newton & Perkins' (1982) derivation in the Grt-Cpx-Pl-Qtz system estimates comparable pressures with other barometers applied to adjacent samples.

6. The albite-jadiete-quartz system, calibrated by Holland (1980) and Gasparik & Lindsley (1980) to estimate pressures, appear to suffer from calibrational problems due to (a) attainment of equilibrium in their experiments, caused by the slow diffusional rate of Al, and (b) complex quaternary solid solutions that are inadequately assessed using simple binary systems; these barometers were therefore applied with caution, and are able only to bracket the possible peak pressures of the nPCM granulites.

7. Ferry & Spear's (1978) Grt-Bt thermometric calibration calculated temperature values which most closely match those estimated using Grt-Opx thermometry, and this early derivation was systematically applied throughout the nPCM specimens. The Indares & Matignole (1985) thermometer, designed to negate the over-estimation of temperatures caused by Ti substitution in Phlogopite, was found to be too dependent upon the selection of the Grt mixing-model. The magnitude of the correction applied by their thermometer is thus brought into question, and therefore this calibration was not used.

8. Thermometers in the Grt-Opx system were evaluated with the conclusion that Sen & Bhattacharya's (1984) calibration produces the most consistent temperatures, in agreement with Faulhaber & Raith (1991). Harley's (1984b) Grt-Opx thermometer produces lower temperatures than other formulations. It is concluded that this is an inherent calibrational discrepancy.

9. In the few Grt-Cpx bearing specimens, both Ellis & Green's (1979) and Powell's (1985) thermometers were used, both producing equivalent, and consistent values.

10. Bertrand & Mercier's (1985) two pyroxene solvus thermometer consistently reproduces the most consistent temperatures when applied to mafic composition granulites, consistent with the conclusion reached by Carswell & Gibb (1987b).

11. Grt-Chl thermometry using the calibration of Dickenson & Hewitt (1986), and the Laird (1989) modified version, estimates temperature values comparable with the Grt-Bt thermometer of Ferry & Spear (1978), however this finding is suggestive only, as it is based upon a limited number of comparisons.

12. The two internally consistent programmes, GEO-CALC by Berman (1988), and THERMOCALC by Powell & Holland (1988), and Holland & Powell (1990), were applied to assemblages where there are few single-assemblage calibrations, or to depict pseudosections ( $\log_a Vs \log_a$ ). Both programmes provide useful *P*,*T*,*X* and  $\log_a$  information about assemblages, with pressure and temperature values converging in well defined experimental systems.

Pressure-temperature trajectories derived for regions in the nPCM are characterized by similar shallow gradients, indicative of cooling dominated, post-peak histories. In contrast, East Lambert Glacier regions, have statistically steeper paths.

A comparative analysis of P-T paths established for the East Antarctic region, and Gondwana continental-fragments, is hindered by reliable age constraints, however some features are common throughout the region: (a) peak Archaean conditions are characteristically high temperature and pressure events, and are usually followed by isobaric cooling of substantial duration, (b) a Proterozoic event, characterized by the re-establishment of geothermal conditions, and post-dating the formation of the preserved peak metamorphic assemblages, is a widespread feature. This synchronous(?) tectonic episode retains predominantly a decompressional component, in many East Antarctic areas, for example the East Lambert Glacier paths, the Larsemann Hills and Rauer Island trajectories, (c) the strongest evidence correlating this decompressional event with the paths dominated by cooling, experienced by the nPCM rocks, is the observation that their gradients follow a continuum, changing from the steepest in the east to the shallowest, and lowest pressures, in the west. Preliminary radiometric age dating also supports this correlation, & (d) these conclusions implicitly support the hypothesis that a continuous Proterozoic crustal section is exposed from the Rauer Islands to the western nPCM, and that this probably experienced synchronous changes of metamorphic conditions; the differences in preserved P-T paths reflect the level of crust from which the rocks are exposed.

An eloquent tectonic model devised for the Lambert Glacier region (Chapter 7), is based on the observation of high-strain early structures, such as  $MY_1$  mylonites and intrafolial  $F_2$  sheath folds, which through microstructural analysis, were interpreted to have formed during high-grade metamorphic conditions (Chapter 3). The model is analogous to the modern Himalayan convergence, where shallowly subducted crustal-collision is occurring, and now because of extensive crustal thickening impeding convergence, has produced a measurable change in the compressive-stress direction. Such a rotation of the compressive vector is interpreted in the Lambert Glacier region where the inferred stress which produced the south to southeastly  $MY_1$  thrusting, rotated to a more southeasterly direction at the initiation of uplift, recorded by the slightly lower metamorphic-grade,  $MY_2$ mylonites. Much later around 500 million years ago, after the terrane had cooled significantly, sub-horizontal  $MY_3$  mylonites record the crustal response to a consistent easterly tectonic transport, over the Lambert Glacier region.

The Proterozoic zone of convergence, inferred from this model, is conjecturally extended eastward as far as the central Australian terrane, where reworking with the same interpreted compressional axes as the Lambert Glacier region, occurred around 1500-1400 Ma (Goscombe 1992b). To the west, the convergence possibly extended as far as Sri Lanka. Available chronological constraints indicate that either compressional reworking was active over the entire belt for a protracted period (possibly from  $\approx$ 1500 to 1000 Ma), or that the convergent Himalayan-style regime was diachronous, commencing in the east, with gradual westward translation with time.

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APPENDICES

characters are the creation of Uderzo, 1962

## APPENDIX ONE

Lithological and structural interpretation map of the Reinbolt Hills Lithological and structural interpretation map of Mt Lanyon Detailed southern cliff section, Mt Lanyon Structural interpretation map of the Mt Béchervaise region Structural interpretation map of the Gorman Crags region Photographic structural interpretation map of Manning Massif









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#### APPENDIX TWO

# Specimen Catalogue

#### R: rock specimen TS: thin-section

University Catalogue Nº	Field N <sup>2</sup>	Rock description	Location	Grid Cords	Preparation
72020	7ь	Felsic granulite	Reinbolt Hills	70°28' S. 72°30'E	R & TS
72021	10	Mafic granulite	_"_	-"-	R & TS
72022	11	Felsic granulite	_''-	-''-	R & TS
72023	12a	Felsic granulite	_"_	-"-	R&TS
72024	12b	Calc-silicate	_''_	_".	R & TS
72025	15c	Felsic (fe-rich) granulite	-"-	."	R&TS
72026	16	Mafic granulite	_''_	_''_	R&TS
72027	17	Ultramafic granulite	_"_	."	R&TS
72028	18	Mafic granulite			R& TS
72029	20	Felsic granulite	-**-	"	R& TS
72020	24	Felsic granulite			D & TS
72031	7.	Felsic granulite		."	D D
72032	265	Falsic granulite		,,	D & TC
72032	200	Felsic granulite			D 2 TC
72033	20	Colo gilionte			D & TC
72034	29a 20h	Cale silicate			
72033	290	Calc-sincate			K & IS
72036	34	Meta-basalic dyke			R & IS
72037	38	Manc granuite	+``= 14		K & IS
72038	45	Ultra-matic granulite	-"-		R & 15
72039	63a	Felsic granulite	-"-	•"•	R & TS
72040	85	Xenolith in Reinbolt Charnockite	<b>-</b> <sup>1*</sup> -		R & TS
72041	103	Felsic granulite	_**-	-"-	R
72042	108	Charnockite	_''-	-"-	R & TS
72043	115a	Felsic granulite	_''-	-"-	R & TS
72044	115c	Felsic granulite		<u>-</u> "-	R & TS
72045	121b	Pelitic granulite	_''-	-"-	R & TS
72046	121c	Pelitic granulite	<b>_</b> "-	-"-	R & TS
72047	121e	Pelitic granulite	_"-	-"-	R & TS
72048	JP/15	Mylonitic charnockite	Jennings Promontory	70°11' S, 72°30' E	R & TS
72049	M/2	Mafic granulite	Mc Kaskle Hills	70°00' S, 73°00' E	R & TS
72050	M/2A	Mafic granulite	-"-	-"-	R & TS
72051	M/3	Felsic granulite	-"-	-"-	R & TS
72052	M/5B	Mafic granulite	_**-	."_	R & TS
72053	M/6	Mylonitic felsic granulite	_!!_	_"_	R & TS
72054	M/7	cale-silicate	-"-	-"-	R & TS
72504	3	Hbl-Grt-Bt felsic gneiss	Mt Meredith	71°12' S, 67°45' E	R
72505	4	Hbl-Grt-Bt felsic gneiss	_''-	_"_	R
72506	7	Bt-semi pelitic gneiss	- 11	.".	R
72507	8	Bt-semi pelitic gneiss	<b>_</b> ''-	-"-	R
72508	9	Bt-Mu? gneiss	_14 _	_''_	R
72509	10	Bt-Grt gneiss	_''_	-"-	R & TS
72510	22	coarse Sill	_''-	.".	R
72511	23	marble with Ol	-"-		R & TS
72512	28	Trem-blue Apatite calc-silic			R& TS
72513	23	Canod with Sahene		н.	D D
72514	48	Grt-Ca Ubl felsio gneiss	14		DETC
72515	50	Mu-gross Gtr-Fluorite pod	_''_	·· -	R
72516	3	Sheath-F in felsic gneiss	Mt Lanvon	71°12'S. 67°10' E	R
72517	ă	Ca amph/ di calc-silicate			R
72518	5	Grt-Kfs felsic oneise		_"_	R
72510	2 R	calc-silicate boudin		_"_	p
72520	1<	Hbl. falsia anaice			p
72521	17	Grt-Rt falsic gnoise			p
72522	21	Libi duka metamombarad			D
14244	21	Cet Sil politio angian			к р.е.тс
1 44 - 2 44 - 2	<i>4</i> 2		• •		1 0L 1 J

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72524 72525 72526 72527 72528 72529	27 29 30 36 41 42	Grt felsic gneiss alkaline basaltic dyke alkaline basaltic dyke Opx? felsic gneiss Grt-Hbl-Fls-Qtz felsic gneiss Grt-Hbl-Fls-Qtz felsic gneiss	-" -"- -"- -"- -"- -"-	20. 20. 20. 20. 20. 20.	R R R R R
72530 72531 72532 72533	1 4 5 13	alkaline basaltic dyke F in mylonite F in my, oriented 068,90 sheared peg with Grt-Bt	Fox Ridge -"- -"- -"-	70°50'S, 67°30' E -"- -"- -"-	R & TS R & TS R R
72534 72535 72536	x 9 10	Bt-Grt semi pelite Grt-Bt semi pelite F in Grt-Bt-Kfs semi-pelite	Brocklehurst Ridge -"- -"-	71°03'S, 67°10'E _''_ _''-	R R R
72537	14	zoned calc-silicate	_"_	-"-	R
72538 72539	13 20	alkaline basaltic with zenolith calc-silicate with reactions	Taylor Platform	71°01'S, 67°05'E -''-	R R
72540 72541 72542 72543 72544 72545 72546 72547 72548 72549 72550 72551 72552 72553 72554 72555	loose float MAN/6 MAN/7 MAN/8 MAN/9 MAN/10 MAN/11 MAN/12 MAN/13 MAN/14 MAN/15 MAN/16 MAN/17 MAN/18 MAN/21	marble+calc-silicate (c/s) c/s boudin in marble di+clinohumite in marble Ca-amph as boudin in marble Ca-amph as boudin in marble layered c/s & marble layered c/s & marble zone between c/s & marble zone between c/s & marble zone between c/s & marble Zone between c/s & marble Mafic granulite Opx granulite? Mafic granulite, purple Qtz layered c/s di+cc+px+Ca-amp across c/s layer, pieces 1->6	Manning Massif,McKinnon G	170°47'S, 67°45'E -''- -''- -''- -''- -''- -''- -''- -	R R R R R R R R R R R R R R R R R R R
77001 77002 77003 77004 77005 77006 77007 77008 77009 77010 77010 77011 77012 77013 77014 77013 77014 77015 77016 77017 77018 77017 77018 77019 77020 77021 77023 77024 77025 77026 77027 77028 77029 77030 77031 77034 77035 77036 77036 77036 77036 77036 77036	LAN/1 LAN/2 LAN/3 LAN/3 LAN/7 LAN/9 LAN/11 LAN/12 LAN/12 LAN/12 LAN/12 LAN/12 LAN/12 LAN/12 LAN/20 LAN/22 LAN/20 LAN/22 LAN/26 LAN/27 LAN/28 LAN/26 LAN/27 LAN/28 LAN/31 LAN/32 LAN/32 LAN/35 LAN/39 LAN/39A LAN/39A LAN/39A LAN/44 LAN/45 LAN/45 LAN/45 LAN/45 LAN/45 LAN/47 LAN/48 LAN/40/1 LAN90/7 LAN90/7 LAN90/7 LAN90/7	Grt-Sil-Bt pelite Grt-Sil-Bt pelite Grt-Bt felsic gneiss Amp-Bt felsic gneiss Amp-Bt felsic gneiss Amp-Bt felsic gneiss Amp-Dyx mafic gneiss calc-silicate felsic gneiss Amp-Cpx mafic gneiss calc-silicate Grt-Bt-Amp felsic gneiss Siliceous late-stage deposits Amp-felsic gneiss Amp-Cpx mafic gneiss siliceous late-stage deposits Amp felsic gneiss Amp-felsic gneiss Amp-felsic gneiss Bt bearing felsic gneiss Bt-Amp-Px mafic gneiss Hem nodule in felsic gneiss Pyrrhotite vein Pyrrhotite nodule Amp-Bt felsic gneiss Amp-Px mafic gneiss Amp-Px mafic gneiss Bt-Amp-Px mafic gneiss Amp-Px mafic gneiss felsic proto-mylonite in granitoid highly strained Amp felsic gneiss	Mt Lanyon	71°12'S, 67°10' E	R & TS R & TS R R R R R R R & TS R & R & R & R & R & R & R & R & R & R &
77038 77039 77040 77041	LAN90/11 LAN90/14 LAN90/15 LAN90/16	porphyroclasts, in felsic + carb gneiss malic gneiss mylonitic Amp felsic gneiss Grossular calc-silicate, with Sphene contact of marble and calc-silicate	s -"- -"- -"- -"-	-"-" -"- -"- -"-	R & TS R R & TS R R

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77042	LAN90/17	boudinaged mafic & felsic gneisses	-"-	-"-	R
77043	MER/1A	marble	Mt Meredith	71°12' S. 67°45' E	R & TS
77044	MER/1B	marble	14	_"_	N 66 1 3
77045	MER/2	calc-silicate	-"-		DATO
77046	MER/6	early mylonite (MY1) in semi-pelite	-"-	.".	DATC
77047	MER/10	mafic gneiss	_''_	."_	Dere
77048	MER/11	Grt-Bt semi-pelitic gneiss	-''-	_"_	D & TC
77049	MER/12	Bt gneiss	_''_		R & IS
77050	MER/13	hematitic veins	- **-	_ "	R
77051	MER/14	felsic aneiss	-"-		R
77052	MER/15	Rt gneiss	"		R
77053	MER/16	felsic aneiss			K D
77054	MER/17	matic gneiss			R
77055	MED/18	folded Bt aneiss			R molificad alai
77055	MED/10	falsia granitoid		· - ··	pousned sia
77057	MED 100	and contract			ĸ
77057	MER/20	Calc-Silicale and contact	74		N N N N N N N N N N N N N N N N N N N
77050	MED 02	Ol bearing granitoid			K & IS
77060	MER/23	Of bearing marble			K& IS
77060	MER/24	Of bearing marble			K
//001	MER/25	Of bearing marble			R&TS
77062	MER/26	Cpx-Amp manc gneiss		•	R
77063	MER/2/	Lamprophyre, Cpx-Phi xysts		-"-	R & TS
77064	MER/28	caic-suicate with blue apatite		-"-	R & TS
77065	MER/29	marble		-"-	R & TS
77066	MER/30	tremolitic rich calc-silicate		-"-	R & TS
77067	MER/31	calc-silicate	- <b>- - -</b>	-"-	R & TS
77068	MER/32	calc-silicate	-''-	-"-	R & TS
77069	MER/33	marble with Ca-Amp and Sphene	-"-		R
77070	MER/34	Grt-Amp-Pl mafic gneiss	-'' <b>-</b>	_*_	R
77071	MER/36	Ol bearing marble	_1*_	_*_	R & TS
77072	MER/37	Ol-Spl bearing marble	_''_	_''_	R & TS
77073	MER/39	calc-silicate	-"-	_**_	R & TS
77074	<b>MER/40</b>	marble	-"-	-"-	R & TS
77075	MER/41	marble with Phl	-"-	-"-	R&TS
77076	<b>MER/42</b>	Ca-Amp bearing calc-silicate	_! <b>*</b> _	-"-	R & TS
77077	<b>MER/43</b>	marble		-"-	R
77078	<b>MER/44</b>	Bt gneiss		_"_	R & TS
77079	MER/45	Grt-Bt gneiss	_" <u>_</u>	.".	R
77080	MER/48	Grossular-Amp bearing cale-silicate	_''_	.".	P & TS
77081	MER/51	calc-silicate	."_		P
77081	MER/52	moraine u/m with lavered Cox			D
77082	MER/53	moraine, time grained Cox			D
77083	MED /54	moraine, fine granted, Cpx			D
11005	MILLIN 34	moranie, epx & plag grin			K
77084	TD/2	Amp rich calc silicate	Taylor Platform	7100115 6700515	D
77004	1F/4 TD/4	interlayered cale silicate & Amp motio	rayior riadonn	11 013,07 03 6	R D
77085	11/4	interiayered cale-sincale & Amp mane			
77007	1P/9 TD/14	Car Sal bassing cale silicate			R & IS
77000	$\frac{1P}{14}$	Cor-spi bearing calc-sincale			Ræis
77000	1P/10 TD/10	basanic dyke			K N
77000	12/19	Amp-Bt gneiss			R & IS
77090	1P/21	Grt semi-peutic gneiss			R&TS
//091	1A90/1	Grt-pelite	· · ·		R & TS
77092	TA90/2	Grt-Amp gneiss		-"-	R
				· .	
77093	BRO/1	basaltic dyke	Brocklehurst Ridge	71°03'S, 67°10'E	R & TS
77094	BRO/2	basaltic dyke	•"-	-"-	R & TS
77095	BRO/3	Amp dominant gneiss	-"-	-"-	R
77096	BRO/4	Grt bearing felsic gneiss	-''-	-"-	R & TS
77097	BRO/5	calc-silicate	-"-	-"-	R
77098	BRO/6	Grossular bearing calc-silicate	_**_	_"_	R & TS
77099	BRO/7	strongly lineated & folded pelite	-"-	-"-	R
77100	BRO/8	Grt-Bt semi pelitic gneiss	-"-	<b>_</b> ".	R & TS
77101	BRO/10	Bt gneiss	-''-	-"-	R & TS
77102	BRO/11	Grt-Sil pelite	14 m w		R & TS
77103	BRO/12	Grt-Sil pelite	_**_	_"_	R & TS
77104	BRO/13	Amn calc-silicate			R
77105	BRO/15	Get bearing felsic gneiss	-"-		DATC
//105	DRO/15	On bearing tensic gitenss		••	K & IS
77106	BE00/1	Grt-Sil pelite	Mt Reab	710010 670000	D
77107	D C 20/1	Grt. Bt angles	With DECH	/ 1 04 3, 0/ 00 B	К D
77107	DE90/4	Grt-Di gneiss			K D & TO
77100	DE90/3	Cat Bt falsis and in		·	K & TS
77110	DE90/4	Con-Di leisic gneiss			K & IS
77110	DE90/3	Un-bi gneiss			ĸ
//111	RF30/9	Amp-Bt mane gneiss	• •	•" <b>-</b>	ĸ
			01111	Ba Da Dine	
//112	SMA Y90/1	strongly lineated Grt-Bt gneiss	SW Mayman Nunatak	71°10'S, 66°55'E	R
77110	01.001	l'anne i De Calai	OIT D' '	709500 /5005	~
//115	01.90/1	ineared Bt leisic gneiss	O Leary Kidges	/0-585,67°2/E	ĸ
//114	OL90/2	BI-Off leisic gneiss	• •		ĸ

77115 77116 77117 77118 77119 77120 77121 77122	OL90/3 OL90/4 OL90/5 OL90/6 OL90/7 OL90/8 OL90/9 OL90/10	Bt gneiss Bt felsic gneiss Ca-Amp calc-silicate calc-silicate Ol-bearing marble calc-silicate felsic gneiss Amp-Bt mafic gneiss	-"- -"- -"- -"- -"- -"- -"-		R R & TS R & TS R & TS R & TS R R R R
77123 77124 77125 77126 77127 77128 77129 77130 77131 77132	MAN/2 MAN/3 MAN/4 MAN/5 MAN/20 MAN/23 MAN/24 MAN/25 MAN/28	felsic gneiss with pseudotachylyte Opx felsic granitoid with sulphides Charnockite with Opx Qtz-rich granitoid mafic gneiss early granitoid, felsic gneiss Qtz-rich felsic gneiss Bt-Amp gneiss Charnockitic with pseudotachylyte felsic granitoid	Manning Massif          -	70°45'S, 67°45'E -''- -''- -''- -''- -''- -''- -''- -	R R R R R & TS R R R R R
77133	MAN/29	Opx-Amp mafic gneiss	-"-	-"-	R
77134 77135 77136 77137 77138 77139 77140 77141 77142	FOX/6 FOX/7 FOX/8 FOX/10 FOX/14 FOX/15 FOX/17 FOX/18 FOX/19	ultra-mylonite layered mafic gneiss ultra-mylonite in Qtz vein early granitoid v. coarse grained Grt gneiss mylonite in Qtz mylonite with feldspar p'clasts Px mafic gneiss Grt p'clasts in ultra-mylonite	Fox Ridge -"- -"- -"- -"- -"- -"- -"- -"-	70°50'S, 67°30' E -''- -''- -''- -''- -''- -''- -''-	R & TS R R & TS R & TS
77143 77144 77145 77146 77147 77148	S90/1 S90/2 S90/3 S90/4 S90/5 S90/6	Grt-Bt gneiss micaceous-Amp & folded mylonite interlayered mafic & felsic gneiss recrystallized mylonite Grt-Bt gneiss Bt-Grt & felsic gneiss contact	Lensink Peak -"- -"- -"- -"- -"-	71°05'S, 65°12'E -''- -''- -''- -''- -''- -''-	R & TS R & TS R R R & TS R
77149	S90/7	Grt-Bt-Hbl gneiss	-"-	_** <u>_</u>	R & TS
77150 77151 77152 77153 77154 77155	W90/1 W90/2 W90/3 W90/4 W90/5 W90/6	Epidote veins on later shear zone felsic gneiss Grt-Sil pelite Opx Qtz-rich granitoid Opx bearing mylonite Grt-Bt gneiss	Wall Peak 	71°05'S, 65°10'E -"- -"- -"- -"- -"- -"-	R & TS R & TS R & TS R & TS R & TS
77156 77157 77158 77159 77160 77161 77162 77162	GOR90/1 GOR90/2 GOR90/3 GOR90/4 GOR90/5 GOR90/6 GOR90/6	F3 fold in Grt-Bt felsic gneiss Grt-Bt felsic gneiss Grt felsic gneiss kyanite? in felsic vein Grt-Bt felsic gneiss Bt-Grt felsic gneiss felsic gneiss felsic gneiss	Gorman Crags -"- -"- -"- -"- -"- -"- -"-	71°00'S, 65°35'E -''- -''- -''- -''- -''- -''-	R R R R & TS R & TS R R
77164 77165 77166 77167 77168 77169 77170 77171 77172 77173	GOR90/9 GOR90/11 GOR90/12 GOR90/13 GOR90/14 GOR90/15 GOR90/15 GOR90/16 GOR90/17 GOR90/18 GOR90/19 GOR90/20	Grt-Bt-Opx gneiss & GOR90/10 micaceous pod Grt-Bt gneiss Grt-Sil pelite Grt-Bt felsic gneiss micaceous pod mylonite with feldspar P'clasts Grt-Bt felsic gneiss Grt-Bt felsic gneiss brecciated calc-silicate & contact calc-silicate micaceous mafic gneiss			R & TS R & TS R & TS R & TS R & TS R & TS R R & TS R R R
77174 77175 77176	GOR90/21 GOR90/22	strained Grt-Bt felsic gneiss strained Bt gneiss	الم	-"- -"- "	R & TS R & TS P & TS
77177 77178 77179 77180 77181	GW90/1 GW90/2 GW90/3 GW90/4 GW90/5	Grt-ba feisic gneiss Grt-Sil fine grained pelite Grt-Sil coarse grained pelite Grt-Sil pelite deformed Grt-Bt gneiss	Gorman Crags West  -"- -"- -"- -"- -"-	-"- 71°02'S, 65°35'E -"- -"- -"- -"- -"-	R & TS R R & TS R & TS R & TS R & TS
77182	SIMON90/1	Grt-Bt gneiss	Simon Ridge	71°05'S, 65°35'E	R & TS
77183 77184 77185	MB90/1 MB90/2 MB90/3	Grt-bearing granitoid Grt-Opx bearing granitoid Grt-Bt felsic gneiss	Mt Béchervaise _''- _''-	70°10'S. 64°50'E -''- -''-	R R & TS R

77186 77187 77188 77189 77189 77190 77191 77192 77193 77194	MB90/4 MB90/5 MB90/6 MB90/7 MB90/8 MB90/9 MB90/10 MB90/11 MB90/12 MB90/13	grt-Sil pelite Bt-Sil-Grt pelite Grt-Sil pelite Grt-Sil pelite calc-silicate boudin Bt-Grt pelite Grt-Opx felsic gneiss Grt-Bt mylonitic pelite Grt-Bt pelite Grt felsic gneiss with sulphides?	-"- -"- -"- -"- -"- -"- -"- -"- -"- -"-		R & TS R & TS R R & TS R R & TS R R R & TS R
77195 77196 77197 77198	H90/1 H90/2 H90/3 H90/4	Grt-bearing felsic gneiss Bt-Opx mafic gneiss Grt-bearing felsic gneiss basaltic gneiss	Hunt Nunataks -"- -"- -"-	70°10'S, 65°02'E _''- _''- _''-	R & TS R R R
77199 77200 77201 77202 77203 77204	D90/1 D90/2 D90/3 D90/4 D90/5 D90/6	Grt-Sil pelite Grt-Sil pelite Grt-Bt-Sil pelite Grt felsic gneiss with graphite Grt-Sil pelite Grt-Sil pelite	Mt Dovers -''- -''- -''- -''- -''-	70°10′S, 65°05′E	R & TS R & TS R & TS R & TS R & TS R & TS
77205 77206 77207 77208 77209 77210 77211 77212 77213 77214 77215 77216 77217 77218 77219 77219 77220 77221	15A 15B 17 27 29C 35 37A 37B 63C 77 91 94 100 114 115B 121A 121D	Bt-bearing pegmatite Amphibole rich pod Cpx-Opx-Spl ultramafic Bt-Opx? felsic gneiss calc-silicate Bt-rich pegmatite deformed charnockite Bt-bearing mafic gneiss Grt-Bt mafic gneiss pegmatitic vein through charnockite Grt-bearing charnockite deformed charnockite Grt-ich felsic gneiss (granitoid) Kfs-Grt granitoid Grt-rich gneiss & Grt separate felsic gneiss Bt-Onx? mafic gneiss	Reinbolt Hills -"- -"- -"- -"- -"- -"- -"- -"- -"- -"	70°28' S, 72°30'E _''_ _''_ _''_ _''_ _''_ _''_ _''_ _	R R R R R R R R R R R R R R R R R R R
77222 77223 77224 77225 77226	M/1A M/1B M/2B M/4 M/5A	Grt-bearing felsic gneiss Grt-Bt felsic gneiss Cpx-Opx mafic gneiss (u/m?) Bt-Opx-Cpx mafic gneiss Bt interlayered & folded gneiss & M8 granitoid= Landing Bluff?	Mc Kaskle Hills -"- -"- -"- -"-	70°00' S, 73°00' E _''_ _''- _''- _''-	R R R R R
77227 77228 77229 77230 77231 77232 77233 77234 77235 77236 77237 77238 77239 77239 77240 77241 77242	JP/4A JP/4B JP/6 JP/7 JP/9 JP/11 JP/20 JP/22 5/22.1 5/22.1	Opx-rich pod charnockite granitoid dyke granitoid dyke contact of charnockite with granitoid aplitic dyke charnockite (x2) magmatically layered peg magmatically layered peg coarse Cpx, in peg coarse Cpx, in peg coarse Cpx, in peg section thro' layering and Cpx Adamellite	Jennings Promontory -"- -"- -"- -"- -"- -"- -"- -"- -"- -"	70°11' S, 72°30' E         	R R R R R R R R R R R R R R R R R R R
77243 77244 77245 77246 77247 77248	WIS 1 WIS 2 WIS 3 WIS 4 WIS 5 WIS 6	Grt-Bt felsic gneiss & Ca-Amp grossular calc-silicate Ca-Amp, Cpx calc-silicate Ca-Amp, Cpx calc-silicate megacrystic Cpx, Ca-Amp c/s Amp-Cpx calc-silicate megacrystic grossular calc-silicate	Mt Wishart, PCM -"- -"- -"- -"- -"- -"- -"-	70°20'S, 65°25'E -''- -''- -''- -''- -''- -''-	R R R R R R R
77249 77250 77251		Grt-Sil-Crd pelite Crd haloe in pelite Crd-Sil-Grt-Bt pelite	Depot Peak (collected by Dr K Stiiwe)	69°02'S, 64°30'E _''- _''-	R R R
77252 77253 77254		sapphirine, Phl, enstatite phl, qtz, feld qtz, feld, phl, ±sapph, ±en	zenolith in Chck, Mawson	67°35'S, 63°30'E _''- -''-	R R R
### APPENDIX THREE

# Microprobe analyses of experimental runs

adj: adjacent analysis gm: groundmass minerals H: analysed in Edinburgh as a check on the calibration of Zn in experimentally produced Gahnitic spinel rev: reversed run 0: below detection limit : not analysed

	T-3165 15	Kbar, 135	or							T-3169, A	, 10Kbar,	1050°C													
	Std Spl	Std Spl	Std Spl	HStd Spl	Spinel	Spinel	Spinel	Spinel	Spinel	Spinel	T-3182, A	, 13Kbar,	1050°C												
Mg №	100.0	. '		50.0	66.7°		50.0		50.0	39.9	39.2	<b>40.1</b>	<u>39.7</u>	<u> 39.3</u>	<b>39.6</b>	Spinel	Spinel	Spinel	Spinel	Spinel	Spinel	Spinel	Garnet	Garnet	Garnet
SiŌ2	0.082	0.105	0.04	0.077	0.092	0.105	0.073	0.09	0.094	0.116	0.14	0.171	0.118	0.71	0.215	39.2	39.1	39.2	41.6	39.4	37.5	41.0	40.8	42.7	42.6
A12O3	54.55	55.219	55.203	55.044	54.993	55.107	54.521	54.944	54.349	60.034	59.419	60.103	59.882	58.672	59.657	0.086	0.11	0.067	0.072	0.965	1.583	0.312	39.145	37.594	30.068
FcO	0.011	0	0	0.054	0.031	0.01	0.04	0.024	0.03	24.495	24.735	24.473	24.754	24.649	24.872	60.037	59.98	60.114	60.559	59.655	60.466	60.673	23.155	22.57	32.634
Fe2O3	-	-	-	· -	-	-		-	•	0	0	0	0	0	0	21.299	21.242	21.428	22.119	22.136	23.158	23.459	28.366	20.427	25.173
MgO	0.008	0.027	0	0.017	0.036	0.018	0.03	0.007	0.03	9.142	8.937	9.197	9.122	8.964	9.162	1.588	1.921	1.598	1.622	-	-	-		7.713	+
MnO	0	0	0.033	0.013	0.01	0.009	0	0.025	0.027	0	0.016	0	0	0	0	8.229	8.263	8.242	8.714	8.083	7.896	8.483	10.948	11.437	10.491
TiO2	0	0	0.089	-	-	-	-	•	-	0.09	0.173	0.013	0	0.045	0.038	0	0	0	0	-	0.106	0	-	0	-
Cr203	0	0	0	-	-	-	-	-		0	0.04	0.073	0	0	0	0	0	0.006	0	-	0.045	0.032	-	0.052	-
Na2O	-	-	-	-		-	-	•		-	-	-	-	-	-	0.107	0	0.007	0	-	0.067	0.06	-	0.007	-
CaO	-	-		-		-		-		0	0.027	0.016	0.065	0	0.048	-	-	-	-	-	-	-			-
K2O	-	-	-	-	-	-	-	-		-	-	-	-	-	-	0.027 -	0.059	0.011	0.005	-	0	0	-	0.124	-
NiO	-	-	-	-	-	-	•			-	-	-		-		-	-	-	-	-	-	-		-	-
ZnO	46.542	46.728	46.84	46.723	46.797	46.581	46.431	46.746	46.276	5.91	5.064	5.864	6.168	6.079	6.102		-	-		•	-		-	-	-
																8.064	8.098	7.919	6.555	7.883	5.305	7.156	0.458	1.028	2.387
Totals	101.193	102.079	102.205	101.928	101.959	101.83	101.095	101.836	100.806	99.787	98.551	99.91	100.109	99.119	100.094									•	
Cations																99.437	99.673	99.392	99.646	98.722	98.626	100.175	102.072	100.952	100.753
Si	0	0.003	0.001	0.002	0.003	0.003	0.002	0.003	0.003	0	0	0	0	0	0	ļ									
Al	1.898	1.938	1.936	1.965	1.963	1.967	1.964	1.964	1.963	1.938	1.945	1.939	1.93	1.923	1.925	0.002	0.003	0.002	0	0.027	0	0	2.943	2.895	2.309
Fc	0	0	0	0.001	0.001	0	0.001	0.001	0.001	0.498	0.518	0.497	0.494	0.494	0.493	1.962	1.956	1.964	1.96	1.956	2.006	1.96	2.052	2.5	2.954
Fc3+	0.102	-	-	0	0	0	0	0	0	0.062	0.055	0.061	0.07	0.078	0.075	0.494	0.492	0.497	0.5	0.515	0.55	0.498	1.784	1.763	1.616
Mg	0.004	0.001	0	0.001	0.002	0.001	0.001	0	0.001	0.372	0.369	0.374	0.371	0.37	0.373	0.033	0.04	0.033	0.04		0	0.039	-	0.146	-
Mn	0	0	0.001	0	0	0	0	0.001	0.001	0	0	0	0	0	0	0.34	0.341	0.341	0.356	0.335	0.33	0.346	1.227	1.313	1.2
Ti	0	0	0.002	•	-	•	-	-	-	0	0	0	0	0	0	0	0	0	0	-	0	0	-	0	-
Cr	0	0	0	-	•	-	-	-	•	0	0	0	0	0	0	0	0	0	0	-	0	0	•	0	-
Na	-	•	•	-	•	•	•	•	•	-	-	-	-	•	-	0.002	0	0	0	•	0	0	-	0	-
Ca	-	•	-	-	•	-	•	-	•	0	0	0	0	0	0	•	-	-		-	-		-	-	-
ĸ	-	•	-	-	•	-	•	-	-	-	-	-	-	-	-	0.001	0.002	0	0	-	0	0	-	0	•
Ni	-	-	-	-	-	•	•	-	-	-	-	-	-	-	-	- 1	-	-	-	-	-	-	•	-	•
Zn	1.102	1.028	1.029	1.045	1.047	1.042	1.048	1.047	1.047	0.13	0.113	0.129	0.135	0.136	0.134	- 1	•	-	-	-	-	-	-	•	-
																0.165	0.166	0.162	0.144	0.162	0.12	0.157	0.025	0.058	0.135
Totals	3.106	2.97	2.969	3.014	3.016	3.013	3.016	3.016	3.016	3	3	3	3	3.001	3										
																2.999	3	2.999	3	2.995	3.006	3	8.031	8.675	8.214

	T.3176 A	12Khar I	105090																
	Spinel	Gar.R	Gamet.C	Spinel	Spinel	Grt.R	Spl.adj	Garnet.C	Garnet.R	Spl.adj	Garnet	Spl.in38.6	Grt.C	Grt.Tr	Grt.R	Spl.adj	Spinel	Spinel	Spinel
Mg №	40.1	43.6	36.3	39.9	40.5	43.8	40.2	42.7	43.4	39.7	38.6	39.9	47.1	42.9	43.3	40.1	39.3	39.2	39.4
SiO2	0.139	39.303	29.663	0.634	0.732	29.559	1.601	33.196	37.433	0.385	32.862	0.464	38.851	29.802	31.862	1.018	0.193	0.181	0.169
Al2O3	61.567	23.117	31.038	60.152	60.438	34.619	60.049	27.622	24.449	63.117	27.825	60.628	22.882	31.099	36.31	60.432	60.56	60.496	60.827
FcO Fc2O3	23.305	25.914	28.032	23.089	22.877	24.607	22.365	26.544	26.587	24.577	27.703	23.13	25.351	25.908	24.789	22.255	23.494	23.327	23.357
MgO	8.762	11.264	8.969	8.595	8.736	10.754	8.444	11.09	11.417	9.099	9.76	8.623	12.685	10.912	10.613	8.358	8.552	8.435	8.533
ZnO	6.599	0.531	1.99	6.567	6.468	2.352	6.235	1.164	0.532	7.139	1.394	6.562	0.329	1.497	2.068	6.849	6.653	6.745	6.494
Totals Cations	100.372	100.129	99.692	99.037	99.251	101.891	98.694	99.616	100.418	104.317	99.544	99.407	100.098	99.218	105.642	98.912	99.452	99.184	99.38
Si	0.004	2.979	2.334	0.018	0.02	2.235	0.044	2.573	2.848	0.01	2.566	0.013	2.941	2.328	2,303	0.028	0.005	0.005	0.005
Al	1.981	2.065	2.879	1.962	1.962	3.086	1.949	2.524	2.192	1.961	2.562	1.969	2.045	2.864	3.094	1.965	1.972	1.976	1.979
Fe Fe3+	0.532	1.643	1.845	0.534	0.527	1.556	0.515	1.721	1.692	0.542	1.809	0.533	1.605	1.692	1.499	0.513	0.543	0.54	0.539
Mg	0.356	1.272	1.052	0.354	0.358	1.212	0.346	1.281	1.295	0.357	1.136	0.354	1.431	1.27	1.143	0.344	0.352	0.348	0.351
Zn	0.133	0.03	0.116	0.134	0.132	0.131	0.127	0.067	0.03	0.139	0.08	0.133	0.018	0.086	0.11	0.139	0.136	0.138	0.132
Totals	3.006	7.989	8.226	3.002	2.999	8.22	2.981	8.166	8.057	3.009	8.153	3.002	8.04	8.24	8.149	2.989	3.008	3.007	3.006

	T-3267, B	,14Kbar, 1	100°C										T-3258, B	,7Kbar, 10	150°C										
	Garnet	Garnet.C	Garnet.R	Garnet.C	Garnet.R	Garnet	Spinel	Spinel	Spinel	Spinel	Spinel	Spinel	Spinel	Spinel	Spinel	Spinel	Cordierite	Cordierite	Cordierite	Cordicrite	Cordicrite	Cordicrite	Cordierite		
Mg N°	51.8	61.0	62.2	58.9	60.1	60.9	59.4	58.5	59.5	58.9	58.5	59.4	47.7	49.8	49.0	49.6	91.4	77.3	73.9	71.6	77.3	85.9	74.5		
SiO2	37.581	38.65	38.241	33.81	35277	40.387	0.289	0.393	0.213	0.159	0.816	0.165	0.757	13.849	1.336	2.395	49.762	49.487	49.069	47.683	49.109	50.202	48.622		
A1203	25.217	20.30	21.5/2	30.085	27.174	23.638	62.281	62.087	01.994	61.897	10	62.157	60.613	33.103	01.901	38.923	33.333	52.392	33.221	37.841	33.348	32.184	34.064		
FCO	43.232	18.799	18.034	19.133	18.897	19.34	14.735	13.238	14.765	13.027	14.994	14.742	18.99	13.03	10.03	18.013	2.111	2.221	3.920	5.117	3.409	5.34	3.013		
Fe203	14.000	14 400	17 000	16416	1000	16.01	14.111	10.025	10.121	10.10	11015		0.776	0 ( 06	10.00	0 205	10 560	10.146	0.411	7.744	10 477	11 404	0 1 1 1		
MgO	14.032	16.489	17.2.39	13.413	16.002	10.91	12.111	12.073	12.171	12.12	11.843	12.1	9.720	8.083	10.08	9,303	12.308	10.103	9.411	1.244	10.477	11.404	8.233		
ZnO	0.735	1.17	1.243	2.009	1.337	0.529	9.373	9.090	9.02	9.204	9.18	9.239	8.38	8.901	8.318	8.333	0.521	0.014	0.43	0.014	0.021	0.433	0.437		
T-1-1-	100 817	101 229	102.040	100 453	00 707	100 004	06 060	00 000	09 162	09 407	07 925	09 422	09 466	102 229	100 265	07 771	08 215	08 190	08 057	09 400	00.024	67 565	06 260		
Cotione	100.817	101.008	102.949	100.432	90.101	100.804	90.909	90.909	96.105	90.407	91.033	90.423	96.400	102.220	100.505	91.111	70.313	70.107	70.UJ1	70.477	39.024	97.303	90.309		
Cations C:	3 807	2 804	274	2 516	2658	2 040	0.008	0.011	0.006	0.004	0.022	0.001	0.001	0 351	0.036	0.067	4 099	\$042	5013	4 807	4 071	5 003	5000		
31	2.001	2.004	2.74	2.510	2.038	2.747	1 093	1 079	1 096	1 083	1 064	1 088	1 068	1 647	1 96	1 9/	1065	3015	4.001	4 516	3 070	3 840	A 148		
Ee	1 453	1 14	1 1 1 8	1 101	1 101	1 181	0 333	0.345	0 336	0 342	0 342	0 334	0 437	0 331	0.419	0 393	0177	0.454	0 506	0 433	0.463	0.283	0.433		
Fe3+	1.433	1.14	1.110	1.171	1.171	1.101	0.555	0.343	0.550	0.344	0.342	0.334	0.451	0.331	0.417	0.373	0.117	0.434	0.200	0.435	0.405	0.205	0.433		
Mo	1 562	1 783	1 841	1 709	1 797	1 84	0 4 87	0 486	0 493	0 4 9 1	0482	0 489	0 399	0 328	0.403	0 387	1 877	1 543	1.433	1 093	1 58	1 724	1 267		
7n	0.041	0.063	0.066	011	0.075	0.029	0.191	0.181	0.181	0.185	0.185	0.185	0.17	0.168	0.165	0.176	0.024	0.046	0.032	0.046	0.046	0.033	0.033		
																	,								
Totals	8.084	8.061	8.094	8.165	8.135	8.034	3.001	3.001	3.002	3.005	2.995	3	2.995	2.825	2.983	2.963	11.031	11.000	10.985	10.915	11.039	10.982	10.903		
												•													
	T-3270/72,	B ,12Kba	r, 1050°C		a · .	a · .	a · •	<b>A</b> .	0	0	~	•	163.91	a · .	a · •	o · ·	<b>a</b> .	<b>a</b> .		<b>a</b> . <b>b</b>	<b>a</b>	0.0	<b>a</b> . <b>b</b>	~	•
M- NR	rev.Spi	rev.Spi	rev.Spl	rev.Spi	Spinel	Spinel	Spinel	rev.Grl	rev.Ga	rev.Opx	rev.Opx	rev.Opx	Spinel	Spinel	Spinel	Spinel	Gamel	Garnet	Garnel.C	GameLK	Game	Gamel.C	Gamel.K		Opx 70.5
Mg N	37.4	39.2	20.4 0.790	0.250	J7.7 0.224	1529	39.0	26 196	26 752	11.3	11.3	12.1	J9.2 0.605	0.00	31.9	28.3 0.11	28 720	10.5	28.025	22 600	28 002	27 170	21.0	12.0	10.5
A1203	63 441	62 060	62 071	63 507	63 /07	60.036	61.05	20.100	20.133	16 243	14.00	40.104	61.066	62 864	67 265	62 812	20.2.27	40.020	20.203	33.022	31.042	22 544	20.70	15 500	43.670
F=0	15 808	16 022	15 957	16 553	15 524	15 585	15 / 33	15 264	15 573	1575	15 240	15 875	16 20	16 436	16 762	16 821	16.066	14 817	16 552	15 741	15 263	30 160	17.007	13.309	15 822
MaQ	13,000	13 064	12 573	10.555	13.021	12 301	12 788	16 853	16 872	21 066	21 468	22 071	13 278	13 169	12 031	13 204	20.000	10.660	20.024	10.741	18 287	0.102	13 663	23 171	21 187
7.0	6318	6 4 1 4	619	6236	5.818	5 695	6 046	10.855	3 303	0.739	0.645	0 559	6 191	6715	6 37	6237	1 791	1 061	1 265	1 937	2 854	0.635	3 209	0.698	0.809
110	0.510	0.414	0.17	0.250	5.010	5.075	0.040	5.001	3.303	0.137	0.015	0.337	0.171	0.715	0.21	0.237		1.001	1.200	1.237	2.034	0.072	3.407	0.070	0.007
Totals	100.811	99.239	97.58	99.474	97,189	96.045	97.067	101.08	99.147	101.133	98.142	100.941	98.33	99.466	99.144	99.274	99.586	99.03	98.04	96.548	106.394	101.507	101.712	100.245	98.136
Cations																									
Si	0.054	0.02	0.021	0.01	0.009	0.042	0.023	1.941	2.02	1.658	1.713	1.719	0.016	0.008	0.019	0.003	2.825	2.984	2.927	2.578	2.612	2.85	2.122	1.623	1.623
Al	1.945	1.973	1.978	1.989	1.993	1.963	1.978	3.399	3.262	0.684	0.61	0.566	1.964	1.975	1.964	1.978	1.99	1.952	1.798	2.35	2.589	2.127	3.317	0.663	0.716
Fc	0.346	0.356	0.361	0.368	0.351	0.356	0.35	0.946	0.983	0.47	0.468	0.474	0.366	0.366	0.375	0.376	0.993	0.905	1.039	1.009	0.877	1.934	1.104	0.488	0.489
Mg	0.507	0.517	0.506	0.508	0.525	0.501	0.516	1.862	1.899	1.169	1.174	1.223	0.532	0.523	0.515	0.529	2.273	2.142	2.341	2.199	1.872	1.14	1.501	1.252	1.168
Zn	0.121	0.126	0.124	0.122	0.116	0.115	0.121	0.212	0.184	0.019	0.017	0.015	0.123	0.132	0.126	0.123	0.098	0.057	0.07	0.11	0.145	0.036	0.175	0.019	0.022
Totals	2.973	2.992	2.99	2.997	2.994	2.977	2.988	8.36	8.348	4	3.982	3.997	3.001	3.004	2.999	3.009	8.179	8.04	8.175	8.246	8.095	8.087	8.219	4.045	4.018
	T. 2270/72	B 12Kha	- 10509	continued			NA 01																		
	1-3270772,	D , I & K D U	, 1050 C,	One	0.1	Soinel	Scinat	0	Ga	C-1	Ca	Coinal	Soind	641	6-12	Coinal 2	Sainal 2	C-12	Calmal 2	0 2	0-1	0.11	6-1-14	0-5	0
Mo Nº	713	697	70.3	68.8	697	59.6	59.6	70.8	69.5	66.4	69.2	59.2	58.8	607	707	Spineliz SO 8	50.7	60.0	50.8	711	601	713	58.5	60.6	50.2
SiÔ2	46 67	41 931	44 265	41 202	40 781	0.074	1 024	43 919	39 594	27 367	45 644	3 792	3 733	39 121	41 788	1 569	4 468	34 784	2716	48 200	30 15	42.46	1246	41 12	2 376
A12O3	12.772	17.785	19.782	21.91	20.166	62 686	62 236	18 163	21 819	36 837	20 669	60 835	59.685	26 198	21 347	62 567	60.043	29 545	61 469	15345	24 046	30.73	62 12	23 974	60.84
FeO	16.242	16.298	15.652	15.933	16.297	16.135	15.644	15.202	15.389	15.696	14.303	15.714	15.371	15.146	15.25	15.67	15 693	15455	15 538	15 613	157	11 944	16 226	14 4 52	15471
MgO	22.622	21.037	20.811	19.736	21.035	13.383	12.944	20.753	19.688	17.44	18.012	12.787	12.299	19.573	20.64	13.06	12.808	20.063	12.937	21.543	20.023	16.654	12.852	18.543	12.599
ZnO	0.549	1.21	1.087	1.464	1.158	6.481	6.697	0.819	0.982	3.073	0.604	5.933	5.768	2.39	1.331	6.232	6.224	2.729	6.161	0.746	1.893	0.881	6.224	0.984	5.927
					1																				
Totals	98.855	98.261	101.597	100.245	99.437	<del>9</del> 8.759	98.545	98.856	97.472	100.413	99.232	99.061	96.856	102.428	100.356	99.098	99.236	102.576	98.821	101.456	100.812	102.669	98.668	99.073	97.213
Cations															_			_							
Si	1.711	1.561	1.577	1.499	1.501	0.002	0.027	1.605	2.956	2.036	3.278	0.1	0.101	2.791	3.024	0.042	0.118	2.505	0.072	1.709	2.844	2.916	0.033	2.989	0.064
AL	0.552	0.78	0.831	0.939	0.875	1.981	1.964	0.782	1.921	3.232	1.75	1.891	1.896	2.204	1.821	1.955	1.864	2.508	1.92	0.641	2.059	2.488	1.957	2.054	1.933
re Ma	0.498	0.307	0.400	0.485	0.502	0.362	0.35	0.465	0.961	0.977	0.839	0.346	0.346	0.904	0.923	0.347	0.346	0.931	0.344	0.463	0.954	0.686	0.363	0.879	0.349
nig 7n	1.2.30	1.10/	1.103	1.07	1.134	0.333	0.310	1.15	2.191	1.934	1.928	0.502	0.494	2.081	2.226	0.316	0.303	2.153	0.511	1.138	2.168	1.705	0.512	2.009	0.506
241	0.013	0.003	0.029	0.039	0.031	0.128	0.132	0.022	0.034	0.109	0.032	0.113	0.115	0.126	0.071	0.122	0.121	0.145	0.121	0.02	0.102	0.045	0.123	0.053	0.118
Totals	4.012	4.048	4.008	4.032	4.063	3.008	2.989	4.004	8.083	8.348	7.847	2.954	2.952	8.106	8.065	2.982	2.952	8.242	2.968	3.971	8.127	7.84	2.988	7.984	2.97

	T-3276, A	J2Kbar. 8	50°C																					
	Garnet	Garnet	Garnet.C	Gamet.R	Spinel	Spinel	Spinel	Garnet	Garnet	Garnet	Spinel	Spinel	Spinel	Garnet	Garnet									
Mg N°	2.0	6.5	46.3	44.0	33.6	39.5	36.8	44.2	45.1	42.9	42.7	42.0	41.3	44.1	27.4									
SiÕ2	36.077	35.46	39.487	38.459	1.725	4.658	0.12	39.589	38.92	39.029	0.178	0.961	0.319	38.949	36.422									
A12O3	19.832	21.782	22.936	25.372	59.098	56.178	60.431	22.889	23.987	23.983	61.209	61.049	60.224	23.341	23.733									
FcO	44.68	41.271	25,901	25.88	25.829	17.467	23.847	27.155	25.764	26.3	21.051	21.607	20.983	26.351	34.44									
Fe2O3																								
MgQ	0.517	1.6	12.513	11.394	7.334	6.421	7.783	12.055	11.874	11.075	8.798	8.775	8.266	11.668	7.305									
ZnO	0.329	0.456	0.322	0.383	6.704	13.291	8.135	0.302	0.386	0.269	9.379	8.003	9.781	0.321	0.565									
Totals	101.435	100.569	101.159	101.488	100.69	98.015	100.316	101.99	100.931	100.656	100.615	100.395	99.573	100.63	102.465									
Cations																								
Si	2.973	2.901	2.96	2.872	0.047	0.131	0.003	2.959	2.923	2.942	0.005	0.026	0.009	2.943	2.821									
Al	1.927	2.101	2.027	2.234	1.916	1.857	1.97	2.017	2.124	2.132	1.974	1.959	1.969	2.079	2.167									
Fc	3.08	2.824	1.624	1.616	0.594	0.41	0.551	1.697	1.618	1.658	0.482	0.492	0.487	1.665	2.231									
Fe3+																								
Mg	0.064	0.195	1.398	1.268	0.301	0.268	0.321	1.343	1.329	1.244	0.359	0.356	0.342	1.314	0.843									
Zn	0.02	0.028	0.018	0.021	0.136	0.275	0.166	0.017	0.021	0.015	0.189	0.161	0.2	0.018	0.032									
Totals	8.064	8.049	8.027	8.011	2.994	2.941	3.011	8.033	8.015	7.991	3.009	2.994	3.007	8.019	8.094									
																,								
	T-3277, A	IIKbar, 8	50°C								1	T-3187, A	,11Kbar, 1	050°C										
	Spinel	Spinel	Spinel	Gamet	Garnet	Garnet	Garnet	Gamet	Garnet	Spinel	Spinel	Spinet	Spinel	Spinel	Spinel	Spinel	Spinel							
Mg №	39.9	40.4	41.5	43.5	44.0	34.9	42.0	44.2	41.9	37.7	41.9	40.7	38.4	38.8	40.9	40.9	40.3							
SiO2	1.711	1.945	2.4	39.526	39.316	35.583	38.304	38.325	39.063	0.203	0.715	0.201	0.252	0.701	0.937	0.899	1.003							
A12O3	59.84	60.79	59.441	22.685	22.836	26.59	23.183	24.657	23.011	60.772	60.49	61.756	61.255	61.168	61.269	61.568	61.312							
FcO	22.012	22.369	21.06	27.199	27.08	28.925	27.356	26.536	27.519	24.307	21.519	23.323	24.013	23.826	23.007	23.239	23.195							
Fc2O3																								
MgO	8.193	8.508	8.395	11.735	11.951	8.702	11.129	11.804	11.151	8.236	8.695	8.986	8.413	8.478	8.912	9.034	8.794							
ZnO	7.949	7.506	7.654	0.303	0.276	1.17	0.413	0.662	0.332	6.673	8.08	6.155	6.209	6.116	6.198	6.072	6.307							
<i>~</i> •			00.05				100 005	101 001	101.07/			100.401	100.140	100 000	100 000	100.010								
1 otais	99.705	101.118	98.95	101.448	101.459	100.97	100.385	101.984	101.076	100.191	99.499	100.421	100.142	100.289	100.323	100.812	100.611							
Cations															0.000									
Si	0.047	0.052	0.066	2.971	2.955	2.733	2.921	2.865	2.954	0.006	0.02	0.005	0.007	0.019	0.025	0.024	0.027							
AI	1.936	1.935	1.924	2.01	2.023	2.408	2.084	2.173	2.051	1.9/1	1.963	1.98	1.9/8	1.967	1.961	1.901	1.939							
rc	0.505	0.505	0.484	1.71	1.702	1.828	1.745	1.039	1.74	0.339	0.495	0.331	0.33	0.544	0.522	0.525	0.520							
1-63+	0.000	0.0.10		1015		0.007			1.0/2	0.000	0.052	0.0/1	0.040	0.015			0.055							
Mg	0.335	0.342	0.344	1.313	1.339	0.990	1.203	1.313	1.257	0.338	0.357	0.364	0.343	0.345	0.361	0.364	0.355							
ZA	0.101	0.149	0.133	0.017	0.010	0.000	0.025	0.037	0.019	0.130	0.104	0.124	0.120	0.123	0.124	0.121	0.120							
Totals	2.984	2.981	2.973	8.023	8034	8 061	8 038	8 049	8 021	3.01	2,999	3 004	3,004	2.998	2.993	2.995	2 993							
	2.000					0.001		0		2.01	1													
	T-3201, A	,12Kbar, 9	50°C														16.3.91							
	Spinel	Spinel	Spinel	Spinel	Spinel	Spinel	Garnet	Garnet	Garnet	Garnet	Garnet	Garnet	Garnet	Gamet	Garnet	Garnet	Spinel	Spinel	Spinel	Garnet C	Garnet R	adj.Grt	Gn.C	Grt R
Mg N°	40.3	39.9	40.3	41.8	40.2	40.3	35.7	51.9	46.1	36.9	36.3	44.0	45.0	50.1	33.3	49.8	39.5	39.1	39.0	26.1	29.3	42.2	42.1	46.3
SiO2	0.244	0.864	0.233	0.382	1.733	1.061	35.427	40.423	39.988	36.842	35.917	38.327	40.14	40.347	37.254	40.564	0.146	0.286	0.468	37.537	37.653	27.806	35.003	40.124
A12O3	60.654	60.409	60.706	60.891	60.389	60.521	26.974	23.557	22.914	25.153	25.381	24.156	23.202	23.484	22.738	23.432	59.201	59.839	59.77	21.129	21.385	35.162	28.386	24.1
FeO	19.059	18.767	18.994	18.654	18.345	18.395	27.579	23.266	25.821	28.282	28.814	26.34	26.185	23.912	30.851	23.72	19.624	20.008	19.992	35.187	33.875	24.565	26.325	25.248
MgO	7.215	6.991	7.203	7.509	6.917	6.949	8.58	14.085	12.415	9.265	9.234	11.605	12.006	13.476	8.651	13.188	7.2	7.217	7.183	6.972	7.874	10.085	10.746	12.226
ZnO	12.896	12.561	12.917	13.042	12.791	12.977	1.482	0.357	0.39	1.012	1.189	0.773	0.351	0.257	0.569	0.347	12.826	12.679	12.569	0.499	0.461	4.466	2.664	0.414
Totals	100.068	99 597	100.053	100 478	100 175	99 903	100 042	101 688	101 528	100 554	100 535	101 201	101 884	101 476	100.063	101 251	98 007	100.026	00 087	101 324	101 249	102 084	103 124	102 112
Cations	100.000		100.000	100.710	100.113	22.203	100.042	101.000		100.334	100.001	101.201	101.004	101.970	100.003	101.231	20.331	100.049	11.704	101.344	101.240	102.004	103.124	102.112
Si	0.007	0.024	0.006	0.011	0.048	0.029	2.734	2.972	2.983	2 827	2773	2 888	2.985	2 98	2 906	2 999	0.004	0.008	0.013	2 951	2 942	2 12	2 622	2 062
Al	1.987	1.979	1.988	1.982	1.959	1.976	2.454	2.042	2.015	2 276	2.31	2.146	2.034	2.045	2 091	2.042	1 972	1 97	1 966	1 958	1 971	3 175	2 507	2.903
Fc	0.443	0.436	0.441	0.431	0.422	0.426	1.78	1.431	1.611	1 815	1.86	1 66	1.629	1 477	2 013	1 467	0.464	0 467	0 467	2 314	2 214	1 574	1 640	1 550
Mg	0.299	0.29	0.298	0.309	0 284	0.287	0.987	1.543	1.38	1.06	1.062	1.303	1.331	1 483	1 006	1 453	0 301	0.407	0.700	0.817	0.017	1 151	1.049	1 345
Zn	0.265	0.258	0.265	0.266	0.26	0.265	0.084	0.019	0.021	0.057	0.068	0.043	0.019	0.014	0.033	0.019	0.268	0261	0.259	0.000	0.027	0.253	0 147	0.023
																				0.000	0.041		0.147	0.04.3
Totals	3.001	2.987	2.998	2.999	2.973	2.983	8.039	8.007	8.01	8.035	8.073	8.04	7.998	7.999	8.049	7.98	3.011	3.006	3.004	8.069	8.072	8.283	8.125	7.988

	T-3201, A	,12Kbar, 9	50°C, con	linued										T-3193, A	ISKbar, 1	050 °C									
	GameLC	Garnet.R	Gamet	adi Spl										Spinel	Spinel	Spinel	Spinel	Spinel	Spinel	Spinel	Gamet	Garnet	Gamet	Garnet	Garnet
Mg N°	44.6	40.6	34.5	39.5										40.0	39.9	· 39.9	38.8	39.0	40.8	39.7	42.3	42.1	39.8	41.5	41.9
SiO2	36.847	34.504	34.495	0.146										0.475	0.169	0.379	0.164	0.182	1.181	1.465	39.696	38.394	38.764	39.378	39.479
AI2O3	24.539	28.668	25.783	59.201										60.333	59.902	60.104	59.985	59.914	59.794	59.526	23.225	23.902	23.182	22.806	22.817
FcO	25.168	26.493	30.067	19.624									*	18.156	19.192	19.108	19.69	19.649	17.302	19.087	27.175	27.084	27.596	27.295	27.529
MgO	11.372	10.159	8.901	7.2										6.785	7.142	7.121	6.998	7.055	6.667	7.046	11.195	11.036	10.258	10.879	11.135
ZnO	0.643	2.324	1.879	12.826										14.368	12.724	12.769	12.883	12.675	14.37	12.658	0.582	0.696	0.721	0.511	0.545
Totals Cations	98.569	102.148	101.125	98.997										100.117	99.129	99.481	99.72	99.475	99.314	99.782	101.873	101.112	100.521	100.869	101.505
Si	2.842	2.609	2.681	0.004										0.013	0.005	0.011	0.005	0.005	0.033	0.041	2.972	2.942	2.955	2.981	2.973
Al	2.232	2.555	2.363	1.972										1.982	1.984	1.981	1.981	1.981	1.97	1.949	2.05	2.105	2.083	2.036	2.026
Fc	1.624	1.675	1.955	0.464										0.423	0.451	0.447	0.461	0.461	0.404	0.443	1.701	1.692	1.759	1.728	1.734
Mg	1.307	1.145	1.031	0.303										0.282	0.299	0.297	0.292	0.295	0.278	0.292	1.249	1.228	1.165	1.227	1.25
Zn	0.037	0.13	0.108	0.268										0.296	0.264	0.264	0.266	0.262	0.297	0.26	0.032	0.038	0.041	0.029	0.03
Totals	8.042	8.114	8.138	3.011										2.996	3.003	3	3.005	3.004	2.982	2.985	8.004	8.005	8.003	8.001	8.013
	T-3202, A	J2Kbar, 1	100 °C											ľ	T-3204, B	,12Kbar, 1	100°C								
	Spinel	Spinel	Spinel	Spinel	Spinel	Spinel	Spinel	Spinet	Spinel	Spinel	Spinel	Spinel	Spinel	Sill	Spinel	Spinel	Spinel	Spinel	Spinel	Spinel	Spinel	Sill			

	- printer																					
Mg №	41.3	40.8	41.0	41.5	41.4	40.5	39.9	40.7	40.1	40.1	40.0	40.3	40.0	•	60.8	60.9	60.3	60.6	60.6	60.3	60.9	-
SiÕ2	0.505	0.103	0.546	0.098	0.149	0.357	0.26	0.37	0.591	0.205	0.116	0.265	0.359	40.287	0.366	0.773	0.599	0.627	0.133	0.265	1.211	36.279
Al2O3	62.016	61.982	61.693	61.517	61.72	61.335	60.61	60.702	60.823	60.898	60.965	60.623	60.576	57.13	62.985	62.868	62.477	63.335	62.934	62.211	62.236	62.099
FeO	22.804	22.998	22.82	22.609	22.534	23.564	23.757	23.322	23.173	23.645	23.848	23.539	23.468	1.263	15.452	15.448	15.478	15.579	15.589	15.441	15.218	0.743
Fe2O3																						
MgO	9.005	8.887	8.887	9.001	8.916	9.012	8.847	8.978	8.695	8.893	8.902	8.928	8.759	0.216	13.449	13.525	13.212	13.438	13.47	13.172	13.267	0.188
<b>7</b> n <b>O</b>	6.455	6.245	6.214	6.388	6.256	6.377	6.19	6.178	6.238	5.949	6.063	6.35	6.285	0.297	6.706	6.684	6.738	6.601	6.556	6.739	6.794	0.243
Totals	100.785	100.215	100.16	99.613	99.575	100.645	99.664	99.55	99.52	99.59	99.894	99.705	99.447	99.193	98.958	99.298	98.504	99.58	98.682	97.828	98.726	99.552
Cations																						
Si	0.014	0.003	0.015	0.003	0.004	0.01	0.007	0.01	0.016	0.006	0.003	0.007	0.01		0.01	0.021	0.016	0.017	0.004	0.007	0.032	
Al	1.977	1.99	1.978	1.987	1.991	1.967	1.967	1.967	1.969	1.973	1.973	1.966	1.968		1.98	1.967	1.973	1.976	1.985	1.981	1.957	
Fe	0.516	0.524	0.519	0.518	0.516	0.536	0.547	0.536	0.532	0.544	0.547	0.542	0.541		0.345	0.343	0.347	0.345	0.349	0.349	0.339	
Fc3+																						
Me	0.363	0.361	0.36	0.367	0.364	0.365	0.363	0.368	0.356	0.364	0.364	0.366	0.36		0.534	0.535	0.528	0.53	0.537	0.53	0.527	
Zn	0.129	0.126	0.125	0.129	0.126	0.128	0.126	0.125	0.126	0.121	0.123	0.129	0.128		0.132	0.131	0.133	0.129	0.13	0.134	0.134	
Totale	2 000	3 004	2 007	3.004	3.001	3 006	3.01	3 006	2 000	3.008	3.01	3.01	3 007		3.001	2 007	2 007	2 007	3 005	3 001	2 080	

	T-3303, B	9Kbar, 10	50°C								
	Spinel	Spinel	Spinel	Spinel	Spine1	Spinel	Cordierite	Cordierite (	Cordierite (	Cordierite	Cordierite
Mg N°	55.7	56.7	56.3	55.7	55.8	56.1	84.9	83.7	78.4	83.6	88.6
SiÕ2	0.08	0.377	0.679	0.89	1.112	1.522	51.003	50.544	55.628	50.75	50.843
A12O3	63.865	63.069	63.429	63.375	63.232	63.214	33.641	34.378	30.322	33.503	34.502
FcO	17.415	16.975	17	17.35	17.286	16.918	3.646	4.085	4.483	3.977	2.903
Fe2O3											
MgO	12.262	12.481	12.319	12.216	12.249	12.124	11.564	11.782	9.154	11.389	12.635
ZnO	7.07	7.211	7.05	7.117	6.947	7.059	0.327	0.347	0.281	0.22	0.372
Totals Cations	100.692	100.113	100.477	100.948	100.826	100.837	100.181	101.136	99.868	<del>99</del> .839	101.255
Si	0.002	0.01	0.018	0.023	0.029	0.04	5.044	4.968	5.487	5.041	4.968
Al	1.992	1.977	1.977	1.968	1.963	1.958	3.922	3.984	3.526	3.923	3.974
Fe	0.385	0.378	0.376	0.382	0.381	0.372	0.302	0.336	0.37	0.33	0.237
Fc3+											
Mg	0.484	0.495	0.485	0.48	0.481	0.475	1.704	1.726	1.346	1.686	1.84
Zn	0.138	0.142	0.138	0.138	0.135	0.137	0.024	0.025	0.02	0.016	0.027
Totals	3.001	3.002	2.994	2.991	2.989	2.982	10.996	11.039	10.749	10.996	11.046

	Spinel	Spinel	Spinel	Spinel	Spinel	Spinel	Spinel	Spinel	Garnet	Garnet	Gamet	Gamet	Garnet.C	Garnet.R	Garnet.C	Garnet						
Mg N°	38.7	39.3	39.7	38.9	39.9	39.6	39.9	39.4	40.8	41.7	41.5	40.7	47.8	47.5	41.3	41.7						
SiO2	0.239	0.271	0.181	0.295	0.206	0.219	0.147	0.216	38.733	38.827	38.358	39.014	38.547	37.477	37.341	37.786						
A12O3	58.891	58.953	58.684	58.031	58.799	58.699	58.851	58.355	23.504	22.888	23.206	22.912	23.687	24.656	23.226	23.731			-			
FeO	15.38	15.243	15.266	15.501	15.222	15.219	15.232	15.265	26.902	27.339	27.3	27.625	25.042	24.875	26.908	26.989						
MgO	5.442	5.551	5.63	5.539	5.69	5.606	5.688	5.561	10.392	10.977	10.853	10.627	12.872	12.627	10.647	10.815						
ZnO	19.325	19.108	19.129	18.969	19.447	19.348	19.576	19.216	1.157	0.932	0.72	0.897	0.812	0.757	1.181	1.278						
Totals	99.277	99.126	98.89	98.335	99.364	99.091	99.494	98.613	100.688	100.963	100.437	101.07 <b>5</b>	100.96	100.392	99.303	100.599						
Cations	0.007	0.009	0.005	0.000	0.006	0.006	0.004	0.006	2 044	2 048	2 026	2.06	2 806	2 833	2 801	2 885						
31	1.096	1 097	1.065	1 077	1 0 2 1	1 021	1 000	1 091	2 106	2.340	2.520	2.50	2.000	2 107	2 12	2.005						
АI Г.	1.700	1.707	1.703	1.711	0.264	0.265	0.264	0.269	1 71	1 726	1 242	1 752	1.574	1 572	1 742	1 773						
10	0.308	0.304	0.300	0.373	0.304	0.303	0.304	0.300	1.71	1.750	1.742	1.755	3.374	1.373	1.744	1 221						
Mg	0.232	0.230	0.241	0.239	0.242	0.239	0.242	0.239	1.177	1.242	0.041	1,202	0.045	0.0423	0.068	0.072						
Zn	0.408	0.403	0.405	0.405	0.41	0.409	0.413	0.409	0.005	0.032	0.041	0.05	0.045	0.042	0.000	0.072						
Totals	3.001	2.998	3.002	3.005	3.003	3.002	3.005	3.004	8.002	8.027	8.03	8.015	8.054	8.068	8.049	8.047						
	T-3310, B	,12Kbar, 1	050°C, col	ntinued			20.4.91															
14 NB	Spinel	Spinel	Spinel	Spinel	Spinel	Spinel	Spinel	Spinel	Spinel	Spinel	Spinel	Spinel	Grt	Cor	Cor	Cor	Cor					
SiO2	0.224	0.363	0.429	1.341	1.924	0.638	1.326	0.874	0.602	0.615	0.826	2.079	38.516	0.739	2.637	10.25	0.739					
A12O3	58.449	61.051	59.823	58.005	61.318	58.221	58.695	58.113	58.015	58.173	58.328	58.32	25.123	93.563	80.294	87.766	93.563					
FeO	15.561	13.536	14.969	15.273	14.548	14.934	14.847	15.263	15.462	15.562	16.235	14.541	26.342	1.582	8.779	1.382	1.582					
MgO	5.827	5.08	5.427	5.385	5.16	5.47	5.261	5.52	5.761	5.731	5.531	5.207	10.951	0.578	3.07	0.324	0.578					
ZnO	18.886	16.242	19.473	19.348	19.052	19.478	19.29	19.356	18.881	18.882	18.477	18.911	0.953	1.408	9.472	0.335	1.408					
	98 947	96 272	100.121	99 352	102.002	98 74 1	99 4 19	99 126	98 721	98 963	99 397	99.058	101 885	97 87	104 252	100.057	97.87					
Totale	20.247	20.212	100.121	,, <u>,</u> ,,,,,,	102.002	20.141	////	<i>yy.</i> 120	20.121	10.705	//		1011000	21.01								
Catione																						
Canons Si	0.006	0.01	0.012	0.038	0.053	0.018	0.038	0.025	0.017	6618	0.024	0.059	2 879									
A1	1 077	2 0.01	1 007	1 0/10	1 078	1 072	1 064	1 06	1 065	1 065	1.061	1 0/18	2 214									
E	0.222	0.234	0.354	0.364	0.222	0.250	0.252	0.265	0.371	0.272	0.387	0.245	1 647									
Ma	0.373	0.317	0.334	6.304	0.555	0.337	0.332	0.303	0.377	0.375	0.307	0.243	1.047									
7.	0.149	0 3/4	0.406	0.407	0.385	0.413	0.404	0.400	0.147	0.245	0 380	0.306	0.053									
2-11	0.4	0.344	0.400	0.407	0.565	0.415	0.404	0.405	0.4	0.377	0.505	0.370	0.055									
Totals	3.005	2.958	2.992	2.987	2.959	2.996	2.981	2.994	3	3	2.996	2.968	8.013									
	T 2104 B	1281	06000																			
	1-3190, B	12 KDar, 1	USU L		11.0	110	6-1-1	C	Cala at	C-inst	C	6-1-4	C + D	040	C a D		4: 0	0.0	C C	C + D	0	0
N. NO	n.spuct	n.apinei	n.Oanet	n.Ganci	nopx	n.opx	Spiner	apinei	apinei	aputer	Gamer.C	ວຍເສດງ		OILC	UILA	auj.spinci a	uj.spinci	OILC 6	GILC	UILA	Opt	Opx
Mg N	20.9	37.0	21.2	20.9	10.4	/1.1	0.80	27.3	31.1	31.2	C.10	38.3	00.3	01.4	00.3	38.8	38.3	39.4	20.2	00.9	09.9	11.2
5102	0.109	2.383	32.08	38.913	40.39	43.808	0.302	0.490	0.2	0.494	37.902	2.004	33.833	38.19	28.080	3.077	1.003	29.047	30.131	40.045	41.067	40.733
AIZUS	02.075	02.338	30.334	20.103	13.033	13.891	02.888	62.408	62.231	62.04	25.119	60.771	20./11	25.527	34.538	61.927	01.230	33.09	21.993	23.364	14.369	12.691
reo	10.838	10.31	19.908	18.033	10.014	16.206	10.32	10.318	10.307	10.283	18.368	10.040	18.6/6	17.233	17.867	15.837	15.587	18.546	20.621	19.166	15.739	15.994
MgO	12.51	12.275	14.961	14.983	22.137	22.345	12.677	12.394	12.529	12.199	10.484	12.598	12.932	12.381	15.369	12.649	12.338	15.252	14.842	16.757	20.556	22.217
MnO	0.043	0.015	0.058	0.074	0.043	0.03	-														_	
ZnO	7.708	7.622	1.517	0.707	0.639	0.646	7.249	7.145	7.571	7.445	0.65	6.742	0.886	0.917	2.143	7.122	6.821	2.732	1.304	0.382	0.905	0.829
Totals	99.363	101.145	98.918	99.417	99.458	98.926	99.436	98.761	98.898	98.461	98.583	98.821	98.067	97.848	97.803	100.612	97.667	101.867	100.911	99.914	98.636	98.486
Cations																						
Si	0.005	0.063	2.437	2.874	1.694	1.681	0.008	0.013	0.005	0.013	2.834	0.071	2.706	2.896	2.156	0.08	0.045	2.187	2.676	2.947	1.722	1.72
Al	1.97	1.924	2.716	2.272	0.587	0.601	1.981	1.979	1.978	1.977	2.211	1.911	2.378	2.247	3.108	1.909	1.95	3.104	2.443	2.045	0.62	0.551
Fc	0.38	0.362	1.269	1.151	0.507	0.497	0.365	0.367	0.369	0.368	1.147	0.358	1.179	1.076	1.147	0.345	0.352	1.144	1.276	1.18	0.482	0.492
Mg	0.502	0.479	1.694	1.649	1.205	1.222	0.505	0.497	0.503	0.491	1.834	0.501	1.793	1.711	1.758	0.493	0.497	1.677	1.637	1.838	1.121	1.218
Mn	0.001	0	0.004	0.005	0.001	0.001																
Zn	0.153	0.147	0.085	0.039	0.017	0.018	0.143	0.142	0.151	0.149	0.036	0.133	0.049	0.051	0.121	0.137	0.136	0.149	0.071	0.021	0.024	0.023
Totals	3.011	2.975	8.205	7.99	4.011	4.02	3.002	2.998	3.006	2.998	8.062	2.974	8.105	7.981	8.29	2.964	2.98	8.261	8.103	8.031	3.96 <del>9</del>	4.004

T-3310, A ,20Kbar, 1050℃

256

Opx 69.9 47.067 14.369 15.739 20.556

0.905 98.636

> 1.722 0.62 0.482 1.121

0.024 3.969

	T-3320. C	17Kbar. 1	000 °C																						
	Spinel	Spinel	Spinel	Spinet	Spinel	Pyrone C	Grt R	fn er Grt	Alm C	Grt.R	adi Grt	Grt	Pv C	Grt R	adi Grt	Alm C	Gri R I	Grt R 2	adi Grt	Alm C	Grt R	adi Grt			
Me Nº	44.4	44 0	451	452	451	97.8	62 1	337	156	43.1	25.3	50.4	98.9	40.7	35.0	4.3	32.9	38.8	58.6	4.0	21.8	38.9			
sin	0.428	0155	0.286	0 477	0.971	44 428	40 211	41 351	31 064	40 355	37 673	39.917	44 485	38 616	37.901	35.519	34.866	37.348	40.378	33.294	37.081	39.027			
A1203	58.962	58 476	58 586	59.065	58 298	25 708	35 733	24 266	27.085	22 919	21 923	23 545	25 727	23 233	22 364	19617	25 083	21 911	23.974	22,799	23 213	21 682			
E-O	12 147	12 241	11 896	11 792	11 491	1 246	12 911	27 198	36.075	27 122	34 133	24 164	0 588	27 813	30 323	42 763	29 33	29278	20.021	42 313	33 924	28 978			
1.0	5 444	5 20	5 469	5 4 4 4	5 204	20 519	11 201	7 761	2 7 27	11 500	6 40	12 700	31.005	10.604	0 1 50	1.086	8067	10 14	15 011	0.000	5312	10 365			
MgO	02 200	3.37	2,408	3.444	3.304	30.318	11.091	1.701	3.131	0.727	0.47	13.777	01093	0.074	1.067	0.521	2,006	0.955	0.914	0.791	0.675	0.906			
ZnO	23.369	23.443	23.381	23.41	12.090	0.239	0.360	1.200	2.404	0.737	0.047	0.017	0.178	0.017	1.007	0.551	3.000	0.000	0.014	0.761	0.073	0.000			
Totale	100.20	00 705	00 617	100 248	08.062	102 150	101 333	101 842	100 365	102 642	101.066	102 242	102 003	101 173	100.814	99 516	100 352	00 837	101 098	100 186	100 205	100 858			
Cotiona	100.29	33.703	99.UTT	100.240	70.702	104.137	101.112	101.042	100.505	102.042	101.000	102.242	104.075	101.175	100.014	<i>)).510</i>	100.332	<i>)).012</i>	101.070	100.100	100.205	200.020			
Cations	0.010	0.004	0.000	0.014	0.000	2.046	3 304	2 0.95	2 527	3 004	2056	2.043	2 042	3 031	2 021	2 07	1 727	2 009	2.051	2 768	າດກາ	2 080			
31	0.012	0.004	0.008	0.014	0.028	2.943	2.190	3.083	2.321	2.990	2.930	2.991	2.542	2.731	2.931	1.024	2.737	2.908	2.731	2.700	2.727	2.707			
AI	1.977	1.98	1.98	1.979	1.971	2.009	2.929	2.134	2.397	2.000	2.028	2.043	2,000	2.019	2.039	1.734	2.321	2.011	2.003	2.2.34	2.101	1.750			
re	0.289	0.294	0.285	0.28	0.276	0.069	0.751	1.697	2.454	1.684	2.24	1.489	0.033	1./03	1.901	2.991	1.920	1.907	1.224	2.942	2.24	1.830			
Mg	0.231	0.231	0.234	0.231	0.227	3.015	1.232	0.863	0.453	1.274	0.759	1.515	3.065	1.21	1.056	0.135	0.944	1.211	1.733	0.124	0.625	1.185			
Zn	0.49	0.497	0.495	0.493	0.485	0.013	0.03	0.07	0.144	0.04	0.049	0.044	0.01	0.046	0.061	0.033	0.174	0.049	0.044	0.048	0.039	0.046			
Totals	2.999	3.006	3.002	2.997	2.987	8.051	7.738	7.849	8.175	8.000	8.032	8.034	8.056	8.031	8.048	8.063	8.102	8.086	8.017	8.116	7.992	8.032			
	T-3320, C	,17Kbar, 1	000 °C, co.	münued																					
	Pyrope cer	Gnt edge	Gnt edge	Alm cen	Gnt edge	n gr adj Gr	Gnt	Gnt	Gnt			Sill	Sill	gm Sil											
Mg N°	99.2	52.8	50.6	4.4	41.2	28.2	28.6	27.3	38.2			-	100.0	100.0											
SiÔ2	44.786	40.657	40.708	35.467	37.061	37.749	38.221	38.173	38.621			24.485	25.577	37.168											
A12O3	25.847	23.221	27.642	20.431	26.013	22.434	21.446	21.468	22.463			56.542	56.742	61.762											
FeO	0.476	22.931	23.22	42.615	25.223	32.791	32.467	33,795	28.075			7.695	7.579	0.902											
MeO	31 318	14 42	13 349	1 091	9.907	7 231	7.29	7.126	9.725		-	3.112	3.094	0.089		· .									
7.0	0.229	0.77	1 627	0 533	0.982	1 151	0.708	0.709	1 237			7 047	6.46	0.261											
<b>L</b>	0.227	0.11		0.232	0.202		0	0.102																	
Totals	102.656	101.999	106.546	100.137	99.186	101.356	100.132	101.271	100.121			98.881	99.452	100.182											
Cations																									
Si	2 944	2 982	2 86	2 941	2 834	2 937	3	2 98	2 974			0 727	0.751	1 004											
A1	2.003	2.008	2 280	1 007	2 348	2.058	1 984	1 976	2 039			1 979	1 963	1.968											
E.	0.005	1 407	1 364	2.055	1 615	2.030	2 121	2 206	1 808			1.577		1.500											
PC M	0.020	1.407	1.304	2.933	1.015	2.134	2.151	2.200	1.000		E.2.	0.101	0 196												
Mg	3.009	1.370	1.398	0.133	1.131	0.839	0.833	0.829	1.110		LC24	0.191	0.180	0.02											
Zn	0.011	0.042	0.084	0.033	0.056	· U.000	0.041	0.041	0.07			0.138	0.135	0.004											
<b>~</b> ``		0.015					0 000	0.000	0.007			0.154	0.14	0.005											
Totals	8.053	8.015	7.995	8.061	7.984	8.034	8.009	8.032	8.007			3.188	3.175	3.001											
	T.1170 C	17Khar I	በስብዓሮ ቀሳ	milwuod																					
	C-1540, C	Alm C		Ca D	Sainal	Cardi	Casti	CAC	Durona C	tudo rie	den	edi Sel	Durana C	unde rier	D Alm	Alm C	Ca	C.a	D D.	р <b>р.</b> ,	0	0.04	D Ca	C-	C.
M. NP	01				aputer	UR AUJ	UR.auj		ryrope.C	1was run	101	auj.spi	ryrope.C		R.AIB	Am.C	20.0	Un an a	K.ry	K.ry	UN (7.7	C.UR	K.OR	un	un
MIG IN'	21.9	0.6	43.4	44.0	40.4	30.7	30.8	48.0	79.3	89.1	00.7	43.8	C.00	14.9	50.4	23.3	29.9	1.10	51.0	30.0	67.3	33.9	49.3	29.0	55.2
SiO2	36.155	33.603	38.276	38.007	0.153	39.038	36.797	38.617	44.042	42.407	40.517	0.775	38.438	40.554	38.213	36.515	31.476	37.763	38.235	39.418	40.934	39.645	39.303	39.694	44.022
A12O3	20.707	22.097	22.354	25.281	58.177	24.568	26.808	22.65	25.386	24.356	25.28	57.311	27.987	23.543	22.109	21.219	21.469	27.288	23.813	30.87	26.165	23.165	25.705	25.564	33.565
FeO	36.012	39.065	25.826	24.666	10.96	19.965	19.56	23.954	0.812	5.592	18.372	11.157	15.705	11.916	28.982	35.254	33.752	25.882	22.974	18.973	15.693	20.41	19.618	30.528	16.164
MgO	5.672	1.91	11.131	10.886	5.303	14.647	14.441	12.723	30.458	25.566	15.896	5.289	17.491	20.008	9.317	6.006	8.075	6.547	13.427	13.915	18.083	14.502	10.78	6.995	11.163
ZnO	0.757	1.023	0.858	1.219	24.227	1.351	2.485	0.913	0.242	0.43	0.788	23.359	0.713	0.634	0.763	0.803	0.648	0.629	1.44	1.098	0.795	0.851	2.928	0.694	0.867
Totals	99.303	97.698	98.445	100.059	98 87	99.569	100 091	98,857	100.94	98 351	100.853	97 891	100.334	96.655	99 384	99,797	101.42	98.109	99.889	104 274	101 67	98 573	98 334	103 475	105 781
Cations	00.00		20.110		20.04		.00.071	20.031	100.74	20.331		21.021		20.033	,,		******	Ju.107	,,,,		101.07	20.273			

0.023

1.968

0.272

0.23

0.502

2.995

2.777

2.384

0.949

1.883

0.038

8.031

2.986

2.043

0.734

2.195

0.034

7.992

2.974

2.028

1.886

1.081

0.044

8.013

2.929

2.007

2.365

0.718

0.048

8.067

2.927

1.977

2.204

0.94

0.037

8.085

2.911

2.48

1.669

0.752

0.036

7.848

2.888

2.121

1.451

1.511

0.08

8.051

2.769

2.556

1.115

1.457

0.057

7.954

2.91

2.193 0.933

1.916

0.042

7.994

2.981

2.054

1.284

1.625

0.047

7.991

Si

Al Fe Mg Zn

Totals

2.93

1.979

2.441

0.685

0.045

8.08

2.829

2.193

2.75

0.24

0.064

8.076

2.965

2.042

1.673

1.285

0.049

8.014

2.878

2.257

1.562

1.228

0.068

7.993

0.004

1.986

0.265

0.229

0.518

3.002

2.909

2.158

1.244

1.627

0.074

8.012

2.747

2.36

1.221

1.607

0.137

8.072

2.952

2.042

1.532

1.45

0.052

8.028

2.949

2.004

0.045

3.039

0.012

8.049

2.976

2.015

0.328

2.674

0.022

8.015

2.94

2.163

1.719

0.042

7.979

1.115

2.972

2.291

1.241

1.215

0.163

7.882

2.957

2.245

1.902

0.777

0.038

7.919

2.965

2.665

0.91

1.12

0.043

7.703

Totals	3.004	2.985	2.979	8.066	8.053	8.012	8.037	8.044	8.032	8.027	8.048	8.044	8.05	8.028	8.06	8.04	3.002	3.005	3.001	3.003	8.011	8.026	7.925	2.99	3.004
	T-3335, A+	C ,20Kbai	r, 1200°C,	p:piece N <sup>e</sup>	, continue	ed																			
	Spinel	Spinel	Gn C	Grt R	Grt R	Spinel p4	Spinel	Grt	Sil	Spinel p5	Spinel	Grt C	Gri R	adj Grt	Py C	adj Grt S	pinel p6	Spinel	Spinel	Spinel	Sill	РуСрб	Grt R	adj Alm	Grt R
Mg №	44.1	44.7	47.2	47.1	45.0	42.2	41.6	44.1	33.3	44.9	44.3	55.2	51.1	47.1	72.2	49.6	45.2	45.1	45.0	44.5	28.9	81.2	47.2	45.5	48.4
SiO2	0.551	0.995	38.721	39.391	41.258	0.482	0.442	34.378	39.387	0.14	0.147	39.969	39.422	38.878	41.65	39.428	0.397	0.113	0.329	0.101	36.858	42.229	38.918	37.664	39.592
A12O3	60.333	59.947	22.716	22.809	22.313	60.085	59.209	29.228	59.758	60.13	60.329	23.156	22.923	22.421	23.517	22.844	60.186	60.393	60.083	59.96	61.764	24.051	22.673	24.23	22.632
FcO	17.818	17.601	25.119	25.322	24.44	17.947	18.063	25.142	1.441	17.404	17.538	21.861	23.643	25.24	14.365	24.182	17.544	17.424	17.235	17.432 H	Fe3+ 1.1	9.552	25.448	25.54	24.723
MgO	7.897	8.002	12.594	12.63	11.219	7.352	7.22	11.151	0.399	7.959	7.826	15.132	13.847	12.622	20.913	13.337	8.122	8.037	7.914	7.865	0.328	23.174	12.752	11.96	13.026
ZnO	12.885	12.796	0.922	0.916	0.971	13.577	13.571	3.176	0.276	13.283	13.635	0.776	0.851	0.877	0.67	0.885	13.259	12.838	13.422	13.307	0.29	0.676	0.919	1.396	0.895
Totals Cations	99.484	99.341	100.072	101.068	100.201	99.443	98.505	103.075	101.261	98.916	99.475	100.894	100.686	100.038	101.115	100.676	99.508	98.805	98.983	98.665	100.834	99.682	100.71	100.79	100.868
Si	0.015	0.028	2.94	2.958	3.097	0.013	0.012	2.571	1.056	0.004	0.004	2.955	2.949	2.953	2.965	2.957	0.011	0.003	0.009	0.003	0.994	2.981	2.939	2.853	2.97
Ai	1.976	1.962	2.033	2.019	1.975	1.979	1.974	2.577	1.889	1.985	1.984	2.018	2.022	2.008	1.974	2.02	1.974	1.991	1.981	1.986	1.963	2.001	2.019	2.164	2.002
Fc	0.414	0.409	1.595	1.59	1.534	0.419	0.427	1.573	0.032	0.408	0.409	1.352	1.479	1.603	0.855	1:517	0.408	0.407	0.403	0.41	0.032	0.564	1.607	1.618	1.551
Mg	0.327	0.331	1.425	1.414	1.255	0.306	0.304	1.243	0.016	0.332	0.325	1.667	1.544	1.429	2.219	1.491	0.337	0.335	0.33	0.329	0.013	2.438	1.435	1.35	1.456
Zn	0.264	0.262	0.052	0.051	0.054	0.28	0.283	0.175	0.005	0.275	0.281	0.042	0.047	0.049	0.035	0.049	0.272	0.265	0.277	0.276	0.006	0.035	0.051	0.078	0.05
Totals	2.996	2.992	8.045	8.032	7.915	2.997	3	8.139	2.998	3.004	3.003	8.034	8.041	8,042	8.048	8.034	3.002	3.001	3	3.004	3.008	8.019	8.051	8.063	8.029

	T-3335, A +	C ,20Kba	r, 1200°C, j	p:piece N <sup>a</sup>	•																				
	Spinel pl	Spinel	Spinel p1P	yrope cer	Grt.R	Grt.R	Alm C	Alm R	Alm C	Alm R	adj Grt	Pyrope C	Py R	Py R	Pyrope C	Py R	Sil gm	Spinel p2	Spinel	Spinel	Alm C	Alm R	Alm R S	ipinel p3	Spinel
Mg №	38.8	39.6	39.6	92.8	54.1	43.4	40.4	35.9	30.4	40.0	41.9	98.6	75.5	44.9	73.0	45.5	26.9	42.1	41.3	40.9	44.7	44.8	44.4	43.6	43.6
SiO2	0.168	1.125	1.859	43.85	39.649	39.15	38.672	37.836	37.895	38.748	37.489	44.376	41.388	39.567	42.684	39.52	37.311	0.23	0.308	0.117	39.235	39.122	41.387	0.907	0.132
AI2O3	59.443	59.882	59.315	25.271	23.169	26.17	22.515	22.165	21.896	22.358	24.196	25.606	23.909	22.8	25.45	23.368	60.513	59.781	60.138	59.555	22.888	22.586	23.937	60.555	59.762
FeO	18.795	18.009	18.151	4.027	22.614	26.396	28.169	29.807	32.098	28.164	26.904	0.796	12.616	26.448	14.462	26.463	Fc3+ 1.1	18.144	18.3	18.201	25.859	26.001	25.044	17.635	17.595
MgO	6.683	6.624	6.67	29.042	14.965	11.373	10.699	9.374	7.877	10.535	10.896	30.626	21.839	12.088	21.968	12.39	0.343	7.401	7.213	7.076	11.713	11.839	11.221	7.643	7.646
ZnO	13.9	14.28	14.222	0.306	0.781	0.85	0.869	0.794	0.725	0.702	0.872	0.076	0.529	0.784	0.617	0.749	0.241	13.938	13.813	13.706	0.826	1.023	0.84	13.448	13.423
Totals	98.989	99.92	100.217	102.496	101.178	103.939	100.924	99.976	100.491	100.507	100.357	101.48	100.281	101.687	105.181	102.49	100.289	99.494	99.772	98.655	100.521	100.571	102.429	100.188	98.558
Si	0.005	0.031	0.052	2 935	2 936	2.861	2 95	2 942	2.96	2.965	2 863	2.952	2 947	2 964	2.916	2.936	1.011	0.006	0.009	0.003	2.968	2.965	3.04	0.025	0.004
Al	1.982	1.966	1.939	1.994	2.023	2.254	2.025	2.032	2.016	2.017	2.178	2.008	2.007	2.014	2.05	2.047	1.934	1.976	1.98	1.986	2.041	2.018	2.073	1.97	1,985
Fe	0.445	0.419	0.421	0.225	1.4	1.613	1.797	1.938	2.097	1.803	1.718	0.044	0.751	1.657	0.826	1.644	0.038	0.425	0.427	0.43	1.636	1.649	1.538	0.407	0.415
Mg	0.282	0.275	0.276	2.897	1.651	1.238	1.216	1.086	0.917	1.202	1.24	3.036	2.317	1.35	2.237	1.372	0.014	0.309	0.3	0.298	1.32	1.337	1.228	0.314	0.321
Zn	0.29	0.294	0.291	0.015	0.043	0.046	0.049	0.046	0.042	0.04	0.049	0.004	0.028	0.043	0.031	0.041	0.005	0.289	0.285	0.286	0.046	0.057	0.046	0.274	0.279
Totals	3.004	2.985	2.979	8.066	8.053	8.012	8.037	8.044	8.032	8.027	8.048	8.044	8.05	8.028	8.06	8.04	3.002	3.005	3.001	3.003	8.011	8.026	7.925	2.99	3.004

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	T-3320, C	17Kbar, 10	00°C, coi	rtinued
	fn Gr sep Gn	Gr sep Gn	Gr sep Ga	Gr sep Gnt
Mg №	42.6	39.0	38.8	31.1
SiÕ2	40.7	38.765	38.143	38.616
AI2O3	23.92	21.211	25.147	21.969
FeO	23.706	27.67	26.025	31.996
MgO	9.862	9.945	9.264	8.106
ZnO	0.737	0.795	0.965	0.735
Totals	98.925	98.386	99.544	101.422
Cations				
Si	3.076	3.029	2.915	2.981
A)	2.131	1.954	2.265	1.999
Fe	1.498	1.808	1.663	2.065
Mg	1.111	1.158	1.055	0.932
Zn	0.041	0.046	0.054	0.042
Totals	7.857	7.995	7.952	8.019

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	T-3337 A	20Kbar 8	50%																						
	Spinel	Spinel	Spinel	Spinet	Spinel	Spinel	Spinel	Spinel	Spinel	Spinel	Spinel	Snipel	Soine)	Spinel	Spinel	Spinel	Spinel	Spinet	Spinel	Spinel	Spinel	Spinel	Soinel	Spinel	Spinel
Ma NP	44.1	18.6	J4 5	173	15 8	187	18.8	18.6	13 0	103	46.6	46 1	48 4	47.0	467	46.8	48.0	46.8	45 4	45.8	42.0	467	43 3	43.2	46.2
NIGIN	44.1	40.0	9.4.5	47.3	43.6	40.7	40.0	40.0	43.5	47.3	40.0	5176	40.4 6 41 5	47.0	1 222	1643	2 424	2 459	2 260	3 193	1 602	0.002	0.000	1 40	1717
5102	0.374	1.893	2.104	2.223	2.115	3.123	3.88	4.039	4.1	4.110	4.024	5.170	3.413	0.52	1.344	1.042	2.424	3.430	2.209	2.102	2.093	0.993	0.862	1.47	1.717
A12O3	58.264	59.311	58.558	57.515	59.6	57.028	55.835	55.771	58.174	56.618	61.954	55.32	54.704	59.491	57.021	57.548	58.243	56.002	59.443	37.338	36.769	59.838	39.366	38.987	58.364
FcO	14.815	12.469	13.694	12.441	13.469	11.735	11.593	11.13	13.503	12.173	12.033	12.268	13.267	12.993	10.521	10.513	10.458	10.35	12.213	11.998	12.684	14.383	14.103	14.366	12.19
MgO	6.574	6.605	6.18	6.26	6.379	6.245	6.202	5.907	5.937	6.643	5.913	5.906	6.997	6.477	5.161	5.2	5.431	5.128	5.712	5.703	5.149	7.077	6.042	6.124	5.871
ZnO	17.577	19 632	18.358	18.619	18.505	19.609	18.499	19.81	17.361	17.76	17.208	18.14	18.322	20.26	23.431	23,757	23.09	23.064	21.125	20.971	20.901	17.727	19.537	19.305	20.964
Totale	97 604	99.91	98 894	97.058	100 728	97 747	96 009	96 677	99.075	97 312	101 732	96.81	98 705	99 741	97 4 56	98.66	99 646	98.002	100 762	98 212	98 1 96	100.018	100.13	100 272	99 106
Cotione	71.004		70.074	11.030	100.120	20.042	70.007	20.011	<i></i>	J1.312	101.132	20.01	20.105	22.144	21.100	20.00	,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,	,			20.120			100.212	,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,
Calibits	0.011	0.062	0.050	0.064	0.076	0.000	0.112	0.116	0114	0.116	0 122	0.147	0 157	0.015	0.020	0.047	0.069	0.000	0.062	0.062	0.077	0.028	0.025	0.042	0.040
21	0.011	0.033	0.039	0.004	0.076	0.069	0.112	0.110	0.114	0.110	0.125	0.147	0.152	0.013	0.039	0.047	1.000	1.007	0.005	0.002	0.077	1.0/7	0.023	1.042	0.049
AI	1.977	1.95	1.945	1.942	1.933	1.911	1.893	1.880	1.905	1.880	1.943	1.855	1.809	1.98	1.939	1.95	1.938	1.890	1.947	1.933	1.919	1.907	1.974	1.949	1.931
Fe	0.357	0.291	0.323	0.298	0.31	0.279	0.279	0.267	0.314	0.288	0.268	0.292	0.311	0.307	0.256	0.253	0.247	0249	0.284	0.287	0.304	0.335	0.331	0.337	0.289
Mg	0.282	0.275	0.259	0.267	0.262	0.265	0.266	0.252	0.246	0.28	0.234	0.25	0.292	0.272	0.224	0.223	0.228	0219	0.236	0.243	0.22	0.294	0.253	0.256	0.248
Zn	0.374	0.404	0.382	0.394	0.376	0.412	0.393	0.419	0.356	0.371	0.338	0.381	0.379	0.422	0.504	0.504	0.481	0.489	0.433	0.443	0.443	0.365	0.405	0.4	0.439
Totals	3.001	2.973	2.968	2.965	2.957	2.956	2.943	2.94	2.935	2.941	2.906	2.925	2.943	2.996	2.982	2.977	2.962	2.952	2.963	2.97	2.963	2.989	2.988	2.984	2.976
	T-3337, A	20Kbar, 8	50°C, con	anued																					
	Garnet	Garnet.C	Garnet R	Gamet	Garnet g	m.Garnet	Garnet	Grt.adj	Garnet	Garnet	gm.Grt	gm.Grt	GriR	m.Garnet	Garnet	Gamet	Garnet	Gamet	Garnet	Garnet S	Sillimanite	Qtz	Quz		
Mg Nº	37.5	9.2	45.1	39.1	· 39.8	40.2	35.3	43.4	38.5	43.1	24.8	36.3	39.2	38.3	38.2	28.4	36.4	39.8	33.4	37.8	7.1	-	-		
SiO2	33 136	35 754	38 642	31.053	32 914	40 133	34 114	38 436	34 434	38 479	34 774	28 402	35.418	36.409	38.554	35.623	34.273	31.786	36.483	35.436	36.622	78.505	85.23		
A1203	30.15	21.063	25 882	32 639	32 713	28.77	31 526	24.82	27 178	24 254	24 582	38 496	35 552	30 716	25.485	24 933	32,883	37,288	25.547	25,793	63.055	6.894	4.843		
FeO	27 235	40.500	24 842	25 083	24 732	31.035	24 493	26 47	27 425	26 311	33 753	22 195	18.455	25 483	28.033	32 268	26 268	23 148	29 443	28 137	Fe3+ 15	1 848	0.814		
Man	0153	2 305	11 446	0 3 4 6	0192	11 735	7 506	11 307	0.64	11 175	6263	7 114	6 682	8 805	0 716	7 196	8 4 53	8 605	8 271	0 503	0.046	0 543	0.241		
7-0	9.133	2.303	0.606	3.340	2 2 2 1	0.50	2.000	0.44	2 569	0.447	0101	2 562	3 607	1 410	0.364	1.1.70	0.455	2 2 4 1	1 142	1 515	0.040	2 564	0.591		
Znu	4.044	0.322	0.390	1.8/9	3.321	0.59	2.032	0.44	2.300	0.447	0.08	3.304	2.007	1.419	0.304	1.30	0.34	3.341	1.142	1.313	0.247	2.004	0.301		
Totate	103 319	100 152	101 408	100.0	102 862	112 262	00 671	101 563	101 245	100 666	100.052	00 760	08 714	102 022	102 152	101 38	102 217	104 168	100 886	100 474	101 278	00 354	01 700		
Cotions	103.718	100.133	101.404	100.9	102.002	112.203	39.071	101.303	101.245	100.000	100.032	33.703	20.714	102.922	102.132	101.30	102.217	104.100	100.000	100.474	101.276	50.334	71.109		
Cations				0.005	a							0.000		<b>a</b> (a)	0.000	0.000	0.646			0.00/	0.000				
Si	2.501	2.93	2.874	2.375	2.461	2.752	2.605	2.8/9	2.647	2.907	2.762	2.175	2.639	2.084	2.885	2.115	2.346	2.324	2 808	2.730	0.982				
AI	2.683	2.035	2.27	2.943	2.884	2.325	2.838	2.192	2.463	2.16	2.302	3.476	3.124	2.67	2.248	2.29	2.88	3.213	2.318	2.348	1.993				
Fc	1.719	2.776	1.545	1.662	1.546	1.78	1.564	1.658	1.763	1.662	2.242	1.422	1.15	1.571	1.754	2.102	1.632	1.415	1.895	1.817	0.026				
Mg	1.03	0.281	1.269	1.065	1.023	1.199	0.854	1.272	1.104	1.258	0.741	0.812	0.742	0.977	1.084	0.835	0.936	0.937	0.949	1.104	0.002				
Zn	0.225	0.032	0.033	0.106	0.183	0.03	0.115	0.024	0.146	0.025	0.04	0.201	0.143	0.077	0.02	0.078	0.019	0.18	0.065	0.086	0.005				
Totals	8.158	8.054	7.991	8.151	8.097	8.086	7.976	8.025	8.123	8.012	8.087	8.086	7.798	7.979	7.991	8.08	8.013	8.069	8.035	8.091	3.008				
	T-3422, C	30Kbar, 1	150°C																						
	Garnet	Garnet	Garnet	Garnet	Gamet	Gamet	Garnet	Gamet	Garnet	Garnet	Garnet	Gamet	Garnet	Garnet	Garnet	Garnet	Gamet	Garnet S	Sillimanite						
Me Nº	44.6	45 5	45 4	44 2	41 6	44 8	447	42.6	450	450	46.0	45 1	44.0	277	455	53 1	61 9	452	31 0						
sing	27 924	20 401	29 211	28 211	29 261	20.269	20 212	20 103	20.052	29 104	20 10	20 773	28 105	28.155	20 200	20.205	20.942	40 574	20.00						
102	31.024	37.401	30.311	30.311	20.201	39.208	38.312	30.173	39.033	30.460	30.49	30.772	30.103	30.233	30.369	39.203	37.843	40.324	38.983						
AIZUS	22.130	11.813	22.103	21.992	21.02	23.231	21.835	21.943	24.345	23.301	22.789	24.528	23.116	22.958	22.36	23.273	23.388	20./54	60.058						
FCU	24.521	23.7	24.6	25.04	26.029	24.92	24.624	26.053	23.894	24.182	24.387	24.367	24.419	23.503	24.699	21.361	18.167	21.638	0.874						
MgO	11.061	11.118	11.466	11.169	10.395	11.367	11.17	10.85	10.967	11.496	11.685	11.234	10.787	12.024	11.544	13.572	16.475	10.046	0.217						
ZnO	3.182	3.041	2.996	2.936	2.914	2.907	2.902	2.896	2.878	2.854	2.844	2.813	2.804	2.799	2.756	2.75	2.63	2.619	0.252						
Totals	99.344	100.083	100.076	99.448	99.219	101.699	98.843	99.935	101.137	100.379	100.195	101.514	99.231	99.539	99.948	100.161	100.503	101.581	100.384						

2.912

2.154

1.531

1.258

0.156

8.011

2.938

2.101

1.574

1.239

0.16

8.012

2.929

2.072

1.505

1.372

0.158

8.036

2.942

2.038

1.583

1.319

0.156

8.038

2.946

2.062

1.342

1.52

0.153

8.023

2.938

2.033

1.811

0.143

8.045

1.12

2.977

2.317

1.329

0.142

7.865

1.1

1.051

1.909

0.009

0.005

2.994

0.02

Cations Si

Al Fe

Mg

Zn

Totais

2.924

2.074

1.585

1.274

0.182

8.039

2.996

2.046

1.507

1.26

0.171

2.935

2.05

1.576

1.309

0.169

7.98 8.039

2.961

2.004

1.618

1.286

0.168

8.037

2.978

1.984

1.694

1.206

0.167

8.029

2.953

2.06

1.567

1.274

0.161

8.015

2.973

1.998

1.598

1.292

0.166

8.027

2.951

1.999

1.684

1.25

0.165

8.049

2.936

2.158

1.502

1.229

7.985

0.16

2.928

2.095

1.538

1.303

0.16

8.024

2.938

2.051

1.557

1.329

0.16

8.035

	T-3442, C	25Kbar, 11	150°C																					
	Spinel	adj Grt	Spl	adj Spl	adj Grt	Spl in Grt	Grt	Spinel	Spinel	Spinel	Spinel	Spinel	Adj Grt	GnC	Spinel	Spinel	Spinel	Grt	adj Spinel	Spinel	Grt	adj Spl	adj Spl Si	llimanite
Mg N°	45.1	46.4	46.0	47.2	47.2	45.3	43.0	44.6	44.8	45.5	45.8	46.2	46.7	44.6	43.4	44.5	44.5	43.3	45.4	44.8	46.4	44.4	45.6	28.6
SiO2	0.115	38.689	3.579	2.382	38.962	0.209	38.461	0.249	0.139	0.144	0.227	2.813	30.525	38.092	5.517	0.228	0.364	37.92	0.225	1.206	39.148	0.789	0.492	39.39
A12O3	57.166	22.118	56.404	57.705	22.761	57.587	22.226	57.92	57.473	56.912	57.467	59.511	28.626	22.885	60.238	57.515	57.431	21.965	56.67	55.587	23.353	57.549	57.727	57.86
FeO	8.633	23.806	8.186	8.42	23.149	8.602	25.373	8.674	8.602	8.536	8.478	8.802	19.925	24.954	7.983	8.857	8.573	24.929	8.328	8.821	23.68	8.568	8.587	1.32
MgO	3.987	11.544	3.92	4.232	11.595	4.01	10.746	3.941	3.93	3.979	4.016	4.222	9.796	11.255	3.438	3.992	3.859	10.703	3.871	4.023	11.516	3.836	4.052	0.289
ZnO	28.772	2.268	27.365	27.499	2.31	28.541	2.515	28.444	28.267	28.495	28.628	27.714	7.654	2.624	27.225	28.669	28.414	2.597	28.384	28.1	2.506	28.584	28.689	0.621
Totals	98.673	98.425	99.454	100.238	98.777	98.949	99.321	99.228	98.411	98.066	98.816	103.062	96.526	99.81	104.401	99.261	98.641	98.114	97.478	97.737	100.203	99.326	99.547	99.48
Cations																								
Si	0.003	2.99	0.102	0.068	2.987	0.006	2.972	0.007	0.004	0.004	0.007	0.078	2.465	2.926	0.148	0.007	0.011	2.966	0.007	0.036	2.966	0.023	0.014	1.076
Al	1.986	2.015	1.903	1.937	2.057	1.989	2.024	1.993	1.995	1.987	1.988	1.936	2.726	2.072	1.901	1.984	1.989	2.026	1.989	1.944	2.086	1.976	1.98	1.863
Fe	0.213	1.539	0.196	0.201	1.484	0.211	1.639	0.212	0.212	0.211	0.208	0.203	1.346	1.603	0.179	0.217	0.211	1.631	0.207	0.219	1.5	0.209	0.209	0.03
Mg	0.175	1.33	0.167	0.18	1.325	0.175	1.237	0.171	0.172	0.176	0.176	0.174	1.179	1.288	0.137	0.174	0.169	1.248	0.172	0.178	1.3	0.167	0.175	0.012
Zn	0.626	0.129	0.578	0.578	0.131	0.618	0.143	0.613	0.615	0.623	0.62	0.565	0.456	0.149	0.538	0.619	0.616	0.15	0.624	0.616	0.14	0.615	0.616	0.013
Totals	3.003	8.003	2.946	2.964	7.984	2.999	8.015	2.996	2.998	3.001	2.999	2.956	8.172	8.038	2.903	3.001	2.996	8.021	2.999	2.993	7.992	2.99	2.994	2.994

.

#### APPENDIX FOUR

## Prince Charles Mountains microprobe data

#### Western region

Mt Dovers, D90/1 D90/2 Mt Dovens, Mt Dovers, D90/3 D90/5 Mt Doven, Mt Dovens, D90/6 Mt Béchervaise, MB90/2 MB90/4 Mt Béchervaise, Mt Béchervaise, MB90/5 Mt Béchervaise, MB90/7 Mt Béchervaise, MB90/8 Mt Béchervaise, MB90/9 Mt Béchervaise, MB90/11 Hunt Nunataka, 1190/1 Gorman Crags, GOR90/1 GOR90/5 Gorman Crags, GOR90/12 Gorman Crags, Gorman Crags, GOR90/14 GOR90/17 Gomman Crags, Gorman Crags, GOR90/21 Gorman Crags, GOR90/23 Gorman Crags West, GW90/3 Gorman Crags West, GW90/4 Wall Peak, W90/2 Wall Peak, W90/3 Wall Peak, W90/5 Lensink Peak, \$90/2 Lensink Peak, 590/5 Lensink Peak, \$90/7 Simon Ridge, SIMON90/1

Nomenclature

Minerals are abbreviated using either the abbreviations listed at the beginning of the thesis, or shortened mineral names.

C: denotes a core analysis

R: denotes a rim analysis

Tr: denotes a traverse though a mineral, usually from core to rim

adj: denotes a mineral analysis adjacent to the previous analysis (unless specified)

symp: denotes a mineral in symplectitic reaction growth incl: denotes an included mineral, usually within the adjacent mineral analysis

r#: denotes the ring number on the thin-section, for reference

#: denotes the analysis number for reference.

	Mt Dover	s, D90/1	20.7.9]																				13.7.91						
	Grt.C.r10	Grt.r10	Grtr10	Grt.r10	Grt.R	GrtR	Phladj.r10	Crd.r10	Kfs.r10	Grt.r5	Crd.r5	Crd.r5	altCrd.r5	altCrd.R5	Grt.C.r8	Grt	Grt	Grt	Grt.R	Phi.adj	PLadj	PLaway	Spl1/2.r6	Spl1/2.16	Spl3_7	Sp13.17	Sp13.r8	Spl3.r9	Sp13.r9
Mg N°	27.0	27.3	26.8	26.2	24.7	22.1	68.2	56.8	-	21.5	72.1	72.2	57.0	56.9	29.1	29.4	28.8	28.5	27.5	72.2	0.0	0.0	27.0	25.4	29.2	28.6	31.3	29.5	28.4
5102	37.05	31.22	37.30	37.20	37.12	36.91	36.66	39.65	63.34	36.63	48.69	48.24	38.83	38.55	37.09	37.40	37.26	37.34	37.05	37.53	61.22	61.17	0.02	0.02	0.01	0.05	0.00	0.00	0.00
AI203	21.57	21.60	21.62	21.42	21.87	22.12	15.57	33.26	18.49	21.22	32.97	32.39	34.06	34.81	21.73	21.69	21.71	21.56	21.70	15.51	23.73	23.26	57.38	56.02	59.10	59.07	58.59	59.01	58.85
reu	32.58	32.56	32.61	32.78	33.36	33.83	12.73	7.09	0.00	33.98	6.54	6.61	5.95	5.31	31.86	31.41	31.60	31.32	31.50	11.39	0.15	0.04	22.77	23.46	21.09	21.47	18.77	24.86	24.95
Fe203			-								•	-	•	-	•	-	-	-	-	-	-	•	0.75	1.24	0.91	0.62	0.54	1.18	1.11
MgO	0.70	0.81	6.69	6.51	6.15	5.39	15.28	5.23	0.01	5.22	9.48	9.61	4.43	3.94	7.35	7.34	7.16	7.01	6.71	16.59	0.00	0.00	4.85	4.69	5.08	4.94	4.93	6.08	5.78
MnO	1.04	0.86	0.93	0.97	0.99	1.07	0.00	0.00	0.00	1.05	0.04	0.03	0.03	0.00	0.87	0.87	0.80	0.81	1.01	0.00	0.00	0.00	0.02	0.00	0.07	0.06	0.01	0.04	0.07
6.202	0.02	0.00	0.04	0.05	0.03	0.05	3.09	0.07	0.00	0.00	0.01	0.01	0.00	0.00	0.02	0.02	0.03	0.02	0.03	3.29	0.01	0.00	0.01	0.04	0.02	0.01	0.13	0.31	0.08
C1203	0.03	0.04	0.07	0.03	0.01	0.00	0.10	0.03	0.00	0.09	0.00	0.02	0.00	0.00	0.01	0.04	0.12	0.06	0.05	0.07	0.00	0.04	1.66	3.24	0.34	0.35	0.46	0.68	0.56
Na20	0.00	0.01	0.00	0.02	0.01	0.00	0.08	0.20	1.34	0.00	0.10	0.09	0.13	0.12	0.00	0.00	0.02	0.00	0.00	0.10	8.27	8.70	-	-	-	-		•	-
C30	0.82	0.88	0.89	0.85	0.84	0.85	0.07	0.64	0.05	0.80	0.00	0.02	1.02	1.03	0.84	0.85	0.87	0.88	0.76	0.00	5.35	4.78	-	•	-	-	-	-	
N:0	0.00	0.00	0.00	0.01	0.00	0.01	8.79	0.21	13.52	0.00	0.00	0.00	0.21	0.27	0.00	0.01	0.00	0.00	0.00	8.94	0.12	0.07	-	-	-	-	•	-	-
760	0.00	0.02	0.00	0.05	0.04	0.04	0.31	0.03	0.00	0.00	0.03	0.07	0.00	0.09	0.00	0.01	0.00	0.05	0.01	0.18	0.06	0.00	0.46	0.46	0.45	0.45	0.25	0.54	0.52
Talala	0.00	0.00	100.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	11.06	10.67	13.17	12.99	16.06	7.64	7.49
10(3)\$	99.81	99.19	100.15	99.87	100.44	100.28	92.68	80.41	90.75	99.00	97.85	97.10	84.66	84.12	99.75	99.64	99.56	99.05	98.82	93.61	98.91	98.06	98.99	99.83	100.24	99.99	99.74	100.34	99.40
	Mt Dovers	, D90/1	13.7.91		26.10.91									Mt Dovers	D90/2	14.5.91		17.7.91							14.5.91		14.5.91		
	Sp13.19	Spl3 19	Sp13_r10	011.Elq2	PLrI	P1.1	PLI	Kfs.rl	Grt.R.r1	Grt.rl	Grt.rl	Grtri		Grt.C	Grt	GnR	Kfs	81.Elq2	81.6Iq2	Sp13.r8	81.8Iq2	Spl3.r8	Spi3.18	Spl3.r8	Crdr11	Grt	Griladj	Grt	Ord_incl
Mg N°	27.2	25.7	30.1	28.4	71.4	•	33.3	-	19.9	26.8	26.6	23.7		26.7	26.6	20.8	-	23.6	23.8	24.0	23.5	24.9	24.1	24.1	76.2	27.1	27.1	27.3	75.4
SiO2	0.03	0.02	0.02	0.00	60.71	61.22	61.20	63.23	36.88	37.33	36.93	37.15		38.49	37.87	37.71	64.36	0.06	0.04	0.00	0.01	0.01	0.01	0.04	48,38	37.74	37.65	38.02	49.01
A12O3	59.43	59.21	58.73	58.99	24.12	23.90	23.67	18.55	21.49	21.70	21.82	21.70		21.35	21.32	20.78	19.14	57.81	57.59	57.79	57.78	57.37	57.54	56.94	33.77	21.86	21.92	22.01	33.40
FeO	25.84	26.35	21.86	22.71	0.11	0.00	0.05	0.00	33.97	32.00	31.98	33.20		32.44	32.80	33.41	0.01	27.08	26.93	26.84	27.04	25.86	26.73	26.10	5.60	32.02	32.28	32.33	5.83
Fe203	1.49	1.50	1.28	0.85			-	-	-								-	0.87	1.23	1.09	0.99	1.12	0.93	0.87	-			•	•
MgU	2.71	3.37	3.33	5.25	0.10	0.00	0.01	0.00	4.72	0.38	0.50	5.79		0.01	0.07	4.93	0.00	4.83	4.92	4.93	4.83	5.00	4.91	4.79	10.05	6.69	6.74	6.81	10.01
Tion	0.07	0.08	0.03	0.04	0.03	0.00	0.00	0.00	1.14	0.78	1.04	0.91		0.63	0.69	0.72	0.00	0.04	0.02	0.01	0.02	0.01	0.02	0.02	0.00	0.61	0.57	0.57	0.06
C-102	0.05	0.04	0.09	0.17	0.01	0.00	0.00	0.01	0.01	0.00	0.04	0.02		0.04	0.30	0.00	0.00	0.07	0.06	0.07	0.05	0.08	0.07	0.34	0.00	0.00	0.00	0.01	0.00
Na20	0.00	0.20	0.72	0.55	7.97	7.09	9.37	0.00	0.04	0.04	0.02	0.00		0.01	0.04	0.00	10.03	0.03	0.00	0.04	0.00	0.73	0.00	0.84	0.00	0.00	0.04	0.00	0.00
C10			-		5 10	\$ 20	0.37	0.01	0.00	0.02	0.00	0.00		0.01	0.01	1.05	2.01	•	-	•	•	-	•	•	0.09	0.03	0.02	0.00	0.09
K10			-		0.25	0.17	4.60	14.05	0.01	0.00	0.09	0.70		0.92	0.67	0.11	0.25	•	-	•	•	-	•	•	0.13	0.90	0.80	0.92	0.02
NiO	0.17	0.54	0.60	0.55	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.05		0.00	0.00	0.04	0.00	0.28	0.20	0.20	0.17	0.35	0.27	0.24	0.01	0.02	0.00	0.01	0.01
7.0	7.26	6 03	11 51	11 27	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05		0.00	0.00	0.01	0.07	6 17	632	6 10	6 20	7 17	6.27	7 5 7	0.02	0.00	0.00	0.05	0.03
Totals	100.85	100 30	100 38	100.40	11.80	08 57	98.25	08 10	00.00	00 35	00.74	00 67		100 50	100.62	08.00	0876	08 13	0814	08 16	07.08	07.68	07.45	07.80	08.04	00.94	100.07	100.72	08.44
						,	,		,,,	,,	,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,	,,,,,,,		100.50	100.02	/0./0	20.10	/0.15	20.14	20.10		11.00	71.45	77.00	70.04	<i></i>	100.07	100.72	<b>JO.44</b>
	MiDow	re 1000/2	14501	76 10 01												Mt Dove	~ D0//3	2011.01										Mt Dove	re D00/5
	Ordinel	Crdinci	Gri R rý	Grt C	Grt Grt	Grt R G	m Ord adi 19	GriR Gri	Crd ad r9	Grt adi	GriC Gri	Phi 2	Phi r?	Phi r9		Gri R	Ph1 adi	Pladi	Gri 6	PhI adi	Get 9	Ph1 adi	Grt 15	Phi adi	Pl adi	Get R		Gri Cr2	GetTrl
Mo No	76.0	773	1011101	207	21.8	180	73.0	196	75.0	211	22 2	650	877	613		22.2	78.5	113	25.0	77 1	27.0	781	221	736	0.0	27.0		30.1	30.3
รเกิง	10.07	48 87	37 27	37.43	36.11	36.34	47.96	36.56	48 10	36.25	36.62	36.75	39.78	3615		38.20	39 57	59.11	38.20	38 57	3811	38 78	37 30	38 58	50 77	38.34		38.15	38.12
APOT	3363	33 58	21.83	21.94	21.60	21.27	32.60	21.32	33.25	21.26	21.10	11 76	14.80	11 50		21.11	14.64	24.79	21.24	14.14	21.21	14 65	20.78	1117	24 33	21.10		21.41	21.30
FeO	5.70	5.87	30.62	30.65	33.23	33.96	6.13	33.87	5.92	32.83	32.96	13.76	8.23	13.48		32.84	9.25	0.16	32.16	9.67	31.00	9.44	32.03	11.03	0.15	30.90		31.11	31.22
Fe2O3	-	-			•	•	•	•			•		-	-		-	-			•	•	•	-	-				-	
MgO	10.15	10.11	7.09	7.26	5.19	4.19	9.31	4.64	9.97	4.92	5.38	14.36	21.26	13.63		5.27	18.99	0.01	6.02	18.33	6.42	18.89	5.10	17.24	0.00	6.43		7.61	7.61
MnO	0.02	0.00	0.63	0.63	0.82	0.91	0.03	0.73	0.00	0.86	0.61	0.09	0.03	0.02		1.94	0.00	0.00	2.15	0.00	1.99	0.00	2.39	0.05	0.00	1.88		0.40	0.24
TiO2	0.00	0.02	0.01	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00	4.86	0.09	4.77		0.00	2.34	0.00	0.00	2.56	0.06	2.36	0.02	3.87	0.00	0.05		0.03	0.00
Cr203	0.02	0.00	0.01	0.03	0.09	0.00	0.02	0.02	0.00	0.00	0.04	0.17	0.01	0.01		0.03	0.02	0.05	0.00	0.08	0.07	0.00	0.03	0.04	0.07	0.02		0.06	0.08
Na20	0.06	0.09	0.04	0.01	0.02	0.02	0.02	0.01	0.04	0.00	0.02	0.05	0.08	0.05		0.00	0.04	7.14	0.00	0.05	0.00	0.06	0.00	0.03	7.28	0.02		0.02	0.02
CaO	0.00	0.01	0.98	0.95	0.93	1.07	0.01	1.16	0.00	1.16	1.09	0.00	0.00	0.00		1.31	0.03	7.09	1.22	0.00	1.23	0.02	1.26	0.01	7.02	1.28		0.96	0.91
K2O	0.01	0.02	0.00	0.00	0.00	0.02	0.02	0.01	0.02	0.01	0.01	9.56	9.98	9.96		0.01	9.87	0.24	0.00	9.73	0.01	9.67	0.00	9.94	0.15	0.03		0.00	0.00
NiO	0.03	0.08	0.00	0.08	0.07	0.03	0.03	0.01	0.03	0.00	0.00	0.13	0.00	0.21		0.00	0.09	0.01	0.00	0.02	0.00	0.06	0.00	0.14	0.00	0.00		0.00	0.09
ZnO	-	-	-	-	-	-	•	-	-	-	-	-	-	•		-	-	-	-	•	-	-	-	-	-			-	-
Totals	98.64	98.59	98.47	98.98	98.39	97.84	96.13	98.32	97.32	97.30	98.12	94.46	94.25	92.88		100.71	94.82	98.92	101.00	93.44	100.09	93.93	98.91	95.04	98.76	100.04		99.73	99.58

Mg N <sup>5</sup> SiO2 Al2O3 FeO FeO FeO TiO2 Cr2O3 Na2O CaO K2O NiO ZnO Totals	Mt Dover: Grt.R.20 30.4 38.30 21.48 31.06 - - 7.63 0.31 0.00 0.07 0.01 0.95 0.02 0.04 99.85	5, D90/5 P1.adj 20.0 60.48 23.77 0.11 - 0.0i 0.00 0.00 7.84 6.21 0.18 0.05 - 98.67	19.11.91 Phinci 71.9 37.38 14.57 11.10 - - 15.94 0.00 4.94 0.12 0.17 0.00 9.79 0.00 9.79	Phlinct 70.8 37.04 14.81 11.42 	Grt.adj 29.3 38.12 21.36 31.62 	Ph1 71.3 37.26 15.79 11.19  5.32  0.19 0.00 9.65  95.00	Phl 72.1 37.01 16.01 10.85 - 15.69 0.00 5.11 - 0.16 0.00 9.92 - - 94.75	Phl 67.2 36.95 15.40 13.14 - 15.11 0.02 4.35 - 0.06 0.01 9.91 - 94.94	Phi 64.1 37.03 15.26 14.33 - 14.34 0.00 4.66 - 0.08 0.00 9.87 - -		Mt Dovers Grt.C.rl 28.6 37.41 21.78 32.27 - 7.27 0.75 0.00 0.00 0.00 0.00 0.00 0.00 0.0	5, D90/6 Grt.R 23.0 37.09 21.32 33.47 - 5.62 0.86 0.01 0.08 0.02 0.82 0.01 0.100 99.38	4.5.91 Grt.R.r2 24.5 37.54 21.66 33.55 6.11 0.72 0.03 0.00 0.00 0.093 0.02 0.01 0.00 100.57	Crd.r2 75.8 57.44 26.95 4.71 8.27 0.00 0.03 0.03 0.02 0.09 0.01 0.08 0.00 97.63	late Crd 59.0 42.07 33.67 5.86 - 4.75 0.06 0.00 0.00 0.00 0.00 0.33 0.14 0.00 0.00 0.33	PhLr4 65.7 37.21 14.92 13.88 	Kfs 64.59 18.69 0.00 0.04 0.00 1.44 0.09 14.09 0.00 0.00 98.94	Kfs 	lim 3.4 0.03 45.63 - 0.89 0.11 52.10 0.00 0.01 0.01 0.01 0.00 0.03 0.00 0.03 0.00	17.7.91 Spl3.R4a 26.7 0.00 57.91 21.97 1.48 4.77 0.06 0.01 0.43 - - 0.13 12.52 99.26	Sp13.R4a 26.1 0.00 57.10 21.21 1.28 4.44 0.07 0.09 0.40 - - 0.11 13.45 98.13	17.8.91 Grt.C.r8 24.0 37.55 21.96 33.44 - 5.91 0.89 0.00 0.01 0.00 0.96 0.02 0.00	Grt.18 28.7 37.64 22.24 32.25 - 7.29 0.89 0.04 0.03 0.01 0.80 0.01 0.07	Grt.R.r8 26.0 37.53 22.17 33.04 - 6.51 0.72 0.00 0.00 0.00 0.00 0.00 0.75 0.00 0.00	Grt.R.r8 27.7 39.98 21.86 30.84 - - 6.63 0.68 0.00 0.04 0.02 0.69 0.02 0.03	Crd.R.r8 71.8 48.94 34.02 6.67 - 9.51 0.03 0.02 0.04 0.03 0.00 0.00 0.00 0.03 - -	Crd.R.r8 71.2 49.58 34.38 6.88 - 9.52 0.00 0.00 0.00 0.00 0.00 0.00 0.01 - -	Crd.C.r8 71.6 48.71 34.00 6.77 - 9.57 0.05 0.04 0.02 0.01 0.00 0.02	Ph1.ad 65.6 37.39 14.79 13.84 
																,,,,,	,,		,		,			10000					
Mg N <sup>6</sup> SiO2 Al2O3 FeO	Mt Dover: Grt.R.r4a 17.t 37.05 21.67 35.43	5, D90/6 Crd.r4a 62.5 40.24 36.72 5.38	Gr1.adj 26.4 36.93 23.04 31.51	Grt.R.r4a 23.3 37.61 21.99 33.28	Crd.adj 73.5 40.32 31.40 5.96	Grt.R.r4a 22.9 37.60 22.29 33.82	Phl.adj 82.5 38.19 17.13 7.78	ilm.R 4.7 0.03 0.00 45.60	Grt.adj 24.6 36.24 21.03 32.93	Grt.R.r7 26.4 37.96 22.29 32.63	Pl.adj 61.33 24.42 0.25	27.10.91 Fsp.r5 66.29 19.93 0.02	PL:r5 66.79 19.81 0.00	PLr1 66.89 20.54 0.00	Grt.R.rl 27.7 37.37 21.92 31.30	Grt.C.rl 27.6 37.20 21.92 31.63	Crd.r6 74.5 48.59 33.35 5.91	Crd.r6 74.7 48.32 33.19 5.82		Mt Béche Grt.C 24.3 37.93 21.78 33.71	rvaise, MB Grt.R 24.5 37.66 21.78 33.88	90/2 Grt.R 19.4 37.45 21.67 34.92	16.6.91 Itm.R 0.9 2.25 0.46 46.06	Hm.C 0.3 0.02 0.00 47.76	Grt.R 20,7 37.77 21.92 34.64	Ph1.adj 73.2 35.53 15.39 10.79	P1 59.74 25.85 0.36	P1 60.35 25.51 0.64	Phi 60.4 44.34 14.57 14.49
MgO MnO TiO2 Cr2O3 Na2O CaO	4.09 1.30 0.00 0.00 0.01 1.06	5.03 0.01 0.00 0.00 0.21 0.49	6.33 0.82 0.01 0.07 0.01 0.89	5.67 0.92 0.02 0.00 0.00 0.89	9.26 0.00 0.03 0.10 0.17	5.65 0.94 0.00 0.01 0.02 0.95	20.54 0.01 0.56 0.01 0.15 0.01	1.25 0.18 50.71 0.04 0.02 0.00	6.02 0.91 3.07 0.05 0.00 0.93	6.58 0.86 0.00 0.05 0.00 0.76	0.00 0.00 0.02 8.09 5.46	0.00 0.00 0.00 0.00 8.67 0.75	0.00 0.00 0.00 0.00 10.15 0.52	0.01 0.03 0.05 6.43 4.70	6.73 0.83 0.00 0.04 0.00 0.90	6.78 0.82 0.00 0.03 0.00 0.93	9.70 0.00 0.00 0.05 0.05 0.03	9.64 0.00 0.01 0.05 0.07 0.02		6.07 0.52 0.03 0.05 0.01 1.41	6.16 0.48 0.06 0.00 0.01 1.28	4.72 0.56 0.14 0.01 0.00 1.38	0.25 0.29 49.22 0.10 0.00 0.87	0.07 0.21 51.55 0.00 0.02 0.00	5.09 0.43 0.15 0.04 0.02 1.41	16.56 0.00 4.70 0.08 0.06 2.27	0.00 0.00 0.04 0.00 7.29 7.14	0.00 0.00 0.00 0.00 7.30 6.65	12.41 0.00 3.19 0.00 0.06 1.56
NiO ZnO Totals	0.00	0.18	0.01 0.00 99.63	0.02	0.04	0.02	9.95 0.05 94.37	0.01 - 97.84	0.00	0.02	0.07 0.00 99.63	2.50 0.07 98.22	0.46 0.00 - 97.74	0.02 98.78	0.06 99.15	0.03 - 99.34	0.02 0.00 97.71	0.00 0.00 97.13		0.01 0.13 0.00 101.63	0.02 0.00 0.00 101.33	0.03 0.00 0.00 100.88	0.12 0.00 99.67	0.01 0.00 0.00 99.64	0.02 0.00 0.00 101.48	0.07 0.00 92.85	0.18 0.08 0.00 100.67	0.64 0.09 0.00 101.18	3.45 0.06 0.00 94.12
	Mt Bécher	vaise, MB	90/4	17.11.91	0.0	<b>.</b>	<b>C</b> . <b>D</b>	<b></b>	<b>.</b>			<b>6</b> I	<i>r</i>	<u> </u>	6 . P	<b>6</b> 1	C . D	0.1.1		6-1-2	C+D-1	¥6.		Mt Bécher	rvaise, MB	90/5	5.11.91	<b>C</b> -1	6-1
Mg N° SiO2 Al2O3 FeO	5plane.15 28.2 0.05 56.16 23.59	27.8 27.8 0.00 55.24 23.36	Grt.R 19.4 37.61 21.23 35.23	23.9 37.99 21.54 33.34	Gri.C 21.3 37.63 21.22 34.15	Crt 25.2 37.88 21.33 32.99	Grt.R 19.0 37.89 21.07 35.12	72.6 49.21 32.70 6.52	72.1 49.37 32.67 6.59	73.0 49.46 32.87 6.51	Spi 23.6 0.01 56.69 27.31	Crd 75.7 49.37 32.59 5.87	Sp1.adj 25.2 0.00 57.77 26.40	Crd 73.0 49.71 32.85 6.41	Grt.R 20.9 37.80 20.95 34.46	Crd 73.9 49.54 32.89 6.18	GILR 21.9 37.61 21.12 34.13	69.7 49.27 32.51 7.22	Cra.r2 72.1 49.12 32.94 6.62	22.6 37.84 21.12 34.29	21.8 37.84 21.11 34.06	KIS 64.42 18.16 0.08		18.2 36.85 20.80 36.00	23.2 37.13 21.01 34.19	24.2 37.37 21.13 33.54	22.9 37.36 21.23 34.42	23.2 37.17 21.06 34.31	23.4 37.09 20.92 33.91
Fe2O3 MgO MnO TiO2 Cr2O3 No2O	1.94 5.59 0.00 0.00 2.92	2.15 5.45 0.00 0.02 2.77	4.76 1.02 0.03 0.00	5.88 0.97 0.05 0.14	5.18 0.87 0.07 0.02	6.23 1.04 0.04 0.07	4.61 1.17 0.00 0.17	9.67 0.07 0.00 0.05	9.55 0.09 0.00 0.00	9.89 0.07 0.00 0.00	1.64 4.99 0.02 0.01 2.72	10.25 0.02 0.01 0.00	0.98 5.16 0.03 0.03 1.53	9.72 0.05 0.09 0.00	5.12 0.99 0.02 0.03	9.80 0.00 0.01 0.02	5.38 1.01 0.00 0.06	9.33 0.08 0.00 0.00	9.60 0.06 0.00 0.03	5.61 0.80 0.00 0.03	5.32 1.00 0.07 0.09	0.02 0.00 0.03 0.00		4.50 0.35 0.01 0.06	5.78 0.25 0.04 0.01	6.00 0.43 0.04 0.00	5.73 0.21 0.03 0.10	5.82 0.37 0.07 0.04	5.81 0.22 0.00 0.09
Na2O CaO K2O NiO ZnO Totals	0.20 9.30 99.75	0.19 9.06 98.25	0.00 0.94 0.01 0.04 -	0.02 0.95 0.00 0.00	0.00 0.99 0.00 0.00 -	0.00 1.04 0.01 0.00	0.00	0.00 0.02 0.03 - 98.31	0.06 0.00 0.00 0.00	0.04 0.03 0.00 0.09 - 98.96	0.17 6.39 99.95	0.05 0.00 0.04 - 98.20	0.25 6.87 99.02	0.03 0.02 0.00 0.07 - 98.86	0.00 0.94 0.00 0.06	0.04 0.01 0.02 0.01 - 98.52	0.00 0.91 0.00 0.05	0.04 0.01 0.00 0.00 -	0.02 0.01 0.00 0.00 - 98.40	0.01 0.92 0.00 0.04 -	0.00 0.94 0.00 0.00	1.58 0.08 14.77 0.02 - 99.15		0.00 0.95 0.02 0.00 -	1.07 0.02 0.03	0.01 1.11 0.01 0.00 99.65	0.02 1.12 0.02 0.06	0.00 1.12 0.01 0.05 -	0.02 1.11 0.00 0.00 - 99,17

	Mt Bécher	rvaise, MB	90/5										13.11.91							17.11.91				Mt Bécher	vaise, MB	90/7	14.5.91		
Mg N° SiO2	Grt 23.8 37.05	Grt 23.9 37 70	Grt 24.5 37.24	Grt.C 24.9 37.31	Grt.R 22.7 36.96	GrtR 22.4 37.05	Fsp.adj 0.0 65.15	Crd.adj 67.4 48.58	Crd.adj 68.4 47.66	P1	PI	Crd 68.8	Spl.R.bt 26.1 0.02	Spl.aGrt 29.1 0.03	Spl.aGrt 25.6	Spl 23.1 0.02	Phl 65.9 17 22	Ph1 66.8 37.48	Phi 66.6 37.97	Phl 66.7 37,47	ađj.R 65.3 37.17	adj.R 64.9 37.40	-	Grt.C 27.6	Grt.R 27.0	Grt.symp ( 19.5	Crd.symp 67.5 37.16	llm.symp 0.8	Phi 59.8
Al2O3 FeO	21.11 34.29	21.15 33.89	20.98 33.64	21.09 33.75	21.05 34.45	21.16 34.22	19.75 0.13	31.59 7.52	31.84 7.40	24.62 0.02	23.79 0.01	31.63 7.30	58.13 21.89	58.20 19.98	57.89 22.16	56.36 22.24	15.16 13.93	14.93 13.68	14.77 13.73	15.10 13.44	15.09 13.93	15.20 14.16		21.58 32.20	21.41 32.17	20.82 34.85	35.59 4.62	0.00	15.16 15.32
MgO	6.01	5.97	6.14	6.27	5.67	5.54	0.00	8.72	8.99	0.00	0.00	9.04	4.53	0.90 4.80	0.93 4.45	1.50 3.98	15.12	14.46	15.38	15.07	14.69	14.70		6.88	6.66	4.73	5.37	0.18	12.78
TiO	0.27	0.32	0.14	0.23	0.34	0.28	0.00	0.00	0.03	0.00	0.00	0.05	0.04	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	е. -	0.59	0.48	0.49	0.01	0.10	0.03
Cr201	0.05	0.02	0.08	0.04	0.02	0.01	0.00	0.00	0.00	0.02	0.00	0.00	0.61	0.00	0.01	1 37	0.05	5.55 0.07	012	0.08	4.30	2.83		0.06	0.04	0.07	0.00	0.15	4.42
Na2O	0.01	0.02	0.01	0.00	0.00	0.02	5.91	0.03	0.05	7.27	7.71	0.04	-	-	•	-	0.18	0.20	0.13	0.16	0.17	0.18		0.00	0.00	0.01	0.07	0.05	0.07
C3O	1.00	1.06	1.12	1.10	1.03	0.99	2.40	0.01	0.00	7.64	6.60	0.01	•		-	-	0.05	0.00	0.01	0.00	0.00	0.03		1.00	0.99	0.84	0.56	0.05	0.00
K2O	0.02	0.00	0.00	0.00	0.00	0.00	5.76	0.01	0.00	0.19	0.17	0.01	•	•	-	•	9.69	10.06	9.95	10.09	9.99	9.88		0.00	0.02	0.03	0.37	0.01	9.52
NiO	0.05	0.00	0.00	0.04	0.00	0.09	0.03	0.00	0.00	0.00	0.00	0.00	0.12	0.10	0.08	0.13	0.06	0.00	0.00	0.06	0.02	0.06		0.00	0.00	0.07	0.18	0.00	0.14
ZnO Totola	-	100.17			-	-	-	-	-	-		-	13.47	15.06	13.02	13.48	-		A					0.00	0.00	0.00	0.00	0.00	0.00
101415	99.81	100.17	99.37	99.90	99.38	99.33	99.13	90.48	93.99	98.10	98.33	90.08	100.04	99.98	99.42	99.21	93.38	94.43	93.60	93.30	93.83	95.55		100.20	99.72	99.01	83.98	97.11	93.24
	Mt Bécher	vaise, MB	90/7	6				<b>.</b>									17.7.91										Mt E	léchervaise	MB90/8
14. MP	ы	GUTO	Musc	Gri	lim 0.4	Grt.C.r4a	Grt.R	Crd.syml	Crd.symi	Grt.R	Crd.adj	Gri.R	PhLadj	Crdadj.Spl Zo č	Trdadj.Sp#	Crdadj.Spl	SpI3.R4	SpI3.R4	Sp13.R4	SpB.R4	SpI3?R2a	SpI3?R2a	SpI3?R2a	SpI3?R2a	SpI3?R2a	SpI3?R2a		GriCit	Grt.R.rl
SiOn	66.63	37 71	10.5	36.00	0.4	20.3	19.3	37.2	30.4	10.8	10.61	18.1	36.50	18 17	10.4	/1.0	21.8	0.00	22.0	22.0	23.8	23.5	23.0	25.7	23.2	24.3		27.0	18.78
AI203	18.05	21.62	35.99	21.10	0.00	21.87	21.56	35.91	36.29	21.63	34.91	21.58	16.79	33.88	33.67	31.05	55.47	55.09	55.33	56.53	53.67	54.13	54.16	54.03	54.28	53.97		21.33	21.33
FeO	0.51	32.97	1.63	35.57	46.01	34.93	35.10	5.80	5.70	36.36	5.27	35.84	14.83	7.01	6.98	6.89	19.92	19.18	19.80	19.88	20.21	20.78	21.15	20.54	21.31	20.31		27.75	28.35
Fe2O3	-	-	-	-	-	•	-	•	-	-			-	-		-	1.08	0.93	1.07	0.59	1.66	1.33	1.48	1.45	1.43	1.49		-	-
MgO	0.00	6.56	1.85	4.33	0.11	5.01	4.71	4.35	4.13	4.12	4.09	4.46	12.56	9.42	9.32	9.46	3.27	3.20	3.28	3.32	3.80	3.79	3.78	3.81	3.82	3.89		5.94	5.56
MnO	0.04	0.38	0.00	0.74	0.10	0.54	0.51	0.00	0.01	0.78	0.00	0.61	0.00	0.03	0.05	0.02	0.00	0.00	0.00	.0.00	0.00	0.00	0.00	0.00	0.00	0.00		4.43	4.64
02	0.05	0.03	0.17	0.08	52.40	0.02	0.02	0.05	0.01	0.02	0.00	0.01	3.99	0.00	0.02	0.00	0.06	0.04	0.10	0.11	0.12	0.13	0.03	0.11	0.03	0.08		0.02	0.00
Na2O	4.43	0.00	0.07	0.02	0.04	0.02	0.02	0.00	0.02	0.00	0.00	0.00	0.08	0.07	0.03	0.00	1.45	1.40	1.50	1.51	2.93	2.00	2.07	2.74	2.91	2.95		0.01	0.02
CaO	0.79	0.91	0.01	0.95	0.02	0.85	0.87	0.47	0.31	0.87	0.52	0.93	0.04	0.00	0.01	0.01	-		-	-	-					-		3.09	2.83
K2O	8.68	0.02	5.56	0.00	0.01	0.02	0.00	0.32	0.32	0.00	0.27	0.00	8.56	0.00	0.00	0.01	-	-	-		•	-	-	-	-			0.01	0.00
NiO	0.00	0.09	0.03	0.00	0.14	0.00	0.06	0.07	0.09	0.00	0.11	0.05	0.18	0.00	0.07	0.00	0.26	0.27	0.26	0.24	0.22	0.21	0.23	0.20	0.22	0.22		0.00	0.00
ZnO	0.00	0.00	0.00	0.00	0.00	•	-		-	-	-	•	-	-	•	-	16.31	16.80	16.56	17.04	14.69	14.30	13.78	14.52	13.67	14.55			
Totals	99.21	100.37	94.89	99.87	98.82	100.37	99.81	85.81	86.51	100.98	85.97	100.37	93.75	98.79	99.23	99.91	97.87	96.90	97.99	99.25	97.31	97.53	97.51	97.61	97.74	97.47		100.95	101.20
	Mr Báche	ervaise MI	R90/8	30 10 91														Mt Béch	ervaise. MI	890/9	14.11.91								
	Pl.adi	Opx.R	P1.adi	Opx.C	Ph1.adj	i Sph.r2	P1.adi	Cpx.r3	PL adj	Cpx.r3	Pl.adj	Cpx.r4	Cpx.lam	Cpx.i5	GrtR	Grt.R		Spl.r2	Spl.r2	Grt.adj	Grt	Grt	Spl.adj	Grt	Spl.adj	Grt	Phł.adj	Grt	SpI.23
Mg N°	-	52.1	- `	52.6	66.6	8.6	- 1	50.8	- '	45.3		25.4	25.5	17.3	0.3	1.1		26.4	24.7	19.6	23.3	22.9	29.6	23.0	28.8	20.1	62.7	22.9	22.8
SiÔ2	48.82	50.27	47.25	51.03	39.23	30.24	44.81	51.32	44.17	51.13	43.81	49.46	49.29	49.74	39.17	39.04		0.00	0.04	37.29	37.59	37.68	0.07	37.74	0.03	37.57	36.32	37.57	0.09
AI2O3	32.43	2.36	33.93	1.90	13.84	2.47	34.92	1.03	35.55	0.76	35.33	1.00	1.04	0.62	20.94	19.36		56.31	56.32	21.01	21.15	21.06	59.07	21.19	56.93	20.94	15.43	21.06	58.48
FeO	0.04	27.78	0.10	27.38	13.38	0.47	0.09	14.75	0.06	15.92	0.07	20.28	20.57	21.19	5.80	7.09		20.74	22.18	35.77	34.24	34.23	22.07	34.15	22.27	33.20	14.25	34.12	24.43
Fe203	-		-	17 00	-			- 0 54	-		-	1 00	206	2 10		0.01		1.01	1.14	4 80	5 9 4	5 71	5 5 5	5 72	5.13		13.42	5 60	106
MgO	0.00	10.90	0.00	17.02	14.99	0.03	0.00	3.00	0.00	1.31	0.00	3.88	3.90	2.49	4 2 1	1.91		4.40	9.47	4.07	0.46	0.45	0.00	0.33	0.00	0.37	0.00	0.31	0.00
TiO2	0.00	1.54	0.00	1.55	3 3 5	35 13	0.00	0.12	0.03	0.10	0.00	0.15	0.11	0.05	4.54	0.14		0.05	0.04	0.00	0.46	0.03	0.03	0.06	0.03	0.05	4.71	0.06	0.05
Cr203	0.03	0.10	0.00	0.05	0.15	0.29	0.00	0.00	0.00	0.05	0.00	0.00	0.02	0.03	0.00	0.01		1.87	2.29	0.04	0.00	0.02	1.25	0.04	1.37	0.05	0.12	0.00	2.05
Na2O	2.34	0.01	1.59	0.01	0.04	0.03	0.65	0.06	0.43	0.07	0.34	0.05	0.08	0.02	0.00	0.02		•	-	0.00	0.01	0.00	•	0.00		0.01	0.14	0.01	-
CaO	16.58	0.09	18.16	0.26	0.04	27.84	19.71	22.97	20.03	23.14	20.14	22.85	23.11	23.69	30.83	31.71		-	-	1.07	1.09	1.00	-	1.15	-	0.88	0.04	1.08	•
K2O	0.04	0.01	0.01	0.00	8.66	0.02	0.02	0.00	0.00	0.00	0.00	0.00	0.02	0.01	0.01	0.00		-	-	0.00	0.00	0.00	•	0.00	•	0.02	9.80	0.00	
NiO	0.00	0.03	0.05	0.06	0.04	0.00	0.01	0.03	0.00	0.02	0.00	0.05	0.01	0.04	0.04	0.01		0.12	0.12	0.00	0.00	0.00	0.15	0.04	0.15	0.01	0.05	0.10	0.11
ZnO		-	-	-		-	-				-	-	-	101.05	-	101 73		14.23	13.10	100.35		100.17	11.49	100.43	10.28	10014	01.25	100.00	12.10
Totals	100.35	99.23	101.10	99.32	94.43	96.92	100.20	100.85	100.28	100.47	99.69	100.34	100.99	101.65	101.22	101.23		99.41	99.49	100.35	100.44	100.17	101.20	100.43	98.80	100.14	94.23	100.00	101.40

			2012																										
	Mt Becher	vaise, MB	90/9 Sel	tim	Salel	Griadi	Selvi	Criadi	Get	Cri P		Mt Béchei	rvaise, MB	90/11	14.5.91	Dht	Dhi	Dt	Di	Cet P -1	Ca Tr	Cutr	Cet Te	GetTe	Cate	Calle	Call	Diadi	Dhi adi
Ma Nº	58.0	N15.12	301 373	1.0	- 3pt.11 - 78 G	225	20.3	221	23.8	177		520	51.6	521	526	68.8	72.6			227	27.9	27 1	281	27.0	28.0	27 4	21.0	FLauj	76.5
SiO2	36.15	63.78	0.01	0.00	0.03	37.44	0.00	37.60	37.76	37.46		49.50	49.94	49.06	48.76	37.41	38.57	48.24	48.51	37.80	38.18	38.71	38 47	38.41	38.46	38.28	37 84	\$6.24	38.78
AI2O3	15.12	17.92	56.40	0.00	57.40	21.19	57.60	21.03	21.03	21.00		3.27	2.13	3.63	3.58	13.72	13.64	32.49	32.14	21.83	21.68	21.84	21.78	21.80	21.67	21.80	21.54	27.51	14.14
FeO	16.11	0.19	23.01	45.86	23.05	34.32	22.62	34.41	33.99	36.41		28.40	28.55	28.22	27.65	13.75	11.90	0.05	0.01	33.06	30.87	31.43	31.01	31.14	31.12	31.42	32.06	0.42	10.14
Fe2O3		-	1.66		1.65	-	1.90	-		-		-	-	-	-	-	-	-	-	-		-		-	•		-	-	
MgO	12.47	0.00	3.95	0.27	5.37	5.61	5.67	5.49	5.96	4.39		17.24	17.06	17.23	17.20	17.01	17.65	0.00	0.00	5.44	6.70	6.67	6.79	6.77	6.80	6.65	5.38	0.07	18.51
MnO	0.03	0.05	0.00	0.01	0.00	0.30	0.00	0.35	0.28	0.33		0.51	0.59	0.54	0.32	0.00	0.07	0.00	0.04	1.01	0.94	1.01	0.82	0.79	0.91	0.91	0.97	0.01	0.07
TiO2	4.75	0.00	0.02	51.51	0.04	0.00	0.00	0.01	0.01	0.01		0.04	0.09	0.06	0.05	2.59	2.57	0.00	0.00	0.01	0.01	0.00	0.01	0.01	0.02	0.06	0.02	0.03	2.74
Cr2O3	0.08	0.00	1.79	0.00	1.36	0.00	1.25	0.00	0.01	0.06		0.15	0.06	0.13	0.11	0.17	0.13	0.00	0.03	0.06	0.09	0.08	0.15	0.09	0.09	0.09	0.06	0.00	0.14
Na2O	0.14	1.72	-	0.00	•	0.00	•	0.00	0.02	0.00		0.01	0.01	0.00	0.01	0.16	0.17	2.57	2.59	0.02	0.01	0.01	0.01	0.02	0.01	0.00	0.01	5.95	0.10
CaO	0.04	0.00	-	0.00	-	1.04	•	1.06	1.08	0.79		0.13	0.13	0.09	0.14	0.00	0.00	15.88	15.66	1.77	2.05	1.93	2.04	2.01	2.07	2.03	2.10	9.59	0.05
K20	9.78	14.38	-	0.01	<u>.</u>	0.00		0.00	0.00	0.01		0.00	0.01	0.00	0.00	9.37	9.69	0.04	0.04	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.01	0.06	9.77
7:0	0.07	0.01	1271	0.05	0.14	0.01	0.18	0.00	0.00	0.05		0.00	0.02	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.03	0.04	0.00	0.00	0.04	0.01	0.00	0.01	0.02
Totale			12.74		10.47		10.55	-	100.13	100 50		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	101.00	100.56	0.00	0.00	10.00	0.00	101.00	0,00	0.00	0.00
1 Otalis	94.73	98.05	99.09	91.12	99.32	99.09	99.37	99.94	100.15	100.30		99.23	98.38	90.9J	97.82	94.19	94.41	99.27	99.02	101.00	100.50	101.71	101.07	101.05	101.21	101.24	99.91	99.00	94.40
	Mr. D.Coba	maine MD	00/11			Line Num			20 11 01																German C		00/1	11 6 01	
	Phi adi	Get C	Grip	Phi adi		Piri	naks, 11907 Di	, DPDI	6711.71 Grt R	Get Tr	Grif	Gri R	Ph1 adi	Gri R	Phi adi	Gri R r?	Ph1 adi	Get Tz	Get C	Gri R	PI	Pht adi	Ph1 adi		GriC	Gri R	Crd adi	Ordadi	Phi
Ma Nº	76.0	27.1	221	78.8		-		58.8	18.2	21.7	21.7	20.0	63.5	165	66 9	17.2	63.0	217	20.5	19.0		500	50 4		325	307	78.0	77.6	70.4
SiO2	38.41	37.92	37.97	39.05		60.05	5972	36.47	37.32	37.47	37.60	37.19	36.79	37.00	36.64	36.89	36.87	37.21	37.07	37.18	60.16	36.14	36.16		38.19	38.19	49.77	49.68	37.13
AI203	14.16	21.93	21.67	14.31		24.02	23.96	15.04	20.85	20.87	20.98	20.91	15.08	20.86	14.95	20.61	15.36	20.83	20.75	20.78	24.17	14.64	14.62		22.12	21.89	33.90	33.57	14.89
FeO	10.45	31.10	33.21	9.38		0.00	0.01	15.91	35.55	34.59	34.20	34.77	14.46	36.60	13.28	35.78	14.25	34.17	34.85	35.17	0.03	15.43	15.70		30.14	30.61	5.30	5.37	11.67
Fe2O3	-	•	-	-		-	•	•	-	•	-	-	-	-	-			•	-	-	-					-	-	-	-
MgO	18.51	6.50	5.36	19.57		0.00	0.00	12.74	4.42	5.23	5.31	4.89	14.14	4.05	15.08	4.18	14.16	5.30	5.04	4.62	0.00	12.95	12.87		8.13	7.60	10.56	10.41	15.55
MnO	0.00	1.04	1.06	0.02		0.00	0.00	0.00	0.42	0.46	0.41	0.44	0.00	0.40	0.00	0.41	0.00	0.56	0.39	0.45	0.00	0.00	0.02		0.52	0.58	0.00	0.00	0.03
TiO2	2.55	0.00	0.00	2.17		0.03	0.02	4.18	0.10	0.07	0.07	0.00	3.98	0.03	3.11	0.00	3.58	0.04	0.03	0.00	0.06	3.85	4.04		0.03	0.00	0.00	0.03	5.28
Cr2O3	0.15	0.02	0.18	0.09		0.00	0.03	0.02	0.00	0.04	0.03	0.02	0.03	0.64	0.03	0.00	0.00	0.02	0.01	0.05	0.00	0.00	0.06		0.06	0.00	0.01	0.00	0.03
Na2O	0.16	0.00	0.01	0.16		7.58	7.37	0.07	0.00	0.00	0.00	0.02	0.11	0.00	0.08	0.00	0.09	0.01	0.00	0.00	7.43	0.06	0.06		0.00	0.01	0.05	0.06	0.05
C30	0.00	2.04	2.21	0.02		6.86	6.91	0.07	1.03	1.24	1.33	1.07	0.00	1.13	0.00	1.03	0.00	1.17	1.34	1.08	6.89	0.07	0.01		1.24	1.15	0.03	0.04	0.00
K20	9.72	0.00	0.02	9.96		0.18	0.22	9.67	0.00	0.00	0.01	0.02	9.58	0.00	10.14	0.09	9.29	0.00	0.03	0.02	0.23	10.02	10.12		0.00	0.00	0.00	0.01	9.91
NiO	0.00	0.05	0.06	0.06		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.05	0.00	0.00	0.01	0.01	0.00	0.09	0.00	0.00	0.00		0.15	0.00	0.00	0.00	0.00
ZnO	0.00	0.00	0.00	0.00			-			-	00.05	-	-	100.17	01.20	-		00.21	00.61		-	02.15	01.65		100.56	100.03	0.00	0.00	0.00
lotals	94.11	100.01	101.74	94.19		98.72	98.23	94.18	99.70	99.90	99.95	99.31	94.17	100.17	93.30	98.90	93.01	99.31	99.31	99.42	98.98	93.13	93.03		100.50	100.03	99.01	99.10	94.34
	Gorman C	taes. GOR	90/1																										
	Phi	PI	Grt.r2	OrdinclGri	CrdinclGrt	Grt.r2	Phlinci	Ph1r3	Grt.adi	Grd.R	Crd.R	Crd.R	Grt.adi	Grt.adi	Grd	Crd	GrLr5	Crdadj.r5	Ph1.adi	Kfs.r5	Grt.r5	PLr5	Ph1.adi	Grt.R.r6	Grt.C.r6	Pl.adi	PLaway.		
Mg N°	69.1	-	32.1	62.1	63.8	29.4	76.6	72.1	29.4	53.4	55.4	51.0	31.0	31.0	62.5	56.5	27.5	42.8	65.9	-	31.6	-	73.5	32.2	32.2	. '	. '		
SiÒ2	37.30	59.56	38.75	37.57	40.77	38.10	38.48	37.79	38.05	40.31	37.92	36.45	41.36	37.56	38.89	38.73	38.41	41.13	38.47	63.64	38.11	59.26	37.46	38.36	38.16	57.69	59.21		
AI2O3	14.88	25.84	21.97	30.22	31.23	21.76	15.38	15.27	21.95	34.28	30.43	32.00	20.99	22.56	33.86	35.89	21.84	39.11	16.04	18.77	21.91	25.47	15.32	21.88	22.06	25.69	25.79		
FeO	12.20	0.01	30.58	7.67	7.92	31.54	9.50	11.16	31.48	8.82	9.44	9.07	29.10	30.17	7.35	6.92	31.65	5.41	14.06	0.11	29.73	0.39	10.53	30.03	30.29	0.51	0.06		
Fe203	•	-	-	•	•	•	-	-	-	-	-	-	-	•	•	•	٠	•	-	-	- 1	-	-	-	•	-	-		
MgO	15.29	0.01	8.12	7.07	7.82	7.38	17.43	16.17	7.35	5.66	6.59	5.29	7.33	7.61	6.87	5.04	6.89	2.26	15.27	0.01	7.71	0.15	16.38	8.00	8.08	0.88	0.00		
MnO	0.08	0.00	0.54	0.04	0.00	0.50	0.00	0.00	0.47	0.00	0.00	0.01	0.56	0.51	0.02	0.00	0.48	0.06	0.02	0.02	0.58	0.00	0.00	0.48	0.58	0.04	0.00		
TiO2	5.02	0.00	0.00	0.00	0.00	0.02	4.88	5.10	0.04	0.05	0.78	0.04	0.07	0.00	0.01	0.03	0.00	0.04	3.88	0.01	0.02	0.06	4.39	0.00	0.02	0.22	0.00		
Cr203	0.14	0.00	0.00	0.02	0.00	0.05	0.12	0.06	0.06	0.04	0.04	0.08	0.00	0.03	0.00	0.00	0.08	0.01	0.02	0.00	0.04	0.01	0.21	0.01	0.07	0.03	0.00		
N320	0.05	7.10	0.01	0.03	0.04	0.01	0.08	0.08	0.00	0.07	0.09	0.06	0.00	0.02	0.06	0.15	0.00	0.22	0.04	0.76	0.00	7.22	0.07	0.00	0.00	6.87	6.91		
C30	0.00	1.10	1.13	0.39	0.50	1.13	0.01	0.03	1.08	0.30	0.37	0.39	1.13	1.11	0.18	0.18	1.13	0.17	0.18	0.05	1.28	0.94	0.15	1.10	1.14	6.79	1.16		
NIO	9.90	0.29	0.00	0.40	0.37	0.00	10.03	10.0/	0.00	0.39	1.21	0.55	0.02	0.00	0.31	0.27	0.02	0.05	8.79	10.00	0.01	0.27	9.09	0.00	0.00	0.70	0.39		
7n0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.00	0.04	0.00	0.07	0.00	0.00	0.00	0.13	0.25	0.07	0.00	0.22	0.00	0.11	0.00	0.09	0.00	0.00		
Totals	94.94	100.09	101.09	83.75	88.71	100.49	95.98	95.89	100.57	89.97	87.21	83.74	100.63	99.57	87.61	87.26	100.64	88 70	96.86	98.91	99 50	98 77	94 31	99.93	100.49	99.48	99 51		
								10.01					100.00	11.21	01.01	· · · · ·	100.04		/0.00	/0./1	12.23	20.27	27.28	11.12	100.77	, , , , , , , , , , , , , , , , , , ,	22.28		

	Gorman (	Crags, GOI	<b>W0/5</b>	17.11.91									Gorman (	Crags, GOF	190/12	2 & 4.5.9	1											9.7.91	
Mg N° SiO2 Al2O3 FeO Fe2O3 MgO MaO TiO2 Cr2O3 Na2O CaO	Gorman G Grt.R 15.1 37.22 20.89 35.13 - - 3.50 1.63 0.00 0.03 0.01 1.69 0.00	Crags, GOI Grt.38 15.4 37.41 20.76 35.13 - 3.60 1.67 0.01 0.07 0.00 1.72 0.02	R90/5 GriR.40 12.9 37.33 21.18 35.60 - 2.96 1.79 0.00 0.00 0.00 0.01 1.55 0.00	17.11.91 Phl.adj 42.4 35.00 16.43 21.61 - - 8.92 0.04 3.61 0.07 0.08 0.02 9.53	Pl 60.07 24.67 0.12 - - 0.00 0.04 0.01 0.00 7.31 6.88 0.11	Gnt.R 13.5 37.39 20.90 35.88 - 3.14 1.76 0.01 0.09 0.00 1.70 0.00	Ph1.adj 41.2 34.99 16.18 21.57 - - 8.49 0.05 4.42 0.03 0.08 0.02 9.61	P1 - 60.65 24.27 0.10 - 0.00 0.00 0.00 0.00 0.00 7.59 6.55 0.22	Grt.R 14.6 37.25 20.76 35.15	Pi.adj 	Ph1.adj 42.0 34.72 15.96 21.29 - - 8.65 0.00 4.26 0.21 0.05 0.00 0.65		Gorman C GrtinSyp 20.1 38.31 21.93 35.08 - 4.97 0.64 0.00 0.02 0.00 0.02 0.00	Crags, GOF 9 SplinSyp 25.6 0.00 58.47 23.31 - 4.50 0.00 0.00 0.00 0.00 0.00 0.00 0.00	(90/12 SplinSyp 26.5 0.09 60.18 23.14 - 4.70 0.00 0.00 0.00 0.00 0.00 0.00	2 & 4.5.9 Grt.R 19.7 37.45 21.35 36.06 - 4.96 0.72 0.02 0.01 0.00 0.79 0.02	/ Grt.trav2 21.5 37.60 21.74 35.10 - 5.40 0.71 0.02 0.00 0.02 0.09 0.02	Grt.C 25.3 38.27 21.79 33.31 - - 6.33 0.50 0.00 0.06 0.01 0.83 0.90	Phi 67.9 37.62 15.03 12.98 	Grt.r2 25.2 38.36 21.78 33.59 - 6.37 0.59 0.00 0.01 0.02 0.82 0.00	Rutile 8.3 6.49 7.20 9.35 - 0.46 0.07 69.65 0.11 0.10 0.07	Spl.R 28.2 0.00 57.00 23.86 	SpI.C.r2 28.4 0.00 57.39 23.99 - 5.33 0.00 0.00 0.00 0.00 0.00 0.00	Grt.R 23.5 37.70 21.61 34.64 0.00 5.98 0.59 0.00 0.00 0.00 0.00 0.80	Grt 24.4 38.06 21.60 34.06 0.00 6.16 0.47 0.00 0.02 0.00 0.83 0.01	Gri.C 25.1 38.19 21.42 33.61 0.00 6.33 0.58 0.01 0.00 0.01 0.81	Ph1.R 83.0 40.23 19.32 6.85 - 18.73 0.00 0.81 0.06 0.21 0.00 8.13	9.7.91 Spi2.R3 30.7 0.01 56.05 18.43 1.18 4.84 0.00 0.01 2.78 -	Sp12.R3 31.5 0.02 56.25 18.20 0.91 4.91 0.00 0.02 2.83
NiO ZnO Totals	0.03	0.03	0.00	0.04 95.34	0.00 99.24	0.00	0.08 95.50	0.00 99.38	0.04	0.00	0.04 94.83		0.00	0.00 11.56 97.84	0.00 11.44 99.55	0.06	0.00	0.01	0.02 95.45	0.00	0.00 93.57	0.00 9.46 95.58	0.00 9.65 96.37	0.00	0.00	0.00 0.00 100.96	0.05 94.39	0.06 16.16 99.52	0.04 16.39 99.57
Mg N° SiO2 Al2O3 FeO Fe2O3 MgO MnO Cr2O3 Na2O Cr2O3 Na2O Cr2O3 Na2O Cr2O3 Na2O Cr2O3 Na2O Cr2O3 Na2O Cr2O3 Na2O Cr2O3 Na2O Cr2O3 Na2O Cr2O3 Na2O SiO2 SiO2 Fe2O3 MgO MnO SiO2 Cr2O3 Na2O3 SiO3 SiO3 SiO3 SiO3 SiO3 SiO3 SiO3 Si	Gorman C Sp12:r3 30.9 0.00 56:22 18:45 0.96 4.82 0.00 0.00 2.73 - - - - 0.06 16:15 99:41	Crags, GOF Spl1 r3 29.7 0.02 56.94 20.39 0.96 5.04 0.00 1.92 - - 0.03 13.74 99.04	890/12 SpH r3 29.9 0.03 56.73 20.33 1.05 5.10 0.00 1.92 - - - 0.08 13.57 98.82	Spt2.r4 25.5 0.00 58.33 22.31 0.99 4.45 0.03 0.45 - - 0.04 13.06 99.69	Sp12.r4 25.0 0.06 57.06 22.00 1.10 4.32 0.07 0.48 - - - 0.04 8 - - 0.07 98.11	Sp12.14 25.8 0.02 57.70 21.92 1.60 4.55 0.04 0.01 0.45 - - - - 0.05 13.10 99.44	Sp12.r4 29.6 0.01 58.71 20.46 1.08 5.05 0.03 0.01 0.48 - - - 0.09 14.24 100.15	Spl2.r4 31.2 0.01 58.13 19.57 0.67 5.12 0.16 0.57 - - - - - - - - - - - - - - - - - - -	Spi2.r4 29.4 0.01 58.55 20.39 0.95 4.96 0.03 0.00 0.51 - - - 0.08 14.31 99.77	Spi2.r2 28.7 0.00 58.37 23.03 2.10 5.62 0.03 0.00 0.81 - - - 0.05 10.58 100.60	Sp12.r2 28.7 0.01 58.32 23.32 1.78 5.63 0.02 0.01 0.86 - - - 0.04 H0.12 100.11	Spil 15 30.7 0.01 56.05 18.43 1.18 4.84 0.00 0.01 2.78 - - - 0.06 16.16 99.52	Spl1 r5 31.5 0.02 56.25 18.20 0.91 4.91 0.00 0.02 2.83 - - - 0.04 16.39 99.57	Spl1.15 30.9 0.00 56.22 18.45 0.96 4.82 0.00 2.73 - - - 0.06 16.15 99.41	Spl1 r5 29.7 0.02 56.94 20.39 0.96 5.04 0.01 1.92 - - - - 0.03 13.74 99.04	lim.r5 2.2 1.00 0.84 23.81 0.00 0.30 0.24 65.14 0.01 0.01 0.01 0.01 0.00 91.34	Spil. 15 29.9 0.03 56.73 20.33 1.05 5.10 0.00 1.92	Spl1.r6 31.1 0.00 57.29 20.63 1.41 5.56 0.02 0.00 1.66 - - - - - - - - - - - - - - - - - -	Spl1 r6 30.5 0.02 57.16 20.86 1.28 5.43 0.00 1.61 - - 0.06 12.60 99.03	13.7.91 Spl1 r7 28.3 0.01 57.79 24.88 1.65 5.83 0.02 0.02 1.18 - - - 0.07 7.62 99.05	Spl1 17 28.6 0.00 58.00 24.82 2.10 6.02 0.06 0.02 1.14 - - - - - - - - - - - - - - - - - - -	Spil r7 31.2 0.00 58.25 21.33 1.05 5.65 0.00 0.00 t.03 - - - 0.03 11.99 99.33	Sp11 #7 30.6 0.04 57.95 21.29 0.95 5.48 0.01 1.04 - - 0.06 12.14 99.01	Sp13.r9 26.3 0.01 58.48 21.60 0.97 4.49 0.01 0.02 0.16 - - 13.70 99.50	Sp12.r9 25.3 0.01 57.84 21.79 0.87 4.28 0.05 0.18 0.34 - - 0.07 13.76 99.18	Sp13 r10 25.8 0.02 58.07 20.75 0.96 4.22 0.03 0.02 0.43 - - - 15.04 99.59	GrtC 17 26.2 37.72 22.10 32.60 0.00 6.50 0.63 0.00 0.00 0.00 0.00 0.80 0.00 0.03	Grt.Tr 27.1 37.14 21.74 32.04 0.00 6.67 0.02 0.04 0.02 0.81 0.01 0.01	Grt. Tr 26.3 37.38 21.74 32.23 0.00 6.46 0.73 0.00 0.03 0.00 0.80 0.00 0.80 0.00
Mg N° SiO2 A12O3 FeO Fe2O3 MgO MnO TiO2 Cr2O3 Na2O CaO	Gorman ( Grt.R 26.7 37.48 21.61 32.35 	Crags, GO Phl.adj 65.6 36.69 14.68 13.39 - 14.33 0.00 4.54 0.04 0.07 0.00 10.07	R90/12 Ph1.adj 66.6 36.81 14.54 13.00 - - 14.53 0.00 4.43 0.02 0.11 0.00 10.06	26.10.91 Phi.r4 69.9 36.88 15.11 11.88 	Ph1:r4 67.0 37.36 17.08 11.96 - - 13.61 0.00 4.06 0.11 0.06 0.01 8.82	Grt.R.r4 21.0 37.03 21.86 34.41 - 5.13 0.60 0.03 0.00 0.00 0.76 0.02	Grt.Tr 25.1 36.89 21.82 33.13 - 6.23 0.52 0.00 0.04 0.04 0.04 0.01 0.85 0.00	Grt.Tr 23.2 36.48 21.71 33.62 - 5.68 0.71 0.00 0.02 0.00 0.78 0.00	Grt.Tr 26.4 37.32 22.02 32.69 - - 6.57 0.65 0.02 0.00 0.00 0.00 0.69 0.00	Gri.C.r4 26.3 37.27 21.99 32.83 - - 6.57 0.61 0.02 0.04 0.00 0.73 0.04	GriR.r4 22.6 36.94 21.71 33.68 - 5.53 0.62 0.01 0.00 0.01 0.78 0.02	Crd.adj 27.9 40.28 38.77 8.22 1.79 0.00 0.03 0.03 0.03 0.20 0.37 0.21	Crd.adj 27.9 41.87 40.89 6.25 - 1.36 0.00 0.02 0.00 0.16 0.46 0.07	PLr12 61.38 23.38 0.03 - 0.00 0.02 0.00 8.26 4.75 0.16	Kfs.r12 63.16 18.65 0.03 - 0.00 0.00 0.03 0.02 1.29 0.07 15.04		Gorman C Ph1.1 88.5 41.12 13.83 5.48 - 23.59 0.00 0.75 0.23 0.50 0.03 9.35	Crags, GOI Phi.2 88.8 41.15 13.52 5.41 - 24.00 0.00 0.47 0.28 0.46 0.06 9.10	R90/14 Anth.3 76.5 57.80 0.25 13.92 - 25.36 0.38 0.02 0.04 0.07 0.60 0.01	17.11.91 Anth.4 76.6 57.93 0.22 13.75 - 25.24 0.44 0.02 0.00 0.04 0.68 0.02	Phi.adj 87.7 40.46 13.61 6.06 - 24.16 0.00 0.56 0.24 0.43 0.02 8.85	Anth.7 77.8 58.16 0.29 13.02 - - 25.56 0.49 0.02 0.03 0.09 0.51 0.02	Ph1.adj 85.0 38.90 12.11 8.13 25.85 0.00 0.38 0.32 0.33 0.00 6.61	Anth.10 77.5 57.74 0.20 13.34 - 25.74 0.35 0.03 0.06 0.06 0.06 0.46 0.02	Phi.C11 88.3 13.63 5.50 - 23.35 0.07 0.67 0.18 0.49 0.03 9 39	Phi.12 88.6 40.83 13.94 5.40 - - 23.51 0.00 0.66 0.25 0.44 0.03 9.25	Ph1.r12 85.8 39.97 11.32 7.55 		

No.

NiO

ZnO

Totals

0.00

0.09

0.00 0.00 0.03 0.00 0.03 0.03 0.00 0.07 0.02 0.06 0.02 0.01

99.34 93.90 93.50 93.93 93.11 99.83 99.53 99.02 99.96 100.17 99.33 89.95 91.09 97.99 98.38

266

0.08

0.08

0.10

0.04 0.00 0.11 0.08 0.04 0.00 0.35 0.09

94.96 94.54 98.48 98.35 94.49 98.25 92.66 97.99 94.50 94.38 92.29

0.18

Mg N° SiO2 Al2O3 FeO Fe2O3 MgO MnO TiO2 Cr2O3 Na2O CaO K2O NiO	Gorman Ci Grt.R 16.5 37.18 21.30 31.86 - - 3.53 1.51 0.02 0.07 0.03 4.82 0.00 0.03	rags, GOR Grt 17.0 36.96 21.24 31.98 - 3.67 1.54 0.00 0.05 0.00 4.65 0.01 0.00	90/17 Ph1.adj 48.4 35.62 13.64 20.19 10.61 0.00 5.03 0.10 0.06 0.02 9.52 0.02	28.5.91 Pl.adj - 56.61 27.50 0.07 - 0.01 0.00 0.05 0.02 5.62 9.57 0.25 0.08	P1.adj 54.73 29.23 0.24 - 0.00 0.00 0.00 0.00 0.00 5.59 9.53 0.21 0.15	Opx.R.r3 43.2 49.75 0.84 33.50 - 14.32 0.45 0.03 0.00 0.00 0.43 0.00 0.00	Opx 42.7 49.17 1.31 33.21 13.88 0.42 0.11 0.00 0.03 0.53 0.00 0.09	Opx 42.8 49.12 1.18 33.22 13.93 0.42 0.08 0.07 0.02 0.55 0.00 0.06	Opx 42.3 48.98 1.41 33.91 13.96 0.35 0.02 0.00 0.02 0.57 0.00 0.00	Opx.R 42.9 49.45 0.98 33.62 	Pl.adj 54.15 28.67 0.11 - 0.02 0.03 0.02 0.00 5.29 10.20 0.28 0.03	Pht.adj 50.7 35.94 14.23 19.08 11.03 0.02 4.96 0.00 0.07 0.00 9.63 0.08	Opx.R 42.7 49.52 0.94 32.56 - 13.63 0.41 0.17 0.06 0.00 0.38 0.00 0.00	Opx 43.2 49.88 0.95 32.25 13.74 0.46 0.12 0.08 0.00 0.45 0.03 0.07	Opx 43.7 49.97 0.89 32.34 14.10 0.44 0.10 0.04 0.04 0.00 0.45 0.02 0.00	Philinel 52.0 35.73 13.57 17.73  10.79 0.08 5.25 0.03 0.07 0.00 9.49 0.00	PLincl 56.03 27.75 0.10 0.00 0.00 0.00 0.00 0.01 5.68 9.98 0.21 0.09	Opx 43.6 49.82 0.95 31.93 - 13.86 0.35 0.23 0.00 0.02 0.50 0.00 0.00	Phl.away 36.37 14.06 18.69  11.13 0.09 4.86 0.10 0.04 0.00 9.87 0.04		Gorman C Grt.C 8.7 36.04 20.79 38.75 - 2.07 0.79 0.03 0.00 0.00 0.00 0.63 0.02 0.00	rags, GOR: Grt.R 8.7 36.04 20.79 38.75 - 2.07 0.79 0.03 0.00 0.00 0.63 0.01 0.00	90/21 Grt.R 8.4 35.97 20.78 38.58 1.99 1.08 0.04 0.00 0.00 0.68 0.00 0.00 0.00	5.91 P1.adj - - 61.67 22.76 0.54 - - 0.02 0.00 0.00 0.00 0.00 8.97 4.26 0.10 0.00	Ph1.adj 49.1 35.04 19.32 18.62 - 10.07 0.02 0.27 0.03 0.05 0.01 9.72 0.00	Grt 6.3 35.29 20.71 38.63 - 1.47 0.00 0.05 0.04 0.65 0.02 0.03	Grt.R 6.5 35.98 20.75 39.36 1.53 0.95 0.00 0.01 0.04 0.68 0.03 0.08	Grt.adj 7.1 35.78 20.69 39.44 1.70 1.06 0.03 0.00 0.01 0.63 0.01 0.63 0.01	Grt.C 10.2 36.06 20.80 37.84 - 2.40 0.85 0.03 0.00 0.00 0.00 0.64 0.00 0.01
ZnO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Totals	100.35	100.08	94.79	99.78	99.67	99.33	98.75	98.64	99.21	99.35	98.80	95.02	97.66	98.03	98.36	92.74	99.87	97.65	95.23		99.11	99.11	99.11	98.33	93.12	97.98	99.40	99.44	98.65
Mg N°	Gorman C early.Phl 39.4	Tags, GOI Kís	890/21 Gri.R 13.0	Grt.adj 13.8	Grt.R 12.2	Phl.adj 46.1	iPhi 47.0	-	Gorman C Grt.R 18.4	Crags, GOI Grt 20.1	190/23 Grt.R 17.8	11.6.91 Gri.R 19.2	P1.adj	Kfs	P1.away	Grt.C.r2 19.0	Grt.R 15.3	Phl.adj 46.3	Phi.away 43.4		Gorman C Grt.C.r3 27.5	Crags West, Grt.R 24.9	, GW'90/3 Grt.adj 22.8	Grt 23.9	16.5.91 Phl.adj 68.8	Philiate 67.5	9.7.91 Spl.incl 26.6	SpLincl 25.9	Spł.R 26.3
Sin	31.13	63.03	3610	36.23	36.04	11.19	31.85		36.77	37.15	36.68	37.01	59.97	63 24	60.60	37.00	36.8.1	31 19	33.67		38 20	37.90	36.96	37.96	36.66	37 50	0.03	0.01	0.03
1001	18 11	19 31	20.07	21.00	20.04	18.81	10.31		21.26	21.21	21.08	21.05	21.16	19.15	2111	21.11	20.07	17.94	1913		21.85	21.68	21.28	21 72	16.02	16.66	57.90	57 18	57.22
- E-0	20.41	0.01	37.56	27.36	20.90	10.01	19.31		21.15	21.24	21.00	21.05	0.05	0.45	0.00	21.71	20.97	10.20	20.63		21.65	21.00	22.07	22.72	10.52	10.00	35.60	37.40	25.76
- FeO	20.03	0.01	37.30	57.50	57.08	19.25	10.76		34.43	33.93	24.28	33.33	0.05	0.05	0.00	33.74	33.30	19.50	20.33		32.38	33.07	33.91	33.03	12.50	13.10	25.00	23.93	25.70
Fe203	-					•	-				-		-	-	•		-	-	-								1.59	1.37	0.98
MgU	1.33	0.01	3.15	3.30	2.93	9.23	9.33		4.30	4.79	4.18	4.49	0.00	0.00	0.00	4.44	3.60	9.33	8.84		6.93	0.10	5.64	5.93	15.51	15.29	5.45	5.54	3.33
MnO	0,00	0.01	0.84	0.89	0.93	0.02	0.04		0.79	0.80	0.79	0.79	0.00	0.00	0.00	0.80	0.96	0.00	0.00		0.40	0.49	0.50	0.47	0.00	0.00	0.00	0.00	0.00
TiO2	3.30	0.00	0.03	0.04	0.00	1.80	1.76		0.03	0.00	0.04	0.10	0.00	0.00	0.00	0.02	0.00	2.92	3.23		0.00	0.01	0.02	0.00	4.02	3.36	0.03	0.05	0.06
Cr2O3	0.00	0.00	0.00	0.03	0.03	0.03	0.03		0.03	0.04	0.00	0.04	0.04	0.02	0.05	0.01	0.00	0.05	0.00		0.00	0.00	0.03	0.00	0.11	0.06	1.71	1.94	1.98
Na2O	0.07	0.83	0.01	0.02	0.03	0.06	0.06		0.00	0.00	0.02	0.00	7.68	0.99	7.89	0.00	0.00	0.01	0.05		0.01	0.00	0.01	0.00	0.10	0.09	-	-	-
CaO	0.01	0.01	0.71	0.71	0.72	0.00	0.00		1.58	1.56	1.49	1.84	5.95	0.01	5.98	1.49	1.49	0.00	0.14		0.97	1.16	1.03	1.09	0.00	0.06	-	-	-
K2O	9.51	15.42	0.01	0.00	0.02	9.28	9.46		0.00	0.00	0.00	0.00	0.21	15.19	0.20	0.01	0.00	9.45	8.61		0.00	0.00	0.00	0.01	9.37	9.02	-	-	-
NiO	0.00	0.00	0.01	0.06	0.00	0.08	0.00		0.00	0.00	0.00	0.00	0.02	0.04	0.04	0.00	0.00	0.07	0.04		0.00	0.00	0.05	0.00	0.00	0.06	017	0.19	0.19
ZeO	0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	7.81	7 39	7 37
Totale	03 58	07.63	00 18	00 78	11 00	93.08	93.63		60.00	00.51	08 57	08.88	98 37	08.08	08 86	08 01	00.42	01 15	01 74		100.05	100.47	00.18	100.80	0.1.35	05.18	100.09	00 70	08.86
I OTALS	<i>,,,,</i> ,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,	77.05	//.50	<i>,,,,</i> ,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,	<i>,,,</i> ,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,	75.00	,,,,,,		,, <u>.</u>	<i>)).</i>	30.57	70.00	10.57	90.00	70.00	30.51	33.42	22.12	75.24		100.55	100.47	<b>77.40</b>	100.00	34.55	33.10	100.05	37.10	90.00
	C		CW OD /										~ ~		CINICOLA														
	Coman C	ags nesi	C-1-7	5-1-7	Cal man		6-1-2	5-1-1	6-1-1	6-1	6.1-11		Gornan C	rags wesi	, UN 90/4	10		6.1.1	6.1.2	6 1 . 2		6 1 G . A	<b>C I D A</b>	<b>c</b> .	<b>.</b> .	<b>.</b>	~ .	<b>~</b> ·	<b>F 1</b>
Ma Mo	26 7	217	3pt12 374	26.0	spisym.	2 3p132	5p112	3pt12	api.1	opinci.i	Spirci.i		1,111	ri	rm Gre	um.ad)	Spir3	- 20C	Spira	Spirs	Spiri	Spi.C.14	- 201K 14	spi.sym	spisym	opi.sym	spisym	Spi.sym	rnisym
AND IN	20.7	24.7	27.4	20.9	21.3	20.8	20.9	28.1	28.0	29.4	21.3				02.9	1.0	19.2	20.0	19.7	19.0	18.1	19.0	19.4	19.6	19.8	19.1	18.5	18.7	61.3
5102	0.03	0.03	0.13	0.01	0.00	0.03	0.03	1.03	0.01	0.02	0.00		58.10	58.29	30.04	0.00	0.08	0.00	0.02	0.01	0.03	0.03	0.01	0.01	0.03	0.01	0.18	0.03	35.13
AI203	57.63	57.80	58.90	28.89	39.80	59.30	59.29	59.00	59.40	58.23	59.04		20.30	20.35	15.04	0.00	56.79	20.89	57.12	57.39	57.29	57.89	57.30	57.76	57.39	58.69	57.78	59.38	15.30
reu	25.40	24.15	25.29	25.30	25.83	25.68	25.51	26.43	25.19	25.06	25.36		-	-	14.45	45.80	21.08	20.36	20.80	20.55	23.35	23.04	22.80	22.95	21.62	22.61	23.50	24.10	14.86
Fe203	1.32	0.54	0.36	0.97	0.43	1.08	0.78	0.00	0.80	0.38	1.15		0.00	0.00	0,00	0.00	1.27	1.06	0.96	0.82	0.93	1.17	1.47	1.34	1.54	0.50	0.41	0.08	•
MgO	5.42	4.64	5.44	5.40	5.50	5.47	5.43	5.78	5.66	5.93	5.58		0.00	0.00	13.76	0.43	2.96	3.00	2.99	2.93	3.00	3.28	3.26	3.32	3.19	3.07	3.05	3.11	13.20
MnO	0.00	0.00	0.03	0.04	0.03	0.05	0.04	0.03	0.04	0.00	0.01		0.00	0.00	0.00	0.14	0.00	0.01	0.00	0.03	0.01	0.02	0.02	0.00	0.02	0.02	0.01	0.01	0.05
TiO2	0.01	0.03	0.02	0.00	0.02	0.01	0.04	0.08	0.04	0.70	0.03		0.00	0.00	4.46	51.31	0.04	0.03	0.08	0.05	0.05	0.02	0.04	0.04	0.04	0.05	0.08	0.04	4.04
Cr2O3	1.70	0.70	0.12	0.15	0.10	0.12	0.12	0.13	0.52	0.84	0.57		0.00	0.02	0.08	0.04	0.90	0.96	0.87	0.86	0.50	0.31	0.34	0.20	0.43	0.61	0.42	0.43	0.06
Na2O	-	-	•	-	•	-	•	-	-	•	-		6.63	6.75	0.06	0.01	-	-	-	-	•	-	•	-	-	•	-	-	0.06
CaO	-	-	-	-	•	•	-	•	-	•	•		8.46	8.25	0.00	0.01	-	-		-	-		-	-	-	-			0.03
K2O	-	-	•	•	-	•	•	•	-	•	•		0.27	0.27	9.91	10.0	-	-	-	•	-	-	-			-	-	-	8.77
NiO	0.19	0.18	0.13	0.13	0.12	0.11	0.14	0.13	0.13	0.13	0.15		0.00	0.02	0.03	0.00	0.04	0.06	0.08	0.03	0.06	0.00	0.03	0.04	0.05	0.04	0.04	0.07	0.04
ZnO	7.72	9.36	7.90	7.88	7.74	7.75	7.90	7.44	8.06	8.14	7.94		0.00	0.00	0.00	0.00	16.84	17.34	17.09	17.57	14.06	14.36	14.33	14.30	15.99	15.68	14.40	14.16	0.00
Totals	99.48	98.02	98.38	98.78	99.69	99.60	99.27	100.05	99.84	99.43	99.83		99.87	99.94	94.42	97.74	100.00	99.71	100.01	100.22	99.28	100.11	99.59	99.95	100.29	101.27	99.86	101.41	92.13
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	Cormen	Cener W're	CW OOM											Wall Des	1. 11/00/2		14 6 01						5						
	Kfs.r4	PhLr4	Grt.R	Grt.C.r5	Grt.R.r5	Grt.r5	P1.15	PLr5	Kfs.r3	P1.r2	PhLr2			wan rea Phi.rl	P.late.rl	Phirt	P.late.rl	P.late.rl	Phiri	P.late.rl	Plate rl	PhLrl	P.late.rl	P.late.rl	Phi.R?	Phi.R2	P.late.R	Plate.R2	PhLR?
Mg N°	-	61.9	22.6	23.0	22.2	22.1			-		61.7		Mg N°	63.3	66.9	64.0	65.1	62.2	62.8	63.8	62.8	62.7	62.4	63.4	50.8	50.6	50.5	49.7	52.3
SiÖ2	65.22	37.10	37.63	37.76	37.50	37.54	58.24	58.29	64.77	58.40	37.13		SiO2	36.02	36.47	35.99	35.91	36.09	36.34	36.04	36.29	36.50	35.76	35.88	33.43	35.21	34.21	35.12	35.25
AI2O3	19.15	15.32	21.69	21.78	21.76	21.91	26.67	26.60	19.22	26.55	15.41		AI2O3	19.66	19.71	19.55	19.78	19.34	19.31	19.54	19.38	19.99	19.82	19.83	18.69	18.86	18.74	18.62	18.89
FeO	0.00	14.84	33.54	33.88	33.88	33.70	0.04	0.06	0.04	0.03	14.90		FeO	14.91	13.78	14.67	14.11	15.40	15.12	15.01	14.92	14.98	15.25	14.91	19.14	17.89	18.68	18.47	17.45
Fe2O3	-	-	•	-	-	-	-	•	-	•	•		MgO	14.46	15.62	14.64	14.78	14.22	14.31	14.85	14.11	14.11	14.18	14.50	11.09	10.29	10.70	10.24	10.72
MgO	0.00	13.55	5.50	5.67	5.43	5.37	0.00	0.00	0.02	0.00	13.47		MnO	0.01	0.03	0.11	0.06	0.04	0.04	0.00	0.03	0.01	0.02	0.00	0.00	0.07	0.00	0.00	0.02
MnO	0.00	0.01	0.42	0.38	0.41	0.37	0.00	0.00	0.02	0.02	0.00		TiO2	0.23	0.20	0.18	0.07	0.17	0.15	0.19	0.20	0.14	0.14	0.20	2.64	3.23	2.90	3.02	2.89
TiO2	0.03	4.38	0.00	0.00	0.06	0.01	0.00	0.01	0.00	0.00	4.24		Na2O	0.18	0.17	0.19	0.17	0.16	0.15	0.15	0.13	0.15	0.17	0.16	0.13	0.12	0.15	0.10	0.12
Cr2O3	0.00	0.13	0.05	0.00	0.07	0.00	0.00	0.00	0.01	0.00	0.07		CaO	0.08	0.10	0.07	0.03	0.02	0.06	0.03	0.02	0.06	0.00	0.04	0.03	0.01	0.02	0.03	0.02
N320	2.77	0.10	0.04	0.00	0.03	0.00	0.81	0.72	1.52	0.00	0.04		K_0	9.18	9.17	9.57	9.75	9.51	9.14	9.29	9.77	9.69	9.51	9.13	8.39	9.69	8.92	9.71	9.87
10	0.02	0.00	1.30	1.32	1.47	1.30	8.39	8.24	0.00	8.42	0.00		r Cl	0.72	0.94	1.24	0.84	0.98	0.72	0.82	0.77	0.96	0.83	0.95	0.33	0.36	0.56	0.55	0.38
NIO	11.03	9.01	0.02	0.01	0.03	0.00	0.12	0.13	13.11	0.28	8.90		CI Tarah	0.00	0.01	0.03	0.02	0.02	0.03	0.01	0.02	0.02	0.01	0.04	0.03	0.02	0.02	0.03	0.02
7n0	0.01	0.01	0.00	0.00	0.09	0.00	0.14	0.00	0.00	0.01	0.03		Totais	95.45	90.18	90.22	95.52	93.94	93.30	93.93	95.65	90.01	93.69	93.03	93.89	95.74	94.90	93.88	90.03
Totals	98.83	94.43	100.19	100.80	100.72	100.18	100.41	100.06	98.76	100.30	94.74																		
	Wall Peal	k. W90/2		17.8.91																									
	Gri.Tr	Grt.Tr	Gri.Tr	Grt.Tr	Gri.Tr	Grt.R	Ph1.adj	P1	Grt.R	Grt.C	Grt	Grt.R	Ph1.adj	P1.adj	PLaway	Kfs	Grt.r4	Gn.R	PI adj	Ch1.24	Ch1.26	Ch1.27	Chl.28	Chi 25	Kfs	Grt.R	Grt.C		
Mg N°	18.8	20.6	21.3	17.4	17.7	16.0	64.4	•	16.2	20.0	18.9	18.1	60.7	-	-	-	19.3	14.5	-	58.8	58.4	59.4	60.0	59.5	•	15.6	21.2		
SiO2	36.22	37.80	37.19	37.33	36.87	37.52	36.81	60.83	36.93	37.84	37.84	37.62	36.04	60.21	58.81	64.87	37.43	37.03	59.01	29.06	28.75	28.41	28.37	29.55	63.83	37.07	37.80		
A1203	22.67	21.90	21.80	21.70	21.75	21.83	20.48	25.30	21.63	21.74	21.88	21.84	20.24	25.75	26.52	19.31	21.79	21.54	26.78	19.30	19.00	19.26	18.53	19.04	18.90	21.55	21.74		
FeO E=203	33.79	34.17	33.70	35.90	35.23	36.14	14.05	0.40	35.26	34.31	34.72	34.79	15.19	0.34	0.00	0.00	34.64	35.70	0.27	21.49	22.23	21.93	20.61	20.70	0.34	35.76	33.98		
MgO	4.38	4.97	5.11	4.26	4.25	3.86	14.27	0.00	3.82	4.82	4.55	4.32	13.17	0.00	0.00	0.01	4.65	3.41	0.00	17.19	17.54	18.04	17.34	17.07	0.03	3.70	5.13		
MnO	1.11	1.09	0.99	1.18	1.12	1.15	0.00	0.01	1.16	1.04	1.14	1.22	0.00	0.00	0.00	0.00	1.36	1.41	0.00	0.13	0.06	0.01	0.07	0.00	0.01	1.45	1.25		
TiO2	0.00	0.00	0.02	0.00	0.00	0.00	0.32	0.05	0.05	0.02	0.04	0.01	0.74	0.04	0.01	0.00	0.00	0.00	0.03	0.10	0.07	0.08	1.20	0.20	0.01	0.02	0.00		
Cr2O3	0.05	0.00	0.04	0.00	0.02	0.06	0.05	0.03	0.01	0.00	0.01	0.00	0.04	0.02	0.00	0.04	0.01	0.06	0.00	0.04	0.08	0.03	0.00	0.03	0.01	0.00	0.01		
Na2O	0.02	0.01	0.02	0.00	0.00	0.01	0.22	7.84	0.01	0.02	0.01	0.01	0.19	7.79	7.07	1.62	0.01	0.03	6.73	0.01	0.00	0.01	0.00	0.02	0.18	0.02	0.01		
CaO	1.51	1.57	1.60	1.10	1.18	1.00	0.06	6.03	1.35	1.54	1.56	1.42	0.03	6.26	7.40	0.06	1.65	1.64	8.12	0.08	0.04	0.07	1.08	0.06	0.00	1.69	1.59		
K20	0.04	0.00	0.00	0.01	0.00	0.00	9.23	0.11	0.01	0.02	0.00	0.00	8.70	0.12	0.18	14.02	0.00	0.02	0.10	0.35	0.27	0.05	0.10	0.59	16.05	0.00	0.02		
NIO 7=0	0.10	0.00	0.00	0.00	0.04	0.00	0.13	0.01	0.02	0.00	0.01	0.00	0.09	0.06	0.00	0,00	0.06	0.00	0.08	0.01	0.10	0.00	0.06	0.05	0.00	0.00	0.02		
Totals	99. <b>89</b>	101.50	100.47	101.47	100.46	101.57	95.61	100.61	100.25	101.35	101.75	101.23	94.43	100.59	99.99	99.93	101.59	100.82	101.11	87.75	88.14	87.88	87.36	87.28	99.35	101.25	101.55		
										•																			
	Wall Peak	. W90/3	_	2.7.91						_	_							<b>_</b> .					~ •			·			
	Grt.C.rl	Grt	Grt	Grt.R	Rutile.adj	Rutile.adj	Rutile	Phi.adj	Ilmenite	PI	Pl	Phi.adj	GrLR	Grt.r3	Phlincl	Pol	Grt.adj	Grin	Grik	Grt.K	Kis.adj	Phi.adj	GILID	CTIU.	P.Iale ID	limenste	GILK	Philadj	Spli 12
Mg N°	21.0	21.5	22.0	21.9	8.7	0.0	0.0	00./	1.9			63.3	10.1	19.1	37.3	36.7	10.9	18./	19.0	18.8		39.8	15.5	25.51	35.0	1.3	17.0	25.05	20.3
5:02	37.81	31.41	31.34	37.17	0.98	. 0.37	0.33	30.82	0.00	03.33	04.03	30.40	37.03	37.01	30.23	33.93	31.31	31.31	37.39	37.43	19 40	30.09	20.98	16 22	33.40	0.03	20.01	33.93	59.12
AL203	21.39	21.79	21.50	21./1	0.50	0.43	0.79	10.03	0.19	22.54	22.02	10.01	21.42	21.01	16.23	10.33	21.42	21.30	21.27	21.30	18.00	15 40	21.28	10.23	17.90	16.93	20.97	10.11	23.12
Fe0	33.12	34.99	34.70	34.94	1.74	13.69	0.02	13.74	40.00	0.39	0.52	14.33	37.03	50.11	10.42	10.05	30.94	30.20	33.00	33.90	0.00	13.49	37.50	11.12	17.00	40.05	50.40	10.07	23.07
NeO	5 22	5 30	5.10	5 10	017	0.07	0.02	14 70	0.10	0.01	0.00	11.07	107	4 70	12.48	12.25	4 20	4 68	471	4 68	0.01	12.96	379	11.23	11.32	0.34	1 21	11.56	516
MaO	031	0.31	0.30	0.30	0.03	0.04	0.02	0.02	0.00	0.01	0.00	0.00	0.33	0.16	001	6.00	0.10	0.32	0.13	0.10	0.01	0.00	0.38	0.00	6.00	0.05	0.39	0.03	0.01
TiO	0.03	0.54	0.00	0.29	90.32	78.26	92.66	1.28	50.89	0.24	0.23	3 18	0.00	0.01	3.52	3.44	0.03	0.04	0.00	0.04	0.01	2.78	0.03	4.24	4.20	51.12	0.00	3.97	0.00
Cr203	0.01	0.01	0.04	0.01	0.04	0.00	0.00	0.07	0.02	0.04	0.03	0.06	0.02	0.04	0.04	0.02	0.01	0.02	0.00	0.01	0.00	0.00	0.03	0.00	0.00	0.03	0.00	0.01	0.22
Na2O	0.00	0.00	0.02	0.01	0.01	0.02	0.00	0.34	0.00	9.32	9.33	0.35	0.01	0.00	0.14	0.19	0.00	0.01	0.00	0.00	1.40	0.12	0.00	0.17	0.16	0.00	0.02	0.14	-
CaO	0.65	0.70	0.71	0.54	0.00	0.02	0.10	0.00	0.01	3.53	3.69	0.01	0.72	0.71	0.01	0.05	0.01	0.66	0.65	0.69	0.00	0.08	0.58	0.00	0.00	0.03	0.72	0.01	-
К2О	0.00	0.00	0.01	0.01	0.01	0.00	0.01	9.39	0.00	0.02	0.04	9.29	0.00	0.00	9.51	9.11	0.00	0.00	0.00	0.02	14.84	9.16	0.00	9.63	9.62	0.00	0.00	9.68	-
NiO	0.03	0.01	0.00	0.02	0.00	0.00	0.00	0.00	0.04	0.06	0.04	0.00	0.00	0.00	0.13	0.04	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.03	0.00	0.07	0.00	0.05	0.03
ZnO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.11
Totals	100.62	100.71	100.17	100.57	93.74	93.07	94.57	95.08	98.52	99.69	100.58	94.55	101.23	100.74	94.71	94.21	100.34	100.83	100.34	100.64	98.92	94.52	100.44	94.78	94.59	98.52	99.49	95.58	99.69

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Mg N <sup>e</sup> SiO2 Al2O3 FeO Fe2O3 MgO MnO TiO2 Cr2O3 Na2O CaO NiO ZnO Totals	Walt Peak Spli 25.6 0.02 57.67 24.00 2.32 5.03 0.00 0.00 0.00 0.00 0.00 0.00 0.00	x, W90/3 Spil 25.6 57.49 23.85 1.90 4.94 0.02 0.02 0.02 0.02 0.11 9.92 98.52	Spli 25.1 0.01 57.73 24.33 1.97 4.89 0.03 0.00 0.30 0.00 0.30 - - - 0.01 9.79 99.05		Wall Peak Grt.rl 23.4 37.78 21.24 31.44 5.37 0.98 0.00 0.00 0.00 0.00 0.00 0.00 0.00	<ul> <li>W90/5 Grt.Tr 24.7</li> <li>37.99</li> <li>21.50</li> <li>31.19</li> <li>5.73</li> <li>0.89</li> <li>0.01</li> <li>0.03</li> <li>0.01</li> <li>3.18</li> <li>0.00</li> <li>0.00</li> <li>100.52</li> </ul>	Grt.C 24.2 38.13 21.68 31.28 	16.5.91 Grt.R 23.2 37.88 21.69 32.02 	Ph1.adj 68.4 37.46 14.58 13.10 - - - - - - - - - - - - - - - - - - -	P1 49.64 31.78 0.01 0.00 0.01 0.00 0.01 0.00 2.93 15.29 0.06 0.00 99.78	Opx.r2 52.i 2.43 28.48 17.34 0.46 0.07 0.04 0.02 0.21 0.00 0.03 0.00 99.51	Opx 52.0 50.29 2.25 28.67 17.41 0.54 0.03 0.00 0.16 0.01 0.00 99.35	Opx.R 51.6 50.47 1.96 29.04 	Opx C.sep 51.4 50.19 2.37 29.05 - 17.27 0.41 0.04 0.02 0.00 0.18 0.00 0.00 99.53	Opx.R 51.2 50.26 2.13 28.88 17.01 0.43 0.28 0.01 0.17 0.00 0.13 0.00 99.39	Ihm adj 2.3 0.03 0.01 44.53 - 0.60 0.55 51.79 0.00 0.00 0.01 0.00 0.00 0.00 97.52	PLadj 48.12 32.90 0.09 0.00 0.03 0.00 0.00 2.31 16.26 0.03 0.00 99.75	Phi.adj 64.0 36.80 14.31 14.67 	Ph1 63.0 37.13 14.64 14.90 - 14.21 0.09 4.49 0.16 0.12 0.00 9.32 0.00 9.32 0.00 95.06		Lensink P Amph.rl 57.0 36.93 13.70 17.69 - 13.18 0.17 3.52 0.73 0.13 0.05 7.95 0.14 0.00 94.17	eak, S90/2 Amph.rl 58.3 42.45 9.11 20.93 - 16.45 0.19 0.11 0.18 0.04 1.52 0.04 0.04 1.52 0.00 91.07	Sphene 27.1 23.89 1.82  0.18 27.48 2.26 0.01 3.74 0.13 0.00 62.82	16.6.91 Amph.rl 56.1 36.63 13.61 18.48 - 13.23 0.11 3.83 0.60 0.09 0.04 8.11 0.00 94.75	Ph1.r2 58.5 37.21 13.28 17.02 13.45 0.06 4.40 0.10 0.11 0.12 8.70 0.02 0.00 94.47	Amph r2 57.9 39.07 9.09 20.38 15.71 0.04 0.07 0.03 0.01 1.69 0.00 0.00 0.00 86.09	Amph.r2 60.2 40.45 7.77 18.29 	Anthoph 58.3 57.10 0.64 21.08 - - 16.56 0.71 1.16 0.05 0.05 0.30 0.00 0.00 97.63	Anthoph 60.4 59.37 0.65 18.77 0.65 18.77 0.01 0.00 0.04 0.35 0.00 0.04 0.00 95.85
	Lensink P Anthonh	eak, S90/2 Anthonh	Amob r3	Amph 13	Ph1 adi	K fe	Pirt	Amob	Amph	Phi adi	Ð	PL-5	Ph175		Con C of	eak, S90/5 Gri	Grt	4.5.97 Grt P	Phi adi	Pladi	Get	Gan	Rt even	Crdeam	Grdeum	Gradi C	Phi	Brn adi	
Mg N°	62.4	60.2	56.9	60.0	57.0	-	-	63.2	62.5	66.9		-	70.4		24.6	22.5	20.2	18.5	52.6		16.3	17.9	53.0	72.3	70.6	15.4	54.3	0.1	
SiÕ2	57.29	58.02	39.04	41.91	37.22	47.45	50.50	38.65	39.28	37.96	50.10	50.22	38.37		37.67	37.35	37.24	37.16	35.41	62.37	36.69	36.81	35.01	48.13	48.03	36.40	35.59	0.01	
A12O3	0.57	0.84	9.59	8.29	13.00	35.07	31.77	10.60	9.79	14.29	32.04	32.03	13.76		21.45	21.23	21.25	21.07	17.82	23.76	20.91	21.11	17.95	32.53	32.67	21.07	17.87	0.00	
FeO	19.25	18.97	21.29	19.41	17.71	0.86	0.03	19:28	19.10	14.38	0.04	0.06	12.72		33.23	34.29	34.74	35.19	17.16	0.12	35.62	35.01	16.32	6.44	6.90	35.29	16.55	45.82	
16203	17.06		1575	16 33	1218	-	-	19 59	1795	16 30	-	0.00	16.05		6.00	5 57	4.03			0.01	3.00	-	10.21	-	0.77	2.60	11.01	-	
MnO	0.64	0.63	016	0.00	0.00	0.43	0.00	011	0.19	018	0.01	0.00	0.12		0.03	1.03	1 3 4	4.49	0.09	0.01	1.67	1.20	0.00	0.08	9.27	1.55	0.02	0.05	
TiO2	0.06	0.05	0.15	0.07	4.00	0.01	0.00	0.21	0.08	2.99	0.03	0.04	3.71		0.03	0.04	0.02	0.04	4.22	0.00	0.02	0.06	3.24	0.00	0.00	0.03	3.35	49.79	
Cr2O3	0.04	0.06	0.04	0.07	0.22	0.00	0.00	0.09	0.13	0.15	0.05	0.00	0.14		0.06	0.05	0.04	0.08	0.15	0.03	0.06	0.06	0.35	0.01	0.01	0.13	0.01	0.00	
Na2O	0.04	0.06	0.03	0.03	0.13	0.51	3.41	0.01	0.02	0.13	3.30	3.24	0.15		0.00	0.00	0.02	0.00	0.04	8.17	0.00	0.03	0.07	0.04	0.10	0.03	0.05	0.03	
CaO	0.21	0.66	1.50	1.82	0.08	1.42	14.43	1.17	1.24	0.01	14.46	14.80	0.00		0.67	0.73	0.83	0.80	0.00	5.19	0.82	0.92	0.00	0.00	0.00	0.85	0.00	0.00	
K2O	0.02	0.02	0.01	0.04	7.88	8.93	0.00	0.14	0.03	8.12	0.08	0.02	8.88		0.03	0.02	0.00	0.01	9.66	0.15	0.02	0.00	9.31	0.00	0.00	0.02	9.43	0.02	
NiO	0.03	0.00	0.05	0.08	0.01	0.04	0.05	0.11	0.09	0.12	0.05	0.00	0.00		0.00	0.02	0.03	0.00	0.06	0.02	0.06	0.00	0.06	0.00	0.01	0.02	0.02	0.00	
ZnO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
lotais	90.10	95.42	87.01	88.23	93.43	94.70	100.21	88.99	87.80	94.04	100.17	100.41	94.80		100.14	100.35	100.43	100.32	95.20	99.93	99.77	99.63	92.64	90.00	96.99	99.00	93.95	96.12	
	Lensink P	eak, \$9077	C Te	14.11.91 C→ C	CHR	DALL and	DI T.	DI	DI	22.11.91	C-		Simon R	idge, SIMO	N90/T	Ca	Colodi	Cotesti	Diadi	Call	Dhiadi	DN	Call	Cet	Ca	Distint	Gra	Ca	Gr
Ma Nº	12.5	Pm.acj 55 g	21.0	217	220	F(0.ac) 56.2	P1.11	ri	ri	10.1	21.5		215	281	28.5	28.6	7011.acg	≠0.01.aug 28.3	FLAG	107	F 111.40g	63.6	- <b>18</b> 2	28.1	28.0	68.8	28.4	27.6	78.1
SiOn	36.85	35 78	37 30	37.63	37 79	35.71	\$7.99	56 51	57 73	37 27	37.72		37.34	37 86	37.79	37.66	37.37	38.42	59.07	36.72	37.26	36.79	37 80	37.60	37.71	36.59	37.54	37.58	37.54
APO3	20.72	15.63	20.83	20.85	20.58	15 41	25.99	26.24	25.86	21.43	21.08		21.05	21.32	21.22	21.31	21.38	20.91	24.83	20.75	15.62	14.35	21.28	21.58	21.33	16.47	21.47	21.41	21.14
FeO	33.94	17.32	29.92	29.75	30.80	17.07	0.03	0.02	0.02	30.46	29.28		30.55	29.89	29.27	29.28	29.24	28.88	0.10	32.17	11.86	13.67	29.21	29.09	29.68	12.46	29.47	29.96	29.48
Fe2O3	-		-	-	-	-	-	-	-	-	-		-	-	-	-	•	-	-	-	-	-		-	-	•	-	•	-
MgO	2.97	12.29	4.46	4.63	4.88	12.27	0.00	0.00	0.00	4.09	4.50		2.25	6.55	6.54	6.58	6.32	6.39	0.00	4.29	14.15	13.40	6.43	6.39	6.48	15.41	6.56	6.41	6.56
MnO	3.09	0.07	3.58	3.23	2.43	0.00	0.01	0.00	0.00	2.36	2.59		0.61	0.44	0.48	0.56	0.57	0.58	0.06	0.66	0.00	0.00	0.60	0.63	0.62	0.02	0.54	0.67	0.59
TiO2	0.00	2.42	0.00	0.02	0.00	2.85	0.00	0.03	0.00	0.00	0.00		0.06	0.00	0.00	0.00	0.00	0.03	0.01	0.05	3.73	5.00	0.11	0.03	0.00	2.68	0.00	0.01	0.03
Cr203	0.02	0.00	0.05	0.02	0.00	0.06	0.00	0.00	0.03	0.07	0.04		0.12	0.05	0.10	0.05	0.00	0.00	0.00	0.00	0.04	0.13	0.09	0.00	0.05	0.10	0.05	0.09	0.05
N320	2.00	0.07	1.70	0.01	2.10	0.00	0.20	5.94 0.69	0.33	0.01	1.67		0.00	0.01	0.00	0.02	0.00	0.00	1.24	0.02	0.00	0.03	1.30	1.59	0.00	0.00	0.01	0.02	0.00
K20	0.01	9.56	0.00	0.00	0.00	9.64	0.15	9.00	0.17	4.10	0.00		0.02	0.00	0.00	0.00	0.01	0.01	0.14	0.02	9.33	9.66	0.00	0.01	0.00	8.28	0.01	0.01	0.02
NiO	0.08	0.00	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.00	0.03		0.00	0.06	0.00	0.13	0.11	0.24	0.00	0.11	0.06	0.00	0.00	0.00	0.07	0.04	0.00	0.02	0.07
ZnO	-	-	-	-	-	-	-	•	-	•	•		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Totals	99.77	93.14	99.95	100.27	99.18	93.13	99.54	98.58	99.00	99.84	99.89		93.54	97.58	96.96	97.15	96.61	97.03	98.22	96.33	92.20	93.04	96.89	96.94	97.60	92.15	97.06	97.62	96.93

	Simon Ri	dge, SIMU	N90/1		6.7.91							
	Grt	Grt	Grt	Grt.R	Grt.R	Grt	Grt.C	Grt.C	Grt	Grt.R	P1.adj	Pl.adj
Mg N°	27.6	28.4	28.2	27.8	26.9	26.7	27.4	27.0	27.3	27.0	•	•
SiO2	37.58	37.54	37.63	37.92	37.70	37.59	37.66	37.84	37.59	37.86	58.45	58.97
AI2O3	21.41	21.14	21.44	21.13	21.24	21.29	21.25	21.24	21.33	21.40	25.42	24.88
FeO	29.96	29.48	29.53	29.54	30.72	31.49	31.00	31.58	31.44	30.95	0.14	0.12
Fe2O3	-		-	•	•	-	•	-	•	•		
MgO	6.41	6.56	6.49	6.38	6.35	6.44	6.55	6.56	6.62	6.43	0.00	0.00
MnO	0.67	0.59	0.41	0.46	0.69	0.60	0.63	0.76	0.74	0.63	0.00	0.00
TiO2	0.01	0.03	0.03	0.02	0.05	0.00	0.00	0.06	0.04	0.00	0.06	0.06
Cr2O3	0.09	0.05	0.06	0.00	0.01	0.07	0.03	0.14	0.13	0.05	0.03	0.00
Na2O	0.02	0.00	0.04	0.03	0.02	0.00	0.00	0.00	0.00	0.01	6.89	7.23
CaO	1.45	1.46	1.39	1.65	1.97	1.53	1.66	1.49	1.61	1.70	7.50	6.82
K2O	0.01	0.02	0.02	0.04	0.00	0.00	0.01	0.00	0.02	0.00	0.26	0.33
NiO	0.02	0.07	0.09	0.00	0.06	0.02	0.10	0.03	0.00	0.00	0.00	0.14
ZnO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Totals	97.62	96.93	97.12	97.16	98.82	99.03	98.88	99.71	99.50	99.03	98.76	98.55

Central and Eastern region

Mt Lanyon	LAN/I
Mt Lanyon	LAN/2
Mt Lanyon	LAN/10
Mt Lanyon	LAN/19
Mt Lanyon	LAN/23
Mt Meredith	MER/10
Mt Meredith	MER/11
Mt Meredith	MER/27
Mt Meredith	MER/52
Brocklehurst Ridge	BRO6
Brocklehurst Ridge	BROII
Brocklehurst Ridge	BRO12
Brocklehurst Ridge	BRO15
O'Leary Ridges	OL90/4
O'Leary Ridges	OL90/7
Taylor Platform	TP14
Taylor Platform	TP13
Fox Ridge	FOX14
Fox Ridge	FOX18
Fox Ridge	FOX10
p-	

	Mi Lanyo	n, LAN/I		29.11.91											Mt Lany	m, LAN/2		29.11.91										
	Grt.R	Grt.Tr	Grt.Tr	Grt. Tr	Grt.Tr	Grt Tr	Grt.C	Grt.R	lim.adj	Ph1.adj	Kfs	Grt.R	llm.adj	Kfs	Grt.R	Grt.R	Ph1.adj	Grt.6	Ph1.adj	Grt.C	Grt	Grt	Grt	GrLR	Ph1.adj	Grt.C	Grt.R	Ph1.ad
Mg N°	21.7	21.9	24.6	26.5	27.4	26.6	27.9	24.2	2.4	70.5	-	23.7	2.4	-	10.8	11.0	38.1	14.0	38.6	25.6	21.3	19.3	17.9	9.7	39.1	24.9	13.7	36.9
SiO2	37.39	37.49	37.48	37.76	37.67	37.96	37.63	37.54	0.01	37.12	62.73	37.36	0.05	64.27	36.87	36.87	34.97	36.97	34.45	37.90	37.63	37.21	36.99	36.86	34.14	37.80	36.73	34.08
AI2O3	20.96	20.84	20.81	21.25	21.04	21.04	21.01	20.93	0.00	16.04	18.41	20.76	0.00	18.11	20.78	20.74	19.99	20.92	19.76	21.26	21.05	20.97	21.12	20.45	19.96	21.40	20.70	19.58
FeO	34.75	34.55	33.65	33.04	32.44	32.47	32.16	33.80	45.61	11.81	0.32	33.62	45.13	0.03	38.27	38.60	21.64	37.74	21.21	33.19	35.37	35.81	36.03	39.10	21.36	33.65	37.46	22.08
Fe2O3	-	-	-	-	-	-	•	-	-	-	-	-	-	-	-	-	-	-	-	-		-	-	-	-	-	-	-
MgO	5.42	5.43	6.16	6.67	6.87	6.59	6.98	6.07	0.63	15.88	0.09	5.87	0.64	0.00	2.60	2.69	7.48	3.44	7.49	6.40	5.36	4.81	4.4	2.35	7.68	6.26	3.33	7.25
MnO	0.10	0.11	0.15	0.01	0.06	0.08	0.16	0.04	0.00	0.00	0.00	0.13	0.01	0.00	0.55	0.45	0.01	0.39	0.00	0.37	0.34	0.27	0.21	0.48	0.00	0.32	0.30	0.00
TiO2	0.00	0.06	0.04	0.02	0.01	0.04	0.01	0.02	52.46	2.79	0.05	0.06	51.33	0.05	0.02	0.04	1.22	0.03	1.25	0.13	0.01	0.04	0.04	0.02	1.23	0.01	0.05	1.87
Cr2O3	0.00	0.01	0.01	0.06	0.06	0.01	0.04	0.08	0.00	0.07	0.04	0.01	0.04	0.05	0.00	0.02	0.02	0.02	0.06	0.01	0.03	0.00	0.01	0.04	0.07	0.05	0.03	0.00
Na2O	0.02	0.00	0.00	0.02	0.01	0.02	0.01	0.02	0.00	0.07	1.22	0.00	0.00	1.61	0.00	0.02	0.14	0.01	0.13	0.02	0.00	0.01	0.00	0.00	0.10	0.00	0.00	0.10
CaO	1.14	1.09	1.11	1.09	1.13	1.10	1.03	1.06	0.00	0.00	0.02	1.09	0.00	0.08	1.05	0.90	0.00	0.91	0.00	0.94	0.94	0.90	0.91	0.92	0.00	0.96	0.99	0.00
K2O	0.02	0.02	0.00	0.01	0.01	0.00	0.00	0.00	0.01	9.78	14.54	0.01	0.00	14.63	0.00	0.02	9.42	0.00	9.29	0.00	0.00	0.00	0.00	0.01	9.32	0.00	0.00	9.80
NiO	0.03	0.03	0.06	0.04	0.00	0.04	0.01	0.02	0.07	0.09	0.00	0.00	0.10	0.02	0.00	0.02	0.05	0.00	0.00	0.00	0.00	0.05	0.00	0.05	0.00	0.00	0.00	0.00
ZnO	-	-	-	-	-	-	-	-	-		-	•	-	-	-	-	•	-	-	•	-	-	-	•	-	•	•	-
Totals	99.82	99.61	99.46	99.97	99.30	99.34	99.03	99.57	98.78	93.63	97.41	98.91	97.30	98.86	100.16	100.36	94.94	100.42	93.62	100.21	100.73	100.05	99.73	100.27	93.87	100.46	99.59	94.75

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	Mt Lanyo Sob+Al	n, LAN90/ Soh+Al	10 Soh+Al	30.8.91 Amp	e/m.Cox	Cpx C rl	Cox.Tr	Cox.Tr	CDX R	adi Amoh	g/m Cox	CON	Cox Tr		adi Amp	Pht r3	adi Amn	Cox C	Cost Tr	Cox R	adi Amn	adi Amo	AmphrS	Amph adi	Phiadi	PI	Amobró	adi Seh	ndi Sob
Mg N°	0.7	-	-	38.8	39.7	33.3	34.1	35.6	36.2	36.7	38.1	49.2	49.1	49.7	31.1	45.4	49.7	39.1	39.6	44.7	30.1	26.1	53.9	51.6	54.3		18.4	auj.5pu -	aoj.spri •
SiO2	27.41	26.60	29.19	45.97	50.73	49.82	50.01	50.15	50.00	44.52	49.74	50.36	50.62	51.33	41.03	35.34	46.34	50.54	49.57	51.04	45.41	39.77	48.39	47.65	35.71	64.48	38.35	30.25	29.69
AI203	10.98	11.86	3.54	7.75	0.34	0.77	0.62	0.58	0.53	10.92	1.21	0.83	0.52	0.54	10.17	15.92	6.81	0.57	1.54	0.54	6.33	10.77	5.53	6.10	14.84	18.96	10.54	1.22	2.58
- FeO	3.12	1.14	1.12	17.20	18.11	20.13	19.80	19.17	19.22	17.03	18.42	15.03	15.59	15.43	23.80	21.41	18.03	18.38	18.58	10.83	25.15	25.30	17.58	18.15	19.89	0.05	27.71	0.61	0.82
MgO	0.00	0.00	0.00	6.11	6.69	5.66	5.77	5.95	6.12	5.53	6.36	8.48	- 8.46	8 54	6 0 5	10.00	10.31	6 07	682	7 63	6.08	5.01	1155	10.84	13.26	0.00	3.51	0.00	0.00
MnO	0.00	0.02	0.00	0.38	0.47	0.38	0.47	0.40	0.48	0.46	0.43	0.46	0.39	0.35	0.28	0.10	0.21	0.43	0.40	0.54	0.47	0.26	0.23	0.20	0.03	0.00	0.20	0.00	0.00
TiO2	32.01	31.33	35.13	0.11	0.05	0.07	0.05	0.05	0.03	0.10	0.01	0.06	0.08	0.07	0.63	2.67	0.56	0.04	0.06	0.05	0.26	0.40	0.37	0.48	0.81	0.03	0.94	36.61	35.86
Cr203	0.00	0.03	0.01	0.00	0.07	0.00	0.03	0.00	0.00	0.00	0.02	0.03	0.00	0.00	0.01	0.06	0.09	0.00	0.00	0.05	0.00	0.00	0.10	0.07	0.06	0.01	0.00	0.06	0.02
CaO	26.16	25.93	28 35	21.22	23 39	23.08	23.26	23 20	23.26	20.61	23 22	23 32	23.66	23.67	11.15	0.06	12.01	23.34	22.41	23 31	0.50	1.21	0.80	0.94	0.08	2.19	1.24	0.03	0.03
K2O	0.01	0.02	0.00	0.02	0.00	0.01	0.00	0.01	0.02	0.12	0.00	0.02	0.02	0.02	1.50	7.89	0.67	0.00	0.11	0.02	0.85	1.62	0.50	0.57	6.71	12.30	1.97	0.00	0.02
NiO	0.01	0.00	0.00	0.00	0.00	0.04	0.01	0.00	0.06	0.00	0.00	0.09	0.00	0.01	0.07	0.00	0.00	0.00	0.00	0.04	0.00	0.03	0.00	0.00	0.15	0.04	0.05	0.03	0.08
ZnO	9777	96 94	07 38	00 NR		100.31	100.45	00.88	100.04	00.61	00 71	-	-	-			06.57	-		- 42	-	-	-	-	-	-	-	-	
ICUE	ו•••	50.54	77.50	<i>,,,</i> ,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,	100.10	100.51	100.45	<i></i>	100.04	33.01	33.12	<b>33.00</b>	99.00	100.20	90.09	93.50	90.57	99.00	99.03	100.42	97.02	90.18	91.21	97.08	91.72	98.12	90.08	97.25	98.02
	NII Lanyo Pi Te	n, LAN/19 Pladi R	GalR	22.11.91 Get Te	Gally	Grt Tr	Get Tr	Crt C	Ры	DI	CriP 1	Gri Tr 1	Cet Tr 3	Get Tr 5	Ca Tr 7	Gri Tr 8	Get Te 0	Get Tr 10	Get Tr 11	Ga Tr 12	Get Tr 13	Gri Tr 14	Get Tr 15	Gri Tr 16	Gri R 17	Gri R	lim adi5	Ilm adi6	RatCH
Mg N°		63.6	20.9	19.7	26.9	30.2	38.6	39.0	68.1		20.2	31.6	39.2	41.5	41.8	38.4	37.6	39.2	40.2	39.9	41.8	42.4	41.1	27.0	19.6	19.5	0.6	0.9	0.0
SiÔ2	50.95	50.41	37.65	37.30	38.03	38.01	38.62	38.80	37.23	50.42	36.16	37.24	37.57	37.70	37.95	37.14	37.29	37.65	37.25	37.29	37.50	37.54	37.62	36.61	35.47	36.51	1.64	0.69	0.01
AI2O3	30.89	31.26	21.39	21.31	21.67	21.69	22.06	22.10	16.72	31.03	20.95	21.44	21.69	21.85	21.87	21.44	21.47	21.76	21.93	21.71	22.03	21.80	21.90	21.28	20.61	20.16	0.76	0.02	0.00
- FeO Ea2O3	0.04	0.00	33.04	33.80	31.81	30.23	27.06	27.31	12.09	0.05	34.20	29.72	27.20	20.37	26.37	21.32	27.98	27.28	26.88	20.01	26.60	20.10	20.48	31.99	33.43	33.96	37.29	39.93	0.52
MgO	0.00	0.07	4.98	4.64	6.58	7.33	9.54	9.79	14.45	0.00	4.87	7.70	9.83	10.51	10.65	9.57	9.46	9.87	10.16	9.90	10.73	10.79	10.35	6.63	4.59	4.61	0.14	0.20	0.00
MnO	0.00	0.00	0.66	0.62	0.47	0.35	0.55	0.42	0.02	0.00	0.79	0.43	0.35	0.45	0.40	0.41	0.44	0.34	0.41	0.45	0.38	0.29	0.40	0.43	0.74	0.89	1.45	1.05	0.08
TiO2	0.04	0.05	0.01	0.00	0.06	0.06	0.00	10.0	2.55	0.03	0.05	0.00	0.07	0.00	0.00	0.07	0.02	0.06	0.05	0.07	0.02	0.00	0.10	0.01	0.07	0.38	53.54	53.88	95.17
N203	3.61	3.20	0.00	0.04	0.05	0.01	0.02	0.00	0.01	1.50	0.00	0.02	0.00	0.05	0.00	0.02	0.03	0.00	0.04	0.00	0.07	0.00	0.00	0.04	0.00	0.02	0.01	0.00	0.15
CaO	13.78	13.30	1.51	1.45	1.48	1.49	1.62	1.49	0.00	14.02	1.46	1.43	1.60	1.48	1.58	1.58	1.60	1.56	1.50	1.48	1.48	1.61	1.51	1.41	1.43	1.49	0.20	0.11	0.00
K2O	0.08	0.31	0.00	0.00	0.00	0.00	0.00	0.01	9.83	0.09	•	•	-	-	-	-	•	-	-	•	•	-	•	•	-	0.00	0.11	0.06	0.00
NiO	0.00	0.00	0.01	0.00	0.00	0.00	0.05	0.00	0.11	0.00	•	•	·	•	-	•	-	-	•	-	-	•	•	-	-	0.07	0.00	0.00	0.00
ZnO Totals	99.41	98.75	99.85	99.16	100.15	99.17	99.51	99.93	93.08	- 99.18	- 98.49	97.98	98.37	- 98.45	98.84	97.55	98.27	98.51	98.21	97.52	98.81	98.16	- 98.36	- 98.40	96.34	98.07	95.13	95.94	95.92
	Mt Lanyo	n, LAN/19		7.12.91						Mt Lanyo	n, LAN/23	72523	7.12.91											~					
	PhLr3	Phlexs	Phi.exs	Phi.r4	Phiexs	Phi	PI	· Pi		Grt.R	Grt.Tr6	Grt.Tr7	Grt.Tr8	Grt.C10	Pl	PLincl42	PLinc118	PLincl21	Rutile	limR	llmR	Grt.adj	Crd.32	Crd.34	Crd.3/	Grt.adj	Phi.Rr2	Phi.C	KIS
Mg N <sup>a</sup>	69.3	70.4	70.0	70.8	69.6	69.7	40.92	50.01		21.4	22.9	32.7	38.1 38.67	38.4	60.58	57 80	58.01	57.88	0.0	0.01	0.02	37.43	43.03	43.52	42.42	37.18	37.22	37.57	64.01
302	38.19	15 56	38.33	15.95	36.28	16 28	30.66	30.17		2073	20.80	21.28	21.54	21.53	24.00	24.91	25.31	25.09	0.00	0.00	0.00	21.00	34.16	32.77	32.90	20.80	16.43	15.41	17.78
FeO	11.90	11.48	11.34	11.37	11.99	11.84	0.06	0.01		33.99	33.70	30.27	27.97	27.86	0.04	0.14	0.37	0.01	0.24	45.48	45.19	34.05	2.83	4.75	5.22	33.38	13.07	13.08	0.13
Fe2O3		-	-	•	-	-	•	•		•	•				-	-	-	-	-	-				-					-
MgO	1.5.05	15.34	14.86	15.47	15.42	15.29	0.00	0.00		5.21	5.63	8.25	9.66	9.75	0.00	0.03	0.00	0.00	0.00	0.45	0.03	0.10 0.59	4.45	5.84	4.20	5.84 0.57	14.90	14.30	0.00
TiO	7 57	7.18	272	2 21	261	2 37	0.00	0.00		0.01	0.01	0.04	0.04	0.08	0.03	0.01	0.02	0.02	94.99	51.50	51.40	0.06	0.01	0.00	0.00	0.01	2.32	3.20	0.01
Cr203	0.04	0.05	0.06	0.01	0.00	0.00	0.02	0.00		0.03	0.00	0.03	0.03	0.00	0.00	0.03	0.01	0.05	0.11	0.00	0.00	0.00	0.06	0.00	0.00	0.03	0.04	0.05	0.02
Na20	0.05	0.07	0.10	0.09	0.09	0.07	3.14	3.34		0.00	0.00	0.00	0.00	0.00	7.64	6.87	6.72	6.70	0.02	0.01	0.02	0.02	0.07	0.16	0.17	0.00	0.06	0.10	0.88
C3O	0.00	0.00	0.04	0.00	0.07	0.03	14.99	14.07		1.09	1.13	1.18	1.13	1.16	6.42	8.29	8.03	7.94	0.00	0.01	0.00	1.04	0.60	0.91	0.73	1.09	0.00	0.00	0.00
K2O	9.96	9.92	9.23	9.83	9.68	9.42	0.08	0.11		0.02	0.00	0.01	0.00	0.00	0.07	0.08	0.06	0.09	0.00	0.02	0.00	0.02	0.19	0.05	0.49	0.02	0.05	0.10	0.00
ZnO	0.07	0.10	0.10	-	0.02	0.13	0.00	0.05		-	-	-	-	-	•	-	-	-	-	•	•	-	-	-	-	-		-	-
Totals	93.52	93.12	92.98	93.13	93.94	93.66	98.78	98.66		98.99	99.56	99.80	99.36	99.52	98.80	98.32	98.60	97.83	95.37	97.59	97.25	99.39	85.45	86.20	86.19	98.94	93.72	93.10	98.08

Mg N° SiO2 Al2O3 FeO Fe2O3 MgO MnO TiO2 Cr2O3 Na2O CaO K2O NiO ZnO Totals	Mr Lanyor Philadj R 66.5 36.98 13.26 - 14.78 0.00 2.41 0.03 0.03 0.00 9.72 0.00 9.72	A, LAN/23, Ph1.adj R 64.9 37.27 15.03 13.99 14.50 0.00 3.42 0.04 0.00 9.80 0.00 9.80 0.03	72523 Grt.R 20.0 37.59 20.77 34.50 - 4.83 0.65 0.02 0.09 0.00 1.09 0.01 0.02 - 99.56	12.12.91 Crd.adj 73.7 48.63 31.84 6.29 - 9.87 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0	Crd away 73.3 49.12 31.80 6.26 - 9.65 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0	Grt.R 23.2 37.73 20.99 33.59 5.69 0.52 0.05 0.02 0.00 1.08 0.02 0.02 0.02	Grt.C 33.8 38.55 21.37 29.88 - 8.57 0.35 0.01 0.05 0.00 1.11 0.01 0.01 0.02 - 99.91	Crd.adjR 77.1 48.80 31.46 5.37 10.11 0.00 0.03 0.00 0.07 0.01 0.01 0.01 0.00 95.85	Pi 59.31 24.47 0.01 - 0.00 0.02 0.02 7.26 7.38 0.16 0.02 - 98.64	Ph1.adj 67.0 37.13 16.11 12.91		Mg N° SiO2 Al2O3 FeO MgO TiO2 Cr2O3 Na2O CaO SiO CaO SiO Cl Totals	Mt Lanyor Pht.Tr.1 65.6 37.41 15.27 13.37 14.30 0.00 3.38 0.15 0.08 0.01 9.50 0.00 0.20 93.66	a, LAN/23 2 66.5 37.10 15.28 12.86 14.30 0.00 3.07 0.10 0.09 0.00 9.65 0.00 0.24 92.69	72523 3 66.5 36.16 15.11 12.60 14.01 0.00 4.74 0.11 0.07 0.03 9.53 0.02 0.23 92.61	4 65.8 37.51 15.30 12.97 13.97 0.09 0.09 0.09 0.09 0.09 0.04 0.24 93.20	5 67.0 37.41 15.77 12.80 14.57 0.00 2.88 0.02 0.11 0.00 9.53 0.04 0.21 93.32	11.12.91 6 44.1 74.10 0.31 0.53 0.23 0.00 24.63 0.09 0.00 0.00 0.24 0.01 0.00 100.15	7 66.3. 36.44 15.15 12.83 14.14 0.00 4.83 0.12 0.10 0.00 9.51 0.04 0.22 93.37	8 66.4 36.65 15.06 12.68 14.08 0.01 4.06 0.07 0.11 0.00 9.64 0.05 0.22 92.63	9 65.5 34.10 14.57 12.51 13.35 9.06 0.08 0.10 0.00 8.98 0.03 0.20 93.00	10 65.7 35.75 15.11 12.88 13.85 0.09 0.09 0.07 0.09 9.75 0.09 0.22 90.89	11 66.8 37.13 14.96 12.89 14.53 0.05 0.05 0.09 0.00 9.77 0.00 0.23 92.79	12 65.9 36.19 14.91 12.71 13.80 0.00 3.12 0.07 0.08 0.00 9.63 0.05 0.22 90.78	13 66,5 37,08 15,59 12,93 14,38 0,02 3,05 0,10 0,08 0,00 9,64 0,01 0,21 93,09	14 63.5 56.97 1.11 1.08 1.05 0.00 37.35 0.06 0.03 0.06 0.65 0.04 0.02 98.35	15 65.8 36.09 14.99 12.85 13.86 0.00 3.12 0.02 0.07 0.00 9.62 0.08 0.26 90.94	16 66.3 36.93 15.52 12.83 14.19 0.00 3.22 0.07 0.09 0.00 9.67 0.02 0.23 92.78	17 64.0 37.69 16.07 12.72 15.15 0.03 2.42 0.04 0.07 0.00 9.70 0.01 0.23 94.13
Mg N° SiO2 Al2O3 FeO MgO MnO TiO2	Mt Lanyot 18 67.6 37.69 15.89 12.65 14.84 0.00 2.99	1, LAN/23 19 66.8 37.51 15.16 12.90 14.57 0.00 3.05	72523 20 66.2 41.97 14.29 11.97 13.16 0.05 3.07	21 65.9 36.95 15.51 13.02 14.09 0.00 3.02	22 69.1 41.49 10.47 6.92 8.68 0.01 19.55	23 66.0 41.44 14.31 12.00 13.06 0.00 2.57	24 64.7 35.65 14.63 13.01 13.37 0.00 3.10	25 65.8 36.50 15.06 12.93 13.96 0.02 3.15	26 65.7 37.13 15.39 13.04 13.99 0.00 3.07	27 65.9 37.00 15.43 13.14 14.25 0.06 3.40	28 66.0 36.61 15.33 13.02 14.21 0.03 3.66	29 68.2 38.52 16.59 12.68 15.29 0.00 2.34	30 66.6 37.18 15.97 13.04 14.61 0.00 2.81	31 66.0 34.72 13.04 11.41 12.42 0.01 13.42	32 66.9 37.58 15.35 12.84 14.55 0.00 3.55	33 66.1 36.78 14.99 12.85 14.06 0.00 3.11	34 65.3 27.90 11.58 9.96 10.53 0.00 25.16	35 65.8 37.40 15.17 13.14 14.18 0.00 3.56	36 66.3 36.78 15.54 12.87 14.23 0.02 3.04	37 67.0 42.67 15.96 13.16 14.97 0.00 2.75	38 66.3 37.16 15.13 12.91 14.26 0.00 3.35 0.10	39 64.9 53.92 11.40 10.02 10.39 0.00 2.80 2.80							
Cr2O3 Na2O CaO K2O NiO Cl Totals	0.07 0.10 0.01 9.75 0.03 0.20 94.22	0.03 0.07 0.00 9.67 0.00 0.27 93.22	0.10 0.07 0.01 8.88 0.01 0.20 93.77	0.08 0.09 0.00 9.85 0.00 0.21 92.83	0.11 0.11 0.06 5.52 0.07 0.17 93.15	0.01 0.07 0.00 8.76 0.03 0.19 95.45	0.14 0.06 0.00 9.65 0.06 0.24 89.92	0.06 0.08 0.01 9.61 0.02 0.23 91.62	0.13 0.10 0.00 9.59 0.00 0.25 92.68	0.08 0.08 0.00 9.69 0.05 0.22 93.38	0.07 0.11 0.00 9.65 0.04 0.20 92.93	0.05 0.09 0.06 9.34 0.09 0.20 95.26	0.12 0.09 0.00 9.69 0.12 0.22 93.83	0.03 0.09 0.01 7.94 0.00 0.19 93.26	0.10 0.07 0.00 9.76 0.04 0.22 94.06	0.06 0.06 0.00 9.64 0.02 0.20 91.76	0.03 0.07 0.03 7.14 0.04 0.16 92.58	0.11 0.09 0.00 9.63 0.02 0.22 93.52	0.07 0.08 0.02 9.60 0.09 0.20 92.52	0.08 0.09 0.14 8.23 0.02 0.19 98.25	0.10 0.07 0.01 9.76 0.06 0.18 92.99	0.02 0.06 0.01 7.19 0.07 0.15 96.03							
Mg N° SiO2 Al2O3 FeO MgO MgO TiO2 Cr2O3 Na2O CaO K2O NiO Cl Totals	Mt Lanyot 40 66.0 37.59 15.63 13.20 14.39 0.01 3.06 0.10 0.00 9.57 0.01 0.22 93.87	h, LAN/23 41 67,4 36,83 15,49 12,62 14,62 0,00 2,98 0,10 0,09 0,00 9,56 0,09 0,22 92,58	72523 42 64.8 35.59 14.93 13.13 13.58 0.00 3.18 0.05 0.09 0.01 9.85 0.05 0.02 90.68	43 64.2 41.38 13.79 12.22 12.30 0.11 4.06 0.05 0.07 0.23 7.66 0.00 0.19 92.06	44 65.4 54.83 11.23 9.51 10.08 0.00 2.30 0.09 0.07 0.01 6.69 0.00 0.13 94.92	45 66.8 10.69 4.40 4.51 0.00 66.10 0.11 0.03 0.04 2.48 0.00 0.05 92.43	46 66.3 37.56 15.33 12.94 14.26 0.00 3.23 0.09 0.10 0.00 9.72 0.05 0.22 93.49	47 66.3 37.39 15.72 13.18 14.54 0.00 2.91 0.03 0.12 0.00 9.65 0.03 0.21 93.77	48 66.1 35.77 14.72 12.64 13.80 0.05 2.83 0.12 0.08 0.00 9.70 0.00 0.00 0.24 89.94	49 67.7 38.18 15.83 12.58 14.78 0.00 2.96 0.05 0.06 0.00 9.64 0.04 0.23 94.37	50 66.8 42.96 14.29 11.41 12.89 0.01 2.39 0.07 0.06 0.00 8.89 0.05 0.19 93.21	Average 66.3 38.60 14.06 14.81 13.01 0.01 6.70 0.07 0.08 0.01 8.72 0.03 0.20 93.32		Mt Lanyo 1 69.4 38.84 13.37 9.83 12.50 0.00 8.85 0.01 0.05 0.00 8.40 0.08 0.07 92.00	n, LAN/19 2 69.3 37.84 15.59 11.64 14.72 0.12 2.67 0.00 0.07 0.00 0.07 0.00 9.90 0.11 0.10 92.77	3 69.6 37.69 15.67 11.81 15.17 0.00 2.31 0.04 0.08 0.02 9.94 0.08 0.08 9.288	4 68.7 37.42 15.49 11.88 14.61 0.00 2.73 0.04 0.07 0.00 9.74 0.10 0.09 92.15	5 69.5 38.13 15.87 11.58 14.81 0.00 2.38 0.10 0.07 0.00 9.71 0.07 0.07 92.78	6 69.4 37.86 15.53 12.01 15.30 0.05 2.38 0.00 0.06 0.00 9.78 0.03 0.08 93.08	7 70.4 38.09 15.57 11.54 15.38 0.04 2.11 0.01 0.04 0.00 9.80 0.05 0.08 92.71	8 71.6 37.86 16.38 10.98 15.52 0.00 1.95 0.08 0.05 0.00 9.93 0.07 0.09 92.90	9 70.2 37.07 15.88 11.29 14.92 0.04 1.97 0.01 0.07 0.02 9.66 0.07 0.08 91.08	10 69.9 37.25 16.60 11.47 14.97 0.00 4.23 0.00 4.23 0.00 0.05 8.93 0.09 0.09 93.73	11 70.0 38.49 15.79 10.87 14.22 0.02 2.20 0.01 0.07 0.10 8.25 0.04 0.10 90.17	12 70.0 38.21 15.76 11.12 14.59 0.03 2.69 0.01 0.09 0.04 8.24 0.06 0.09 90.92	13 68.4 38.25 15.50 11.54 14.02 0.01 2.98 0.08 0.06 8.01 0.10 0.07 90.69	14 70.1 37.74 15.94 11.45 15.09 0.03 2.52 0.01 0.00 9.51 0.02 0.09 92.47	15 70.1 37.72 15.78 11.53 15.13 0.00 2.48 0.03 0.00 9.96 0.03 0.09 92.84	16 69.1 37.46 15.29 11.81 14.81 0.01 2.55 0.03 0.04 0.00 9.94 0.03 0.09 92.06

	Mt Lanyo	n, LAN/19	1												
	17	18	19	20	21	22	23	24	25	26	27	28	29	30	Average
Mg N°	69.16	71.01	69.39	69.38	70.10	70.45	67.37	63.33	68.61	71.78	71.76	69.33	71.18	71.57	69.60
SiO2	37.85	37.89	37.68	37.68	37.47	38.49	38.60	37.83	37.85	32.97	39.63	37.66	41.38	39.22	41.46
AI2O3	15.45	16.00	15.65	15.37	15.59	16.26	16.04	14.98	15.59	16.63	16.76	15.50	21.25	15.49	15.18
FeO	11.86	11.42	11.87	11.65	11.44	11.23	11.58	13.86	11.98	7.80	11.01	11.80	7.97	10.21	10.44
MgO	14.92	15.70	15.10	14.81	15.05	15.02	1.42	13.43	14.69	11.14	15.70	14.96	11.04	14.43	13.29
MnO	0.02	0.00	0.00	0.05	0.00	0.08	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.02	0.02
TiO2	2.74	2.21	2.48	2.63	2.46	2.36	2.82	2.78	2.78	3.96	2.51	2.68	1.65	2.41	2.52
Cr2O3	0.00	0.02	0.02	0.00	0.02	0.04	0.00	0.01	0.00	0.06	0.00	0.03	0.01	0.02	0.02
Na2O	0.06	0.05	0.09	0.04	0.08	0.07	0.06	0.07	0.06	0.13	0.08	0.07	0.10	0.06	0.07
CaO	0.00	0.00	0.00	0.00	0.00	0.05	0.08	0.11	0.02	0.09	0.04	0.00	0.09	0.09	0.03
K2O	10.09	9.73	9.71	9.87	9.84	8.66	7.26	7.26	9.32	6.26	8.18	9.76	7.37	7.33	8.31
NiO	0.13	0.02	0.01	0.00	0.05	0.07	0.09	0.05	0.07	0.04	0.09	0.06	0.00	0.07	0.06
CI	0.08	0.09	0.09	0.08	0.08	0.11	0.12	0.07	0.13	0.08	0.09	0.10	0.12	0.07	0.08
Totals	93.20	93.13	92.70	92.18	92.08	92.42	76.64	90.44	92.47	79.16	94.39	92.66	90.97	89.43	91.46

	Mt Meredi	ith, MER/1	10		14.12.91						Mt Mere	dith, MER/I	1		7.12.91					
	Phi.3	Pl	Ph1.R	GrtR.7	Grt.8	Ph1.inc1	Grt.adj	GrtR.16	Ph1.adj	PI.20	GriR	Grt.Tr3	Grt.C	Pl.adjR	Phl.adj	Kfs	GrtR	Ph1.adi	GrtR	PhLadi
Mg N°	42.2	-	42.4	9.9	15.1	43.8	14.0	10.2	44.1	•	6.8	8.5	9.5	-	30.4	-	6.0	30.2	7.3	29.3
SiO2	34.84	54.69	34.60	36.40	36.41	-34.85	36.56	36.61	34.96	54.97	36.51	36.85	36.78	61.48	33.10	64.41	36.50	33.73	36.68	33.55
AI2O3	16.17	27.42	16.29	20.62	20.71	16.34	21.01	20.41	16.47	27.08	20.64	20.53	20.55	23.21	18.03	17.75	20.39	18.21	20.24	17.88
FeO	21.79	0.05	21.87	33,94	33.68	21.17	33.48	33.90	21.22	0.11	36.31	36.08	36.06	0.04	25.81	0.12	36.33	25.04	36.22	25.45
Fe2O3	-	-	-	-	-	-	-		•	-	•	-	-	-	-	-	-			
MgO	8.92	0.00	9.02	2.09	3.36	9.26	3.06	2.15	9.41	0.00	1.48	1.88	2.12	0.01	6.32	0.01	1.30	6.07	1.61	5.92
MnO	0.01	0.00	0.08	3.90	2.75	0.01	2.77	3.77	0.02	0.00	3.51	3.08	3.24	0.00	0.06	0.02	4.00	0.12	3.63	0.03
TiO2	3.01	0.00	2.87	0.02	0.02	2.65	0.00	0.02	2.57	0.00	0.00	0.00	0.04	0.00	1.65	0.02	0.00	1.77	0.00	2.04
Cr2O3	0.06	0.01	0.08	0.01	0.00	0.09	0.04	0.08	0.08	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.01	0.03	0.04	0.05
Na2O	0.17	5.43	0.19	0.00	0.00	0.23	0.02	0.02	0.18	5.62	0.00	0.01	0.01	8.08	0.05	0.07	0.01	0.11	0.00	0.11
CaO	0.00	10.44	0.17	2.89	2.81	0.01	2.84	2.88	0.04	10.51	1.34	1.30	1.39	5.65	0.02	0.01	1.55	0.01	1 30	0.05
K2O	9.23	0.04	8.79	0.01	0.01	9.16	0.00	0.00	9.09	0.06	0.00	0.01	0.00	0.17	7.99	16.89	0.02	8.93	0.00	8.88
NiO	0.00	0.00	0.08	0.00	0.00	0.02	0.02	0.00	0.00	0.00	0.02	0.01	0.05	0.01	0.02	0.00	0.00	0.01	0.00	0.01
ZnO			-	-	-	-			•	-		-				-	•	•	-	-
Totals	94.21	98.08	94.03	99.88	99.75	93.79	99.81	99.83	94.04	98.33	99.79	99.74	100.24	98.65	93.05	99.32	100.11	94.03	99.81	93.97

	Mt Meredi	th, MER/:	27		Mt Meredith, MER/52, moraine specimen
	Sol	Spl	Срх	Срх	Spi Spi Ol Ol Ol Cpx Cpx Cpx
Mg N°	43.5	43.0	84.6	85.6	59,5 56.7 88,3 89.1 89.1 89.9 94.0 86.2
SiO2	0.03	0.07	52.82	\$2.52	0.13 0.12 40.13 40.30 40.07 52.83 54.15 52.71
A12O3	7.02	6.54	0.11	0.25	26.43 26.09 0.06 0.06 0.08 1.26 0.32 1.27
FeO	18.35	18.01	5.01	4.79	12.24 13.33 11.23 10.37 10.39 3.27 1.93 4.39
Fe2O3	9.83	11.20	-	-	7.22 7.69
MgO	11.73	11.91	15.40	16.06	15.45 14.88 47.32 47.69 47.79 16.24 17.12 15.35
MnO	0.25	0.34	0.22	0.24	0.18 0.20 0.21 0.20 0.25 0.11 0.13 0.40
TiO2	5.63	5.80	0.94	1.26	<b>i</b> .38 1.55 0.03 0.00 0.02 0.40 0.25 0.36
Cr2O3	42.80	41.77	0.03	0.00	32.78 32.33 0.08 0.08 0.11 0.05 0.01 0.00
Na2O	0.02	0.02	0.32	0.65	0.00 0.00 0.00 0.00 0.03 0.24 0.26 0.34
CaO	0.05	0.01	25.32	24.18	0.00 0.00 0.14 0.12 0.18 25.74 26.29 25.37
K2O	0.01	0.01	0.04	0.04	0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
NiO	0.15	0.32	0.05	0.06	0.22 0.17 0.34 0.44 0.31 0.02 0.00 0.03
ZnO		-	-	-	· · · · · · · ·
Totals	95.87	96.00	100.24	100.03	96.04 96.36 99.54 99.27 99.23 100.15 100.47 100.22

Brocklehu	irst Ridge,	BRO6		10.9.91		
Grt.Tr	Cpx.R	CpxTrR	Cpx.Tr	Cpx.Tr	Cpx.Tr	Cpx.Tr
1.9	28.5	25.5	30.4	33.0	35.2	36.5
39.27	50.36	49.88	50.28	50.66	50.26	50.71
20.34	0.58	0.39	0.50	0.48	0.52	0.49
5.60	20.09	20.64	19.57	19.19	18.59	18.25
-	-	-	•	-	-	-
0.06	4.49	3.97	4.80	5.30	5.67	5.90
0.49	0.77	0.99	0.68	0.71	0.80	0.63
0.39	0.07	0.01	0.06	0.03	0.09	0.02
0.00	0.00	0.00	0.07	0.05	0.00	0.00
0.00	0.06	0.03	0.05	0.07	0.04	0.05
33.96	24.01	24.11	24.08	24.05	23.98	23.69
0.00	0.00	0.00	0.00	0.01	0.00	0.00
0.00	0.00	0.09	0.05	0.00	0.06	0.02
÷	-	-	-	•	-	•
100.11	100.43	100.10	100.13	100.54	100.00	99.76

	Brooklah	wert Ridan	<b>BRUK</b>		10 0 01																								
	Cor Tr	Con Tr	Drug T-P	Con T-D	10.9.91 Die 4	Cabaas	C-T-	C	C . T	C. T.	<u> </u>	0.00	<b>A A</b>				-		_	_									
Ma No	25.0	21.7	20.7	22.2	riauj	spiene	GILIT	GULIL	Ga. Ir	GRII	Cpx.adj	GUIR	Grt.1r	Grt. Ir	Grt.1r	Grt.Tr	syp.Cpx	syp.Pl	syp.Cpx	Срх	Sph.R	Cpx.adj	Wol	PI	Grt.R	Pi	Cpx.adj	Grt.R	Wol C
500	53.0	51.7	50.7	55.2		0.0	5.1	1.4	2.1	1.9	32.5	2.3	2.0	1.8	1.7	2.3	36.3		19.6	23.6	0.0	24.1	0.0	-	10.9	-	24.9	0.9	0.0
3102	50.50	30.09	30.19	30.91	44.39	30.39	39.25	39.25	39.37	39.37	50.50	38.94	39.63	39.60	39.46	39.38	50.62	44.28	49.41	49.07	30.69	49.57	51.78	57.43	46.07	41.59	49.78	39.69	51.34
ALCO	0.48	0.57	0.00	0.11	36.05	2.90	20.46	20.19	20.55	20.07	0.65	20.22	20.15	20.39	20.08	20.23	9.60	36.54	13.06	0.81	3.94	0.62	0.08	26.13	23.49	34.88	0.32	19.72	0.12
reu	18.77	19.12	19.30	18.67	0.05	0.53	6.03	6.72	5.98	6.39	18.46	6.11	6.14	6.17	6.24	5.99	13.87	0.08	14.29	21.21	0.39	21.22	0.42	0.07	3.27	0.07	20.95	7.19	0.57
Fe203		-	-		•	-	-	-	-	-	•	-	-	-	-	-	-	-	-	-	•	-	-	•	-	-	-	-	-
MgO	5.67	4.99	4.82	5.20	0.00	0.00	0.06	0.06	0.07	0.07	4.98	0.08	0.08	0.06	0.07	0.08	4.42	0.00	1.94	3.68	0.00	3.78	0.00	0.07	0.23	0.00	3.90	0.04	0.00
MnO	0.78	0.76	0.71	1.29	0.00	0.06	0.56	0.63	0.48	0.59	0.93	0.47	0.52	0.60	0.42	0.49	0.76	0.00	0.45	0.91	0.07	0.87	0.32	0.00	0.39	0.01	0.88	0.91	0.30
TiO2	0.07	0.04	0.09	0.00	0.00	33.17	0.48	0.41	0.40	0.31	0.02	0.43	0.42	0.45	0.46	0.46	0.00	0.00	0.03	0.08	32.84	0.02	0.01	0.02	0.06	0.03	0.01	0.11	0.00
Cr2O3	0.03	0.04	0.00	0.02	0.05	0.05	0.04	0.06	0.06	0.03	0.02	0.00	0.00	0.04	0.04	0.01	0.00	0.00	0.01	0.03	0.01	0.00	0.00	0.05	0.00	0.01	0.06	0.00	0.00
Na2O	0.04	0.04	0.05	0.04	0.33	0.01	0.01	0.00	0.01	0.00	0.04	0.01	0.00	0.00	0.00	0.01	0.35	0.28	0.34	0.06	0.00	0.05	0.01	0.65	0.78	0.35	0.05	0.07	0.03
CaO	23.91	23.68	23.46	23.88	19.80	28.68	33.67	33.04	33.40	33.58	24.11	34.20	33.93	33.60	33.68	34.09	21.05	19.52	20.28	23.54	28.60	23.01	47 34	7 93	18 58	19.17	23.56	33.07	16.53
K2O	0.00	0.00	0.02	0.00	0.03	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.32	0.04	0.10	0.01	0.00	0.00	0.01	7 53	3 36	0.02	0.00	0.01	0.01
NiO	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.00	0.07	0.00	0.05	0.00	012	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.01	0.02	0.00	0.00	0.01
ZnO	-	•	•	•	-	-	-	-	•	•	-	•	-	•	•	-		-	-		-	-	-	-	0.04	0.04	0.00	0.00	0.00
Totals	100.31	99.92	99.31	100.11	100.69	95.77	100.55	100.35	100.33	100.46	99.72	100.46	100.94	100.92	100.50	100.74	101.12	100.74	99.90	99.41	96.54	99.16	99.97	99.88	96.27	96.16	99.51	100.80	98.90
	Brocklehi	urst Ridge,	BRO6																										
	Wol.R	Gn.R	Grt.R	Pl.adj	Срх	Wol	adj.Pi	adj.Pl	Wol	Grt.R	adj.Cpx	adj.Pl	syCpx2	syCpx2	Cpx6	Grt.adj	Grt10	Grt11	Grt12	Grt.R	Cpx.adj	Sph.adj	adj Pl	Wol.r3	Gros.R	Gros.R	Gros.R	Wol	Gros
Mg N°	0.0	0.5	0.5	•	22.5	0.0	-	•	0.0	1.8	25.8	-	22.9	22.6	23.3	1.0	1.5	1.9	1.7	1.9	24.3	0.0	-	0.0	0.8	0.5	0.2	0.0	0.3
SiO2	51.72	39.53	39.76	44.04	49.06	51.75	43.32	44.81	51.89	39.54	49.57	43.90	49.24	48.90	49.30	38.80	38.71	38.79	38.85	38.35	49.07	29.86	43.15	50.82	38.69	38.94	38.63	50.82	38.54
AI2O3	0.00	20.02	20.21	36.43	0.83	0.04	35.79	35.56	0.01	18.44	0.51	36.42	0.79	0.52	0.55	18.74	19.94	19.81	19.88	19.97	0.43	2.94	35.79	0.03	20.23	20.34	20.00	0.02	20.34
FeO	0.49	6.10	5.79	0.03	21.17	0.52	0.08	0.05	0.45	6.47	20.48	0.07	21.80	21.97	21.77	7.68	6.31	6.48	6.38	6.40	21.72	0.48	0.18	0.54	5.75	6.22	6.52	0.44	5.79
Fe203			•	-		-	-	•	-	•	•	-	-	-	-		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MgO	0.00	0.02	0.02	0.00	3.45	0.00	0.00	0.05	0.00	0.07	3.99	0.00	3.63	3.61	3.70	0.04	0.06	0.07	0.06	0.07	3.92	0.00	0.00	0.00	0.03	0.02	0.01	0.00	0.01
MnO	0.37	0.77	0.79	0.00	0.94	0.37	0.00	0.00	0.39	0.76	0.92	0.00	0.67	0.71	0.81	0.54	0.46	0.50	0.47	0.59	0.80	0.08	0.00	0.32	0.96	0.96	0.91	0.21	0.78
TiO2	0.01	0.09	0.09	0.00	0.07	0.02	0.01	0.01	0.00	0.03	0.00	0.04	0.02	0.03	0.05	0.31	0.46	0.45	0.41	0.42	0.04	34.59	0.01	0.00	0.02	0.01	0.04	0.05	0.00
Cr2O3	0.00	0.07	0.00	0.00	0.00	0.03	0.00	0.03	0.00	0.02	0.00	0.03	0.04	0.00	0.00	0.03	0.03	0.08	0.00	0.06	0.02	0.03	0.02	0.00	0.05	0.00	0.04	0.03	0.07
Na2O	0.00	0.00	0.02	0.27	0.06	0.00	0.61	0.25	0.00	0.03	0.07	0.28	0.08	0.06	0.04	0.01	0.00	0.02	0.00	0.03	0.04	0.01	0.25	0.02	0.00	0.02	0.01	0.02	0.01
CaO	46.94	33.58	33.34	19.67	23.25	46.67	19.25	18.47	47.09	31.61	22.96	19.67	24.05	24.21	23.96	34.17	34.38	34.61	34.63	34,38	24.22	29.09	20.59	48.33	34.34	33.99	34.19	48.27	34.79
K20	0.00	0.02	0.00	0.01	0.01	0.03	0.00	0.55	0.01	0.01	0.00	0.02	0.01	0.00	0.00	0.00	0.01	0.01	0.00	0.02	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.01	0.00
NiO	0.03	0.00	0.00	0.02	0.03	0.00	0.06	0.00	0.03	0.00	0.00	0.00	0.07	0.00	0.00	0.06	0.00	0.01	0.04	0.00	0.08	0.00	0.01	0.00	0.00	0.00	0.00	0.05	0.00
7.0	0.05	0.00	0.01	0.02	0.05	0.00	0.00	0.00	0.05	0.00	0.01	0.00	0.02	0.00	0.00	0.00	0.00	0.01	0.04	0.00	0.00	0,00	0.01	0.00	0.00	0.00	0.00	0.05	0.00
Totals	99 57	100.19	100.04	100.47	98.87	99.17	9912	99 77	99.87	96.98	98 51	100.43	100 34	100.00	100 18	100 38	100 35	100.85	100 71	100.28	100 30	97.11	100.01	100.07	100.08	100 50	100.34	00 01	100 32
10(415	//		100.04	100.41	70.07	//. <b>42</b>	<i>,,,,</i> ,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,	,,,,,	<i>,,,,,,</i> ,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,	<i>JU.J</i>	70.51	100.45	100.54	100.00	100.70	100.90	100.55	100.00	100.71	100.20	100.50	<i>y</i>	100.01	100.01	100.00	100.50	100.04	,,,,,	100.51
	Brockleby	unst Ridae	8806		19991																		Brocklehn	rst Ridge	BRO/H				
	Cny 7	Cori	Cors	Cov6	Cry 7R	Gree R	Cnx822	Cox 23	Cnv26r0	Cnx27	Cny 28	40020	Amn30	Amn31	Cox 33	Cox36	Hm	Pl adi	Pl adi	Cor adi	Phiri0		GrtR rl	Crd	Phi	GriC r2	Get R	Soll acti	Soll adi
Ma Nº	28.3	375	313	310	25.0	10.6	20.0	10.8	510	587	565	11.8	41.6	31.6	116	116	11.6		11.00	416	316		120	107	39.6	150	13.3	103	19.6
SIG 1	10.5	10.10	10.01	10.11	10.10	10.0	10.73	10.0	51.10	51.69	50.5	11.0	41.0	41.0	50.70	51.09	41.0	46.60	16 78	51.10	21.00		16 70	47.65	21 22	36.00	37.03	0.00	0.00
5102	49.90	49.49	49.94	47.11	47.17	42.30	47.23	49.00	51.19	0.60	51.54	45.02	42.04	44.J9 P.03	073	112	0.04	31.06	3111	1.02	1130		20.75	47.03	10.03	20.95	20.77	57.10	57 16
A1205	1.25	0.09	10.47	0.00	11 11	10.75	0.37	10.35	0.04	13.36	0.48	9.08	9.70	8.93	12.70	1.12	46.21	54.00	34.11	13.05	14.50		20.70	52.35	10.03	20.93	20.77	20.10	20.29
Feu	20.50	19.07	19.17	19.85	21.51	3.50	19.70	19.75	14.48	13.20	13.92	20.23	20.05	19.17	13.70	14.31	43.31	0.15	0.14	13.31	21.91		30.39	9.17	20.07	30.49	30.73	27.20	50.50
Fe203			-		-	-	-		•	-	-		-	-	-		-	-	•	•					-				
MgO	4.55	5.33	5.60	5.22	3.99	0.23	4.97	4.93	9.90	10.59	10.13	8.16	8.02	9.06	10.18	9.93	0.11	0.00	0.01	9.99	9.51		3.04	1.53	1.69	3.01	3.40	3.92	4.15
MnO	0.75	0.70	0.85	0.67	0.77	0.48	0.67	0.75	0.44	0.34	0.49	0.26	0.33	0.31	0.48	0.50	1.73	0.00	0.00	0.48	0.21		0.36	0.08	0.04	0.29	0.37	0.03	0.00
1102	0.03	0.05	0.02	0.00	0.06	0.01	0.05	0.02	0.09	0.07	0.05	1.53	1.64	1.50	0.12	0.18	51.89	0.00	0.05	0.08	4.33		0.00	0.01	3.62	0.02	0.05	0.05	0.04
Cr2O3	0.00	0.02	0.03	0.00	0.04	0.02	0.00	0.06	0.00	0.07	0.02	0.09	0.15	0.06	0.04	0.03	0.00	0.01	0.03	0.02	0.00		0.01	0.02	0.00	0.10	0.08	0.46	0.35
N32O	0.09	0.09	0.06	0.05	0.07	0.01	0.05	0.05	0.16	0.14	0.11	1.16	1.13	1.06	0.14	0.17	0.03	1.70	1.70	0.13	0.11		0.00	0.18	0.12	0.01	0.03	0.15	0.20
C3O	23.07	24.20	24.43	24.25	24.02	34.32	24.45	24.20	22.84	23.55	23.20	11.85	11.84	12.14	22.91	22.65	0.13	17.70	17.65	23.16	0.01		1.13	0.01	0.00	1.08	1.05	0.01	0.00
K2O	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.01	0.02	0.00	0.00	1.03	1.03	0.88	0.02	0.00	0.00	0.06	0.04	0.01	8.04		0.00	0.01	8.43	0.00	0.00	0.00	0.00
NiO	0.00	0.02	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.01	0.00	0.02		0.00	0.06	0.05	0.00	0.00	0.15	0.22
ZnO			-		-	-	-	-	-		-	-	-	-	-	-	-	-	-	-			-			0.04	0.00	8.53	7.38
Totals	100.20	100.27	100.59	99.82	100.35	99.87	99.75	99.90	99.74	100.49	99.73	97.01	96.72	97.70	99.10	100.16	99.29	100.38	100.50	99.32	93.42		98.68	97.05	93.97	99.60	99.58	99.67	99.87

	Brocklehm	rst Ridge, i	BRO/12													Brocklehu	rst Ridge,	BRO/15		18.12.91									
	GriC.6	Grt.7	GrtR.8	Crd.adj.9	Crd.away	Grt.r1	Split	Spl1.rl	Grt.r2	Spl1_r2	Spl1.r2	Gri.r3	Pl	Crd.adj		Pl	Grt.R	Grt.Tr.5	Grt.Tr.6	Grt.Tr.8	Grt.C.9	GrtR.21	PhLadj.22	Grt.18	Chl.adj16				
Mg N°	17.3	15.8	14.1	62.9	61.5	15.4	18.7	27.9	17.2	19.0	18.2	15.7	-	61.5		-	14.1	15.8	16.6	17.2	17.4	11.5	35.3	14.7	41.1				
502	37.19	37.23	36.71	48.15	48.10	37.02	0.00	0.03	30.94	0.00	0.00	37.00	00.38	47.60		00.81	34.10	37.19	37.10	37.22	37.28	30.80	33.13	30.70 20.81	28.20				
Ean	21.20	37.11	20.00	8.61	896	36 70	27.00	28.63	20.89	20.55	33.87 78.77	36.46	0.02	8.83		24.14	31.67	35.03	34.60	30.87	31.02	35.75	21.05	35 19	27.98				
Fe2O3	-	-	-	-	-								-			-	-		-	-			-4.05	-	-				
MgO	4.22	3.91	3.43	8.23	8.02	3.74	3.83	6.23	4.16	3.89	3.52	3.80	0.00	7.90		0.00	3.20	3.68	3.88	3.95	4.05	2.62	7.38	3.40	10.95				
MnO	0.33	0.37	0.52	0.03	0.01	0.45	0.08	0.04	0.41	0.03	0.02	0.49	0.03	0.11		0.00	2.41	2.05	2.07	1.96	2.03	2.54	0.05	2.02	0.16				
TiO2	0.03	0.02	0.01	0.01	0.02	0.00	0.03	0.06	0.02	0.00	0.03	0.00	0.00	0.05		0.01	0.02	0.00	0.00	0.01	0.00	0.00	0.84	0.00	0.08				
Cr2O3	0.03	0.06	0.08	0.01	0.00	0.07	0.78	0.83	0.03	0.84	1.81	0.01	0.01	0.01		0.05	0.00	0.00	0.00	0.02	0.00	0.01	0.00	0.00	0.01				
Na2O CoO	0.01	0.03	0.03	0.11	0.10	0.01	0.18	0.13	0.01	0.19	0.27	0.00	1.13	0.09		5.07	0.03	0.03	0.03	0.02	0.02	0.02	0.11	0.02	0.08				
K10	0.99	0.99	0.90	0.01	0.03	0.94	0.00	0.00	1.04	0.00	0.02	0.00	0.05	0.00		0.21	0.00	0.01	0.01	0.02	0.00	0.01	7 89	0.00	0.12				
NiO	0.00	0.00	0.01	0.06	0.05	0.00	0.20	0.17	0.03	0.19	0.18	0.00	0.00	0.05		0.01	0.11	0.04	0.00	0.00	0.01	0.01	0.00	0.00	0.00				
ZnO	0.07	0.05	0.01	0.00	0.09	0.00	8.84	5.85	0.00	9.40	11.76	0.11	0.01	0.02					-	•	•	•	-		-				
Totals	100.10	100.83	99.78	97.46	97.45	100.04	100.67	99.73	99.28	101.37	101.71	99.72	99.22	96.98		99.16	100.26	100.31	99.77	99.89	100.09	100.27	92.53	99.67	85.92				
	OLeary Ri	idges, OLS	0/4																										
	Grt.R	Grt.Tr	Grt.Tr	Grt.R	PI	Phl.adj	Grt.R	Phi.adj	PI	lim ri	Cpxr4.4	Cpx.3	Cpx.6	Amph.8	Amph.10	Cpxr3.12	Pl	Zoir 2.19	Zoisite.20	Chl.r2.23	Ch1.24	P1.26	PI.27	Pl	Zoisite.33	SpiR.rl	Spl.4	SpIC.8	Spl.10
Mg N°	14.2	14.0	14.1	13.5	-	48.4	11.2	49.3	-	0.4	86.5	87.5	86.8	79.8	79.9	79.6	-	0.0	0.0	72.8	71.5	•		•	0.0	62.5	63.3	61.7	62.6
5102	37.03	37.11	37.13	36.99	57.32	35.35	37.13	35.40	57.91	0.03	49.46	50.38	49.95	40.56	40.70	53.79	43.71	39.18	38.96	27.62	28.17	68.58	68.84	67.40	40.06	0.00	0.02	0.01	0.02
FeO	21.10	21.10	21.08	35.08	27.17	17.24	21.07	19.63	20.79	45 10	207	4.77	3.38	671	6.68	6.41	35.24	30.51	30.37	21.40	20.93	19.93	19.37	19.95	32.88	02.98	03.13	02.78	03.27
Fe203	-	-	-			13.03	33.00	10.05	0.15	45.10	3.97	5.70	5.00	0.71	0.04	0.41	0.10	5.15	5.05	14.01	13.39	0.01	0.04	0.17	0.57	2.55	271	2.62	20.45
MgO	3.15	3.15	3.18	3.07	0.01	10.03	2.51	10.17	0.00	0.09	14.19	14.85	14.32	14.89	14.87	14:04	0.00	0.00	0.00	22.28	21.97	0.00	0.00	0.00	0.00	15.35	15.59	15.04	15.40
MnO	3.09	3.18	3.27	3.11	0.00	0.08	3.09	0.06	0.00	0.88	0.11	0.00	0.06	0.11	0.06	0.23	0.00	0.04	0.03	0.08	0.18	0.00	0.02	0.00	0.06	0.17	0.15	0.17	0.15
TiO2	0.01	0.00	0.00	0.00	0.02	3.92	0.02	3.53	0.00	50.90	0.81	0.91	0.77	0.76	0.75	0.07	0.03	0.01	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.04	0.00	0.01	0.03
Cr2O3	0.05	0.04	0.05	0.11	0.00	0.09	0.13	0.09	0.00	0.08	0.00	0.09	0.05	0.03	0.07	0.00	0.02	0.00	0.00	0.01	0.00	0.03	0.06	0.04	0.01	0.30	0.21	0.17	0.16
N320	0.00	0.00	0.01	0.01	6.25	0.07	0.02	0.09	6.33	0.00	0.04	0.01	0.02	1.32	1.28	0.06	0.32	0.00	0.02	0.00	0.01	10.83	11.23	10.62	0.20	-	•	•	-
K20	0.00	1.70	1.08	1.74	9.13	0.00	1./1	0.03	8.03	0.01	23.84	20.00	23.90	211	10.22	25.79	20.18	25.06	25.07	0.02	0.10	0.83	0.30	1.02	24.99	-	•	-	-
NiO	0.00	0.12	0.00	0.00	0.15	0.03	0.00	0.03	0.15	0.02	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.04	0.01	0.04	0.02	0.07	0.05	0.07	0.03
ZnO	-	-	•	-	-	-	-	-	•	-	•	-	•	•	-	•		-	-	-	•		-	-	-	2.00	2.03	2.07	2.07
Totals	100.30	100.87	101.09	101.40	100.16	95.58	101.27	94.93	100.00	97.30	100.48	100.77	100.57	97.01	96.84	100.99	99.59	97.99	97.55	86.28	86.97	100.26	99.86	99.23	98.79	99.87	100.01	99.61	100.18
	OLeary Ri	dges, OL9	07															Taylor Piz	atform, TPI	4									
	OIR	OLT.I	II.T.IO	Ol.Tr.rl	SplR.r2	Spi.Tr.r2	Spl.Tr.r2	SplR.r2	CpxSy.r3	CpxSy.r3	Olsym.r3	Olsym.r3	Olsym.r3	Cpx.adj	Cpx.adj	Ol.adj		PLrI	SpLrl	Cor.adj	CpxC.r2	CpxR.r2	Cpx.r3	Plexsl	Plexs				
Mg N°	93.0	93.1	93.4	93.7	85.2	86.5	86.2	85.6	95.4	92.1	93.3	92.9	93.3	94.0	95.0	93.1		-	76.8	0.0	93.0	93.8	92.6	•	•				
SiO2	41.69	41.52	42.03	41.91	0.03	0.02	0.03	0.00	47.04	41.82	42.03	41.79	41.69	42.57	47.09	41.60		38.69	0.05	0.02	53.38	54.16	51.90	43.08	43.73				
AI203	0.01	0.04	0.02	0.03	68.08	68.08	68.06	67.27	11.37	16.04	0.02	0.04	0.00	16.38	12.10	0.01		32.78	66.66	99.94	1.31	1.10	3.84	35.54	35.84				
Fe0 E=203	0.94	0.87	0.32	0.27	1.19	0.30	0.08	0.88	1.75	2.84	0.04	7.08	0.04	2.04	1.84	0.87		0.34	11.01	0.33	2.30	1.98	2.24	0.08	0.04				
MeO	51.67	51.95	5202	52.06	23.15	73.44	23 35	22.03	19.99	18 67	52.00	\$1.07	57 19	18.00	10.85	51.88		0.00	20.42	0.02	16.97	16.87	1572		0.00				
MnO	0.07	0.08	0.04	0.00	0.00	0.00	0.12	0.00	0.00	0.00	0.04	0.03	0.04	0.08	0.00	0.11		0.03	0.10	0.00	0.09	0.10	0.04	0.00	0.05				
TiO2	0.06	0.02	0.02	0.05	0.01	0.00	0.00	0.04	0.99	1.63	0.00	0.03	0.02	1.65	0.93	0.01		0.00	0.00	0.04	0.43	0.21	0.36	0.00	0.00				
Cr2O3	0.07	0.02	0.00	0.00	0.11	0.13	0.10	0.16	0.01	0.05	0.00	0.00	0.03	0.03	0.00	0.02		0.02	0.03	0.03	0.01	0.00	0.00	0.09	0.01				
Na2O	0.01	0.00	0.00	0.00	0.02	0.02	0.00	0.02	1.06	1.21	0.01	0.00	0.00	1.23	1.06	0.00		0.01	0.04	0.00	0.05	0.05	0.15	0.11	0.21				
CaO	0.01	0.01	0.06	0.03	0.03	0.00	0.03	0.03	13.71	13.11	0.04	0.03	0.05	14.11	13.95	0.03		25.18	0.01	0.01	25.89	26.06	25.70	20.95	20.74				
K2O NiO	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.93	1.47	0.01	0.00	0.00	1.56	0.97	0.00		0.01	0.01	0.00	0.00	0.00	0.01	0.01	0.00				
760	0.00	0.05	0.00	0.02	0.00	0.00	0.00	0.02	0.00	0.00	0.08	0.00	0.00	0.01	0.00	0.00		0.00	0.03	0.00	0.03	0.00	0.00	0.11	0.00				
Totals	100.55	100.56	100.71	100.36	99.74	99.01	99.18	98.21	96.90	- 96.84	100.87	100.91	100.66	97.75	97.79	100.54		97.06	98.35	100.38	100.42	100.53	99.95	99.97	100.63				
			,																	100.00	100.12	100.00							

	Taylor P	attorm, TPi	13						
	01	01	01	Spl	Spl	Орх	Opx	Срх	Срх
Mg N°	89.3	91.2	90.8	75.8	68.2	74.7	89.9	92.7	92.2
SiO2	40.36	40.83	40.95	0.17	0.21	52.95	52.53	55.01	53.06
AI2O3	•	-	-	35.52	8.79	4,70	7.73	1.67	3.78
FeO	10.56	8.73	9.20	10.55	12.04	15.29	6.09	2.78	2.81
Fe2O3	-	-		4.57	4.21	0.75	1.87	0.00	0.00
MgO	49.61	50.51	50.83	18.48	14.50	25.30	30.76	19.75	18.59
MnO	0.06	0.05	0.04	0.30	0.11	0.18	0.12	0.05	0.06
TiO2	-	-	-	0.69	0.33	0.33	0.48	0.11	0.26
Cr2O3	0.01	0.05	0.09	31.10	61.20	0.16	0.99	1.85	1.72
Na2O	-	-	-	0.00	0.00	0.00	0.00	0.00	0.00
CaO	0.17	0.13	0.11	0.00	0.00	2.39	1.99	18.65	19.05
K2O	-	-	•	0.00	0.00	-	0.00	0.00	0.00
NiO	0.23	0.39	0.31	0.26	0.00	0.00	0.00	0.00	0.00
ZnO	-	-	•	0.11	0.15	0.00	0.00	0.00	0.00
Totals	101.00	100.68	101.53	101.74	101.54	102.05	102.56	99.86	99.33
	Fox Ridg	e, Fox 10							
	GnC.rl	GrtTr4.r1	Grt3.Tr	Grt2.Tr	GrtR.rl	GrtR.r1	GrtR.rl	PLadj	ilm.ri
Mg N°	10.9	11.1	9.2	8.6	7.3	6.9	8.9	-	0.3
SiO2	36.72	36.69	36.92	36.41	37.16	37.04	36.70	64.77	0.49
A12O3	20.58	20.79	20.80	20.56	20.69	20.81	20.79	24.25	0.07
FeO	36.33	35.99	36.65	37.01	36.72	36.85	36.19	0.43	44.46
Fe2O3	-	-	-	•	-	•	-	-	-
MgO	2.50	2.52	2.08	1.94	1.61	1.54	1.99	0.01	0.08
MnO	1.03	1.20	1.08	0.91	1.14	1.10	1.11	0.00	0.79
TiO2	0.00	0.05	0.01	0.00	0.25	0.47	0.04	0.03	49.64
Cr2O3	0.03	0.00	0.07	0.01	0.03	0.05	0.00	0.05	0.07
Na2O	0.01	0.00	0.03	0.02	0.00	0.01	0.00	7.24	0.08
~ ~						3 00	3 4 8	8 00	0.03
CaO	1.79	1.83	2.53	2.70	2.50	2.00	2.40	2.00	0.02
CaO K2O	1.79 0.00	1.83 0.00	2.53 0.02	2.70 0.01	2.50	0.00	0.01	0.10	0.02
CaO K2O NiO	1.79 0.00 0.00	1.83 0.00 0.00	2.53 0.02 0.01	2.70 0.01 0.02	0.00 0.00	0.00 0.00	0.01	0.10	0.04 0.21
CaO K2O NiO ZnO	1.79 0.00 0.00	1.83 0.00 0.00	2.53 0.02 0.01	2.70 0.01 0.02	2.50 0.00 0.00	0.00 0.00 -	0.01	0.10	0.02 0.04 0.21

Fox Rid	ige, Fox 14		18.12.91							Fox Ridge	Fox 18		
Grt.R	GrtTr.6	GrtTr.10	Grffr.24	GrtTr.27	GrtC.32	Kfs.I	PI	Phi.35	Phi.37	Pi -	Срх	Орх	Phi
11.2	12.1	13.4	13.7	13.5	14.3	-	•	40.5	39.8	•	69.0	54.9	61.4
36.81	36.62	36.85	36.75	36.67	37.28	63.93	60.56	34.67	34.81	54.25	51.61	51.59	37.52
20.54	20.39	20.64	20.77	20.46	20.52	18.90	23.54	15.12	14.69	28.08	1.41	0.62	12.74
36.10	36.40	35.94	34.38	34.17	34.14	0.44	0.00	22.24	22.43	0.00	9.63	25.65	14.43
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-	-	-	-
2.54	2.81	3.11	3.05	3.00	3.20	0.00	0.00	8.50	8.32	0.00	12.01	17.51	12.86
2.27	2.54	2.87	4.22	3.99	3.40	0.03	0.00	0.08	0.00	0.04	0.25	0.64	0.01
0.00	0.03	0.00	0.02	0.00	0.04	0.05	0.00	3.66	3.94	0.00	0.26	0.05	4.53
0.00	0.08	0.02	0.00	0.00	0.00	0.03	0.03	0.02	0.04	0.03	0.16	0.15	0.26
0.0	0.00	0.02	0.02	0.00	0.02	2.47	7.88	0.08	0.07	4.68	0.31	0.00	0.02
1.53	1.19	1.09	1.03	0.97	0.98	0.70	6.07	0.04	0.00	11.46	22.33	0.53	0.00
0.00	0.00	0.00	0.01	0.00	0.00	12.25	0.34	9.48	9.68	0.21	0.00	0.01	9.66
0.10	0.00	0.01	0.07	0.00	0.04	0.02	0.00	0.00	0.01	-	•	-	-
-	-	-	-	-	-	•	•	-	-	-	-	-	-
99.89	100.06	100.54	100.32	99.26	99.62	98.82	98.42	93.89	93.99	98.75	97.97	96.75	92.03

Eastern Lambert Glacier microprobe data

McKaskle Hills, McKaskle Hills, McKaskle Hills, McKaskle Hills, McKaskle Hills, Representative Reinbolt	M2 M2A M3 M5b M6
Reinbolt Hills, Reinbolt Hills, Reinbolt Hills, Reinbolt Hills, Reinbolt Hills, Reinbolt Hills, Reinbolt Hills, Reinbolt Hills, Reinbolt Hills, Reinbolt Hills,	7b 12a 12b 16 29b 38 45 85 121b 121c 121c

Jennings Promontory, JP15

	Mc Kaskl	e Hills, M2		5.9.91																									
	Оря	Орх	Pi.adi	Opx	Opx	Opx.R	Grt.R	Grt.Tr	Grt.Tr	Grt.Tr	Grt.Tr	Grt. Tr	Grt.Tr	Grt.Tr	Grt.Tr	Grt.Tr	Grt.Tr	Grt.Tr	Grt.Tr	Grt.Tr	Grt.Tr	Grt.R	Pl.adj	Grt.R	Grt.R	Pl.adj	Opx.R	Орх	Splinm
Mr N°	62.2	62.5		62.4	64.5	67.0	37.8	36.7	36.8	35.3	34.5	36.7	36.8	36.8	37.2	37.2	37.5	37.6	36.9	36.7	36.8	37.3	. '	34.6	34.5	. '	61.1	60.5	19.9
SiO2	50.44	50.62	50.44	50.53	50.53	50.93	38.63	38.57	38.68	38.29	38.63	38.53	38.74	38.58	38.82	38.96	38.63	38.95	38.78	38.43	38.87	38.74	48.29	38.30	38.10	47.26	50.87	50.51	0.06
A12O3	3.87	4.03	31.29	4.11	4.63	4.47	21.11	21.01	20.99	20.97	20.96	20.93	21.05	20.74	20.82	21.12	20.89	21.05	20.82	20.86	20.91	21.03	32.84	21.13	21.34	33.56	3.25	3.53	58.05
FeO	22.87	22.53	0.17	22.47	21.34	19.94	24.46	24.38	23.93	23.95	24.41	23.16	23.04	22.88	22.91	23.16	22.92	23.15	23.07	23.20	24.18	24.79	0.16	24.52	24.84	0.59	22.91	23.19	33.83
Fe2O3	-	-	-				•		-		-	-		•		-	-				-		. •	-	-	-	-		-
MgO	21.06	21.04	0.01	20.91	21.74	22.72	8.33	7.94	7.81	7.34	7.21	7.55	7.52	7.48	7.62	7.68	7.73	7.84	7.59	7.56	7.89	8.27	0.00	7.27	7.33	0.10	20.15	19.92	4.70
MnO	1.04	0.98	0.00	0.94	0.91	0.65	3.58	3.51	3.28	3.15	3.19	2.98	2.38	2.42	2.36	2.38	2.44	2.66	2.78	2.97	3.46	3.43	0.00	4.74	4.74	0.08	1.27	1.29	1.28
TiO2	0.00	0.00	0.00	0.03	0.00	0.03	0.03	0.03	0.00	0.00	0.00	0.01	0.04	0.11	0.08	0.05	0.08	0.09	0.09	0.07	0.01	0.00	0.01	0.02	0.00	0.04	0.00	0.00	0.14
Cr2O3	0.02	0.06	0.03	0.00	0.00	0.03	0.09	0.03	0.05	0.11	0.00	0.04	0.00	0.00	0.08	0.00	0.06	0.04	0.03	0.00	0.03	0.07	0.02	0.01	0.11	0.00	0.06	0.01	0.22
Na2O	0.00	0.00	3.15	0.00	0.01	0.00	0.00	0.02	0.01	0.00	0.00	0.01	0.02	0.00	0.01	0.00	0.02	0.01	0.00	0.00	0.01	0.00	2.28	0.01	0.01	1.89	0.00	0.01	0.00
CaO	0.15	0.16	14.85	0.13	0.19	0.17	3.20	4.25	4.98	5.58	5.76	6.18	6.96	6.91	6.83	6.80	6.68	6.72	6.56	6.28	4.62	2.94	16.45	3.07	2.57	16.93	0.24	0.28	0.00
K2O	0.01	0.01	0.09	0.01	0.02	0.00	0.02	0.00	0.00	0.00	0.00	0.02	0.00	0.02	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.05	0.01	0.01	0.04	0.02	0.00	0.00
NiO	0.00	0.01	0.01	0.00	0.00	0.01	0.00	0.00	0.01	0.06	0.00	0.00	0.00	0.03	0.00	0.00	0.01	0.00	0.03	0.09	0.00	0.00	0.02	0.02	0.00	0.02	0.02	0.00	0.09
ZnO	-		-			-	-	•	-	-	-	•	-	-	-	•	-	-	-	-	-	-	-	-		-	-	-	-
Totals	99.46	99.44	100.04	99.13	99.37	98.95	99.45	99.74	99.74	99.45	100.16	99.41	99.75	99.17	99.53	100.15	99.46	100.51	99.76	99.47	99.98	99.27	100.12	99.10	99.05	100.51	98.79	98.74	98.37
	Mc Kaski	e Hills, M2			27.10.91						27.10.91													29.10.91	Spinet tan	nellae in m	aenetite us	ed in Fig.	5.3
	Opx12	Pl.adj	Griadi	Grt.C	Grt.Cr6	GrtTr	Grt.Tr	Gri.Tr	Grt.Tr	Grt.Rr6	Pl.adi	PI	Grt.R.14	P1.20	OpxR21	OpxR22	PL23	PI.24	PI.32	Bt.33	Bt.34	Spt.36	Spl.37	Spl.r6.10	Spl.11	Spt.12	Sol.13	Mag.adi	Spl.C.1
Mg N°	61.3	- '	35.8	36.1	36.3	36.1	36.3	35.8	36.8	38.6		•	38.0	•	61.3	61.0	•	-	•	80.5	80.1	22.1	23.2	32.0	0.0	30.9	31.0	0.0	9.1
SiO2	50.45	53.07	38.09	38.21	38.17	38.21	38.00	38.44	38.19	38.34	53.16	52.56	38.21	44.85	49.29	49.41	44.53	52.04	45.55	38.29	38.50	0.05	0.01	0.00	0.01	0.03	0.06	0.04	0.03
AI2O3	3.46	29.54	21.44	21.13	21.38	21.50	21.54	21.33	21.21	21.63	29.28	29.72	21.40	33.28	4.16	3.75	31.30	29.85	34.25	15.01	15.08	57.25	59.18	59.09	59.30	58.25	58.61	0.38	32.76
FeO	22.69	0.08	24.31	24.08	23.61	23.48	23.29	23.79	24.17	24.81	0.30	0.23	25.20	2.23	22.81	23.09	6.77	0.33	0.20	8.61	8.87	35.23	33.29	26.99	26.97	21.19	27.27	29.78	31.39
Fe2O3	-	•	•	•	-	•	•	•	•	•		•	-	-	•		-	-	-	-	-	•	•	3.39	3.42	4.07	3.69	62.80	32.19
MgO	20.16	0.01	7.59	7.63	7.54	7.44	7.46	7.44	7.90	8.77	0.00	0.01	8.67	0.15	20.32	20.24	0.09	0.02	0.01	20.01	20.08	5.60	5.63	7.94	8.06	7.71	7.72	0.00	3.37
MnO	1.49	0.00	4.33	4.31	3.46	3.69	3.68	3.61	3.82	3.97	0.00	0.00	3.92	0.01	1.43	1.30	0.17	0.00	0.03	0.02	0.06	1.58	1.72	0.89	0.88	0.81	0.93	0.04	0.50
TiO2	0.00	0.01	0.01	0.00	0.08	0.10	0.08	0.09	0.04	0.04	0.00	0.00	0.00	0.00	0.00	0.03	0.01	0.03	0.00	0.70	0.73	0.12	0.14	0.00	0.01	0.03	0.02	0.67	0.23
Cr2O3	0.00	0.03	0.01	0.00	0.05	0.04	0.00	0.03	0.03	0.03	0.05	0.06	0.14	0.00	0.03	0.03	0.00	0.00	0.00	0.00	0.00	0.18	0.19	0.13	0.11	0.13	0.10	0.13	0.10
Na2O	0.00	4.19	0.00	0.00	0.00	0.01	0.02	0.00	0.01	0.01	4.61	4.28	0.02	1.48	0.00	0.00	2.02	4.18	1.44	0.11	0.15	0.00	0.00		•		-	-	-
CaO	0.31	12.68	3.65	4.19	6.23	6.21	6.29	5.92	5.07	3.03	12.00	12.52	2.66	16.87	0.18	0.24	14.38	12.41	17.52	0.02	0.00	0.02	0.00	-		-	-	•	-
K2O	0.00	0.17	0.01	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.10	0.11	0.02	0.01	0.00	0.02	0.04	0.15	0.01	10.32	10.30	0.00	0.00	-	•	-	-	-	-
NiO	0.06	0.03	0.06	0.00	0.02	0.03	0.12	0.02	0.00	0.07	0.11	0.00	0.09	0.00	0.00	0.09	0.00	0.01	0.00	0.01	0.01	0.14	0.10	0.10	0.12	0.12	0.08	0.03	0.05
ZnO	•	•	•	-	•	•	•	-	•	-	-	-	-	-	-	•	-	-	•	•	•	•	-	1.26	1.23	1.35	1.31	0.03	0.18
Totals	98.62	99.81	99.50	99.55	100.54	100.71	100.49	100.68	100.44	100.70	99.61	99.49	100.33	98.88	98.22	98.20	99.31	99.02	99.01	93.10	93.78	100.17	100.26	99.79	100.11	93.69	99.79	93.90	100.8(
	Soinat tan	nalise in m	anatite ne	ad in Fig	5 3			1 11 01																				woodum n	
	MagC adi	SolC 17	SolR 18	SolR 10	Solid 38	Mag 42	SolC 44	Sol 3 r6	Soll	Soll	Sol1 1	Solt 2	Sol 1 3	Soll 4	Mag adi	Soll 6	Solt 7	Sol113	Mag adi	Sol 115	Sol 16	Sol 121	Mag adi	Spl1 28	Mag adi	Spl.41	Mag 42	A11 46	Mag. St
Mo Nº	01	95	201	337	37.9	01	33.6	205	00	162	01	61	17.2	78	00	48	12.8	15	71	98	22	00	0.2	108	0.3	22.9	05	0.2	01
Sion	0.03	0.08	0 22	0.11	0.01	0.00	0.04	0.02	0.02	0.01	0.03	0.04	0.05	0.02	0.07	0.04	0.02	0.02	0.03	0.02	0.00	0.26	0.04	0.35	0.03	0.08	0.46	0.11	0.01
APOL	0.34	34 47	58.22	59 39	58.63	0.83	59.15	53 18	1916	48.07	18.45	41 76	47.98	29.26	0.21	22.25	41.95	7 00	10.06	36.49	9.68	58.70	1.01	46.90	2.52	56.17	4.64	73.84	2.65
FeO	29.95	31.47	28.23	26.84	26.63	29.78	26.75	30.83	29.76	30.48	39.90	39.68	29.90	30.62	29.28	31.29	30.80	32.28	32.40	31.02	33.49	31.80	32.78	33.81	33.94	30.33	30.41	22.06	28.31
Fe203	62.75	30.66	3 38	2.82	3 67	61.60	3.07	5 35	11 13	11.68	24.22	0.85	1085	34.50	63.83	42.74	19.77	54.72	54.27	25.99	50.53	2.11	56.14	13.66	51.68	3.01	58.18	0.00	58.57
MeO	0.04	3.49	7 32	8 36	8 24	0.06	8.37	514	2.07	4 47	0.13	0.03	4 63	2.95	0.00	1.99	199	0.69	1.10	3.32	0.97	5.44	0.09	3.14	0.14	5.49	0.22	0.03	0.06
MnO	0.01	0.60	1 19	0.92	0.71	0.24	0.85	130	0.31	1.07	0.78	0.29	1.05	0.54	0.00	0.38	0.85	0.42	0.35	0.70	0.62	1.29	0.61	0.71	0.44	1.23	0.00	0.00	0.08
TiO2	0.84	0.11	0.01	0.01	0.00	1.05	0.00	0.86	015	0.32	9.39	4.42	0 31	0.19	0.11	0.13	0.21	2.43	1.77	0.13	3.47	0.11	4.15	0.18	5.25	0.30	0.12	0.15	0.14
6203	010	0.10	013	0.01	0.12	0.10	0.12	0.00	013	0.15	011	0.10	015	0.12	014	612	015	0.13	0.14	0.14	013	015	015	0.15	016	0.14	0.17	0.14	015
Na20			0.15	-		0.10			0.15											-	•			•		-	-		-
CiO		-			_									-	-		-						-						-
K20			-	-					-		-		-			-							-		-	-			-
NiO	0.06	0.05	0.08	0.13	0.00	0.07	0.07	0.09	0.03	0.08	0.00	0.04	0.08	0.12	0.02	0.03	0.07	0.06	0.03	0.06	0.02	0.11	0.07	0.13	0.00	0.17	0.05	0.04	0.07
ZnO	0.01	0.21	0.70	0.75	1.15	0.03	0.96	0.20	0.07	0.24	0.00	0.02	0.17	0.05	0.00	0.05	0.14	0.05	0.11	0.07	0.00	0.35	0.00	0.21	0.00	0.22	0.00	0.04	0.00
Totals	94.13	101.24	99.48	99.44	99.16	93.76	99.68	97.14	96.13	96.57	93.03	90.32	95.17	98.37	93.66	99.02	97.95	97.80	100.26	97.94	98.91	100.32	95.04	99.24	94.16	97.14	94.25	96.41	90.04
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						Mc Kaski	e Hills, M2	A.	13.9.91																				
	Mag.51	Spl.55	Spl.56	Mag.57		Amp16	Amp17	AmpR	Pl.adj	Срх. В	Cpx.31	Срх.33	Cpx R	Pl.adj	Cpx.R	Срх. 37	Cpx.38	Оря.40	Opx.41	Opx.R16	Орх.С	Орх	Cpx R	adj.Pl	adj Amp	Opx 22	Opx R	Opx.C	Pl.adj
Mg N°	0.4	13.8	7.0	0.0		53.8	53.4	55.7	•	66.8	63.4	65.1	67.3	-	64.6	68.1	70.2	54.3	54.9	53.4	55.1	55.1	54.5		56.3	54.4	55.2	54.3	-
5iO2	0.03	0.02	0.02	0.05		40.66	40.96	41.65	56.24	50.87	50.78	50.34	51.17	55.19	50.37	51.54	52.15	51.11	51.24	51.26	50.56	51.06	51.39	55.34	41.82	51.45	50.60	51.16	55.23
AI203	4.23	47.29	30.72	0.24		11.14	11.07	10.94	27.90	1./1	2.85	2.54	1.37	27.87	2.78	1./3	1.15	0.96	0.85	0.93	1.17	0.90	1.03	28.22	10.82	0.90	0.96	1.00	28.09
FeO E.202	28.81	33.09	32.97	29.00		15.92	16.22	15.32	0.10	10.88	12.00	11.26	10.75	0.29	11.52	10.51	9.91	27.20	26.49	27.64	20.57	26.45	26.93	0.26	12.22	20.89	26.43	27.07	0.17
MaO	0.20	4 37	20.01	03.55		10.41	10.42	10.93	0.00	12.20		11.90	12.11	0.02	1179	1255	1111	1915	1817	17.75	18.20	19.19	1810	0.07	11 23	17.00	18.25	18.06	
MnO	0.09	0.61	0.35	0.02		0.77	0.73	0.15	0.00	6.17	0.43	0.50	0.38	0.02	0.15	0.35	648	0.03	6.12	111	1.00	10.10	101	0.02	0.20	1.06	10.25	1 00	0.00
TiO2	0.16	0.41	012	0.06		2.36	2.29	2 27	0.03	0.26	0.40	0.38	0.24	0.04	0.40	0.26	0.10	0.11	0.09	0.12	0.11	0.13	0.07	0.01	2.19	0.12	0.09	0.11	0.01
Cr2O3	0.15	0.15	0.16	0.15		0.00	0.07	0.04	0.00	0.03	0.07	0.06	0.02	0.00	0.07	0.03	0.00	0.01	0.02	0.01	0.06	0.05	0.01	0.07	0.11	0.01	0.09	0.00	0.06
Na2O	-	•	-	-		1.39	1.34	1.24	5.47	0.27	0.37	0.39	0.27	4.97	0.38	0.29	0.26	0.00	0.01	0.00	0.02	0.00	0.03	5.13	1.28	0.00	0.02	0.00	5.05
CaO	-		-	-		11.60	11.96	11.89	10.54	22.66	21.88	22.11	22.57	10.97	21.82	22.57	22.78	0.78	0.77	0.80	0.84	1.14	0.80	11.14	12.13	0.76	0.99	0.85	10.96
K2O	•	•	-	-		2.03	1.99	1.96	0.23	0.01	0.01	0.02	0.00	0.61	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.02	0.00	0.35	1.93	0.00	0.01	0.00	0.40
NiO	0.04	0.09	0.06	0.03		0.00	0.01	0.00	0.00	0.00	0.00	0.08	0.00	0.00	0.02	0.00	0.00	0.00	0.04	0.01	0.05	0.04	0.00	0.03	0.03	0.02	0.01	0.03	0.00
ZnO	0.04	0.25	0.17	0.00				•		• • •		•••••	•	· · · · ·		• • • •			•	· · · · ·		•					•	· · · · ·	
lotals	91.34	103.03	103.95	93.10		95.78	96.30	96.29	100.51	99.46	100.45	99.49	99.38	99.96	99.60	99.85	99.94	99.26	98.61	99.63	98.67	99.05	99.37	100.57	97.29	99.26	98.45	99.28	99.97
	Mc Kaskle Hills, M2A Opx.28 Cpx.R3 Pl Opx.48 Opx.50 Opx.51 Cpx.52 Cpx.53 Cpx.54 Opx.adi Cmx.adi Pl.adi Amp.60 Kfs. Pl 3Spladi3 Mao 4 Mao 5 Spl 6 Spl 1 llm 2 llm 2 Spl 4 Spl 5 llm 8 Spl 9																Mc Kaskle	Hills, M3											
	Opx.28	Cpx R3	Pl	Opx.48	Opx.50	Opx.51	Срх.52	Cpx.53	Cpx.54	Opx.adj	Cpx.adj	PLadj	Amp.60	Kfs	PI	3Spladj3	Mag.4	Mag.5	Spl.6	Spl.1	lim 2	llm.2	Spl.4	Spl.5	ltm.8	Spl.9		PLr2	Opx.R
Mg N°	54.1	67.0	•	55.2	56.1	<b>Š</b> 5.5	66.8	66.8	68.6	55.2	70.5	- '	55.7	•	-	36.1	0.1	0.6	34.7	18.7	2.9	2.4	30.2	30.8	1.8	25.5		-	75.1
SiO2	50.91	51.48	55.38	50.69	51.70	51.28	51.17	51.15	51.94	51.29	52.01	56.66	41.74	64.62	54.86	0.03	0.03	0.02	0.05	0.05	0.00	0.00	0.02	0.06	0.00	0.21		44.37	52.65
AI2O3	0.78	1.56	28.15	1.14	0.72	0.90	2.37	2.13	1.50	0.83	1.34	27.57	10.83	18.57	28.48	57.91	0.26	1.55	58.57	46.83	0.00	0.00	57.14	57.38	0.00	52.48		35.34	4.16
FeO	27.36	10.99	0.22	26.64	26.46	26.67	11.11	11.31	10.60	26.83	9.88	0.13	15.69	0.06	0.19	18.58	28.47	29.85	20.61	26.68	46.24	45.79	22.21	22.21	45.43	20.97		0.20	15.69
Fe203	•		•					-			-	-		-	•	2.50	01.39	56.87	2.82	10.90	0.00	0.00	3.33	5.05	0.00	9.98		0.00	26.62
MgO	18.11	12.55	0.01	18.42	18.98	18.67	12.55	12.75	12.97	18.50	13.28	0.02	10.07	0.00	0.00	0.02	0.03	0.27	0.92	5.42	0.75	0.03	0.37	0.09	0.40	5.70		0.00	20.33
TiO	0.99	0.43	0.00	0.99	0.97	0.94	0.38	0.49	0.45	0.90	0.40	0.08	0.21	0.04	0.03	0.12	0.01	1.09	0.27	0.10	4118	45.02	0.20	0.19	1578	0.11		0.00	0.08
Cr203	0.07	0.20	0.02	0.10	0.09	0.07	0.10	0.25	0.05	0.08	0.01	0.04	0.08	0.00	0.00	0.59	0.47	0.49	0.54	0.40	0.05	0.06	0.49	0.49	0.04	0.43		0.00	0.00
Naro	0.00	0.31	5 30	0.00	0.00	0.01	0.35	0.35	0.27	0.01	0.21	5.73	1.33	0.39	5.18	-		-	-	•	-	-	•	-	-	-		0.58	0.01
CaO	0.71	22.65	10.62	0.78	0.61	0.81	22.16	21.56	22.19	0.70	23.10	9.99	11.72	0.05	11.09		-				-	-	-	-	-	-		19.44	0.36
K2O	0.00	0.00	0.41	0.01	0.00	0.01	0.00	0.00	0.00	0.01	0.01	0.44	1.88	14.66	0.23	-	-	-	-	•	-	•	•	-	•	-		0.00	0.00
NiO	0.02	0.00	0.00	0.01	0.02	0.06	0.10	0.03	0.04	0.05	0.00	0.00	0.08	0.00	0.00	0.05	0.04	0.03	0.10	0.07	0.03	0.01	0.05	0.10	0.01	0.04		0.00	0.00
ZnO	-	-	•	-	-	-	•	•	-	-	•	-	-	•	•	13.44	0.00	0.07	11.10	6.57	0.02	0.00	10.55	10.61	0.00	12.42		-	
Totals	98.95	100.19	100.11	98.82	99.55	99.51	100.57	100.03	100.14	99.36	100.40	100.68	95.77	98.40	100.06	99.95	91.11	91.21	101.09	103.87	92.12	93.33	102.86	103.16	92.89	102.51		99.94	99.95
	Mc Kaskle	e Hills, M3		5.9.91																									
	Opx.Tr	Opx.Tr	Opx.Tr	Opx.R	P1.adj	Amph.r2	Amp.Tr	Amp.Tr	Amp.Tr	Amp.R	Pl.adj	Opx.14	Pl	Amp	Amr3R	Amp.Tr	Amp.Tr	Amp.Tr	Amp.Tr	Amp.Tr	Amp.Tr	Amp.R	P1.adj	Opx.adj	PLadj	PI.Tr	Pl.Tr	Pl.Tr	Pl.Tr
Mg N°	73.9	74.4	74.9	75.4	-	73.7	72.1	72.6	72.9	72.5	-	76.7	-	74.6	74.6	73.5	73.9	73.4	73.A	72.8	72.9	74.3	-	75.4	-	-	•	-	•
SiO2	51.94	51.97	52.49	52.80	44.39	41.63	41.28	41.18	41.23	41.19	44.24	53.26	44.40	41.34	41.43	41.18	41.51	41.53	41.06	41.01	41.22	41.44	44.47	52.19	44.92	45.03	43.75	44.07	44.22
AI203	4.80	4.82	4.30	3.68	35.44	14.74	14.89	15.40	14.81	14.66	35.33	3.38	36.02	15.18	14.77	15.13	15.25	15.32	15.06	14.98	15.14	14.91	35.80	4.32	35.90	35.66	36.02	36.00	36.36
re0 Eat01	10.20	15.80	15.74	15.47	0.43	9.45	9.87	9.75	9.62	9.81	0.20	15.06	0.20	9.23	9.23	9.49	9.40	9.58	9.46	9.60	9.68	9.18	0.35	15.57	0.24	0.23	0.06	0.16	0.37
Man	25 40	25 74	26.38	26.61	0.00	14.85	14 20	14 57	1156	-			-	-	1510			14.95				-	-	26.96		-	-		-
MnO	0.33	0.43	0.38	0.43	0.09	015	011	0.16	011	0.20	0.00	£1.76 £1.75	0.00	015	015	0.10	0.04	013	014	0.11	0.01	0.18	0.00	20.60	0.00	0.00	0.00	0.00	0.02
TiO2	0.07	0.08	011	0.06	0.00	1.11	1 58	1 40	1.49	1.11	0.00	0.01	0.03	1 17	1 30	1.41	1 3 7	1 37	1.47	1.40	1.10	1 20	0.02	0.00	0.00	0.07	0.00	0.01	0.00
Cr2O3	0.01	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.04	0.00	0.00	0.00	0.03	0.04	0.06	0.02	0.06	0.01	0.07	0.02	0.05	0.03	0.02	0.00	0.00	0.00	0.00	0.07	0.02
Na2O	0.03	0.00	0.00	0.03	0.60	2.60	2.47	2.70	2.58	2.54	0.63	0.01	0.75	2.57	2.58	2.50	2.57	2.54	2.55	2.57	2.59	2.47	0.59	0.01	0.79	0.79	0.44	0.55	0.52
CaO	0.44	0.43	0.37	0.36	19.60	12.11	12.13	12.03	12.06	12.19	19.68	0.27	19.39	12.25	12.21	12.07	12.18	12.27	12.21	11.97	11.93	12.20	19.74	0.37	19.28	19.20	20.23	19.90	19.92
K2O	0.01	0.00	0.00	0.00	0.01	0.71	0.58	0.61	0.58	0.64	0.01	0.00	0.03	0.67	0.64	0.62	0.61	0.62	0.61	0.59	0.62	0.73	0.00	0.00	0.01	0.01	0.00	0.01	0.02
NiO	0.04	0.03	0.00	0.00	0.00	0.11	0.01	0.00	0.00	0.09	0.01	0.04	0.04	0.00	0.10	0.04	0.03	0.00	0.00	0.00	0.00	0.02	0.04	0.00	0.01	0.03	0.00	0.02	0.01
ZnO	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	•	-	-	•	•		•	-	-	
I OTAIS	99.89	99.30	99.17	99.48	100.56	91.40	97.23	97.84	97.08	97.24	100.10	100.23	100.89	97.79	97.66	97.43	97.91	98.22	97.27	96.80	97.34	97.35	101.03	99.67	101.15	101.04	100.58	100.75	101.48

Mg N° SiO2 Al2O3 FeO FeOO MnO TiO2 Cr2O3 Na2O CaO K2O NiO ZnO Totals	Mc Kaskk PIR - - - - - - - - - - - - - - - - - - -	e Hills, M3 Opx.R 76.6 53.21 3.61 15.02 27.64 0.33 0.06 0.03 0.00 0.42 0.00 0.42 0.00 0.05	Opx.Tr 75.9 52.54 4.17 15.23 26.87 0.47 0.06 0.00 0.00 0.00 0.00 99.74	21.9.91 Opx.C 75.9 52.35 4.41 15.17 	Opx.Tr 75.6 52.60 4.46 15.35 -76 0.35 0.05 0.04 0.00 0.39 0.00 0.00 -100.00	Opx.Tr 75.5 52.55 4.12 15.59 26.96 0.38 0.08 0.03 0.02 0.35 0.00 0.02	Opx.R 76.3 53.06 3.29 15.31 - 7.65 0.42 0.02 0.02 0.00 0.32 0.02 0.00	Spl.adj 48.6 0.02 59.18 25.26 	PI.Tr20 44.47 36.17 0.30 0.00 0.00 0.00 0.00 0.00 0.00 0.57 19.81 0.02 0.00	P1.Tr 44.30 35.56 0.18 0.00 0.00 0.00 0.00 0.80 19.39 0.03  100.28	P1.Tr 44.58 35.60 0.16 0.00 0.00 0.00 0.00 0.81 19.38 0.01 0.00	P1.Tr 44.49 36.03 0.13 0.00 0.00 0.00 0.00 0.54 19.76 0.12 0.06 101.14	Pl.Tr 43.66 35.86 0.15 0.00 0.00 0.03 0.00 0.39 20.57 0.00 0.07 100.73	Opx.adj 76.0 3.84 15.28 0.00 27.15 0.35 0.04 0.05 0.01 0.37 0.00 0.00	Spl.R 57.0 0.25 63.15 18.55 2.34 15.34 0.03 0.03 0.31 - - - 0.09 0.13 100.45	Spl.Tr 51.3 0.02 60.24 19.18 5.77 14.40 0.21 0.00 0.29	Spl.Tr 51.1 0.02 60.31 19.55 4.91 14.07 0.18 0.02 0.32 - - - 0.06 0.10 99.54	Spt.Tr 50,5 0,00 60,11 19,61 5,33 13,98 0,25 0,00 0,29 - - - - - - - - - - - - - - - - - - -	Spl.Tr 49.7 0.01 59.85 19.86 5.51 13.76 0.24 0.01 0.27 - - - - 0.09 0.11 99.71	Spl.Tr 50.0 0.02 59.16 19.39 6.03 13.95 0.21 0.01 0.28 	Spl.Tr 48.8 0.01 59.29 20.05 5.88 13.58 0.22 0.04 0.28 	Sp1.Tr 48.5 0.02 59.17 20.11 6.26 13.60 0.22 0.02 0.22 0.02 0.29 	Spl.Tr 52.5 0.01 18.85 4.80 14.35 0.23 0.00 0.29 - - 0.00 0.00 98.84	Spl.Tr 50.4 0.01 59.90 19.65 5.43 13.95 0.19 0.03 0.24 - - - - 0.06 0.11 99.57	Spl.Tr 50.5 0.03 60.29 19.73 5.19 13.96 0.25 0.03 0.23 - - - - - - - - - - - - - - - - - - -	Sp1.Tr 50.4 0.01 60.42 19.84 5.19 13.95 0.22 0.01 0.23 - - 0.08 0.08 100.03	Spl.Tr 51.2 0.00 60.39 19.35 5.37 14.24 0.22 0.00 0.23 - - - - - - - - - - - - - - - - - - -	Spl.Tr 48.4 0.02 58.60 19.96 6.52 13.57 0.17 0.03 0.23 	Spl.Tr 47.5 0.01 58.300 7.46 13.60 0.25 0.03 0.24 - - 0.07 0.11 100.07
	Mc Kaskie	Hills, M3		continued			Mc Kaskk	Hills, M5	ь	3.10.91																			
Mg N° SiO2 Al2O3 FeO Fe2O3 MgO	Spi.Tr 48.5 0.00 58.67 19.83 6.59 13.62	Spl.Tr 49.3 0.03 60.23 20.11 6.15 13.99	Sp1.R 48.8 0.02 59.63 20.26 5.62 13.53	Spl.R 46.6 0.01 57.94 20.45 7.15 13.15	Opx.adj 75.2 52.30 3.75 13.60 2.73 27.28		sym.Pl 46.97 34.02 0.10	sym.Pl 46.82 34.00 0.19 0.00	Phi 64.2 37.80 13.08 14.62	Phi 63.1 38.03 13.17 14.99 -	Kfs 63.79 18.51 0.05 0.00	Cpx.33 66.8 51.46 1.69 10.84	Cpx.34 65.2 51.09 2.22 11.34 -	Cpx.C 65.2 51.07 2.58 11.17	sym.Pl 47.20 33.85 0.13 	Cpx.R37 67.2 51.36 1.75 10.77	PLincl 54.14 28.92 0.21 0.00	Cpx.Tr40 65.5 50.69 2.25 11.29 12.06	Cpx.Tr42 64.0 50.93 2.27 12.25 -	Cpxtr43 64.8 50.43 3.07 11.34 -	CpxR44 69.8 51.60 1.08 9.78 12.72	Amp.r4 53.3 41.64 10.91 16.42 	Opx.13 49.8 50.46 0.72 29.52	Opx.5 50.1 50.70 0.70 29.27 16.47	Pht.adj 64.1 37.84 13.13 15.10 - 15.15	Opx.8 50.0 50.67 0.76 29.27	Opx.R10 52.2 50.73 0.71 28.32 17.38	Pl.adj 47.63 33.24 0.43 -	symPh 63.4 38.99 13.05 15.14 14.72
MnO TiO2 Cr2O3 Na2O CaO K2O NiO	0.19 0.02 0.25	0.25 0.05 0.22	0.20 0.03 0.23 - - - 0.07	0.20 0.06 0.24 - -	0.38 0.08 0.00 - -		0.00 0.02 1.60 17.46 0.05 0.00	0.00 0.00 0.05 1.61 16.95 0.04 0.07	0.12 4.12 0.14 0.03 0.03 9.79 0.00	0.14 4.29 0.23 0.02 0.03 9.81 0.07	0.04 0.00 0.01 0.55 0.00 15.75 0.11	0.28 0.21 0.10 0.19 22.19 0.00 0.00	0.40 0.27 0.19 0.27 21.66 0.00 0.00	0.40 0.25 0.19 0.28 21.79 0.00 0.00	0.05 0.01 0.04 1.70 17.29 0.03 0.07	0.39 0.20 0.22 22.06 0.01 0.00	0.00 0.00 4.56 11.48 0.22 0.03	0.41 0.28 0.15 0.28 21.82 0.00 0.11	0.42 0.26 0.21 0.24 20.44 0.00 0.00	0.41 0.30 0.13 0.25 21.28 0.01 0.01	0.43 0.16 0.16 0.20 21.96 0.06 0.05	0.23 1.98 0.33 1.12 11.91 2.36 0.03	0.96 0.11 0.05 0.02 0.73 0.02 0.02 0.02	1.11 0.10 0.02 0.02 0.80 0.00 0.00	0.00 3.74 0.28 0.04 0.00 10.08 0.01	0.86 0.07 0.05 0.00 0.74 0.01	0.93 0.09 0.01 0.00 0.59 0.00 0.01	0.05 0.04 0.00 1.93 16.65 0.05 0.05	0.13 3.54 0.28 0.04 0.05 9.92 0.06
ZnO Totals	0.12 99.37	0.13 101.23	0.14 99.73	0.13 99.41	0.00 100.12		100.22	99.73	94.46	95.18	98.81	99.20	99.38	99.47	100.32	99.35	99.56	99.34	99.26	98.96	98.20	97.45	99.04	99.19	95.37	98.88	98.77	100.02	95.92
Mg N° SiO2 Al2O3 FeO Fa2O3	Mc Kaski Opx.14 52.5 51.09 0.83 28.15	e Hills, M Ksp 64.51 18.43 0.04	5b Amp.C 54.0 41.18 10.94 15.91	5.10.91 Amp.R 54.5 42.38 9.95 15.79	Opx.19 51.3 50.92 0.80 28.55	sym.Pi 46.17 33.70 0.35	Ph1.adj 63.9 37.67 12.86 15.03	P142 46.50 34.29 0.15	Ph1.adj 62.2 37.55 12.91 15.38	I Cpxr2 64.0 50.78 2.28 11.87	2Cpxr2 64.2 50.77 2.47 11.49	30pxr2 52.4 50.92 0.71 27.83	4Opxr2 52.2 51.14 0.81 28.18	80pxr5 53.2 50.62 0.99 27.47	9Cpxr5 63.5 50.68 2.19 12.76	100px 53.7 51.05 0.92 27.23	11OpxR 54.1 50.83 0.84 27.17	12CpxR 67.7 51.46 1.54 10.77	13CpxR 67.3 51.45 1.66 10.83	14CpxR 67.2 51.20 1.79 10.81	150pxR 54.4 51.75 0.89 27.25	16Opr6 52.9 51.08 0.91 27.83	17Cpx 67.7 51.27 1.55 10.63	200pxC 52.7 50.69 0.93 27.92	21 CpxC 66.1 50.69 2.14 11.05	26CpxR 65.2 51.21 1.92 11.60	27OpxR 53.2 51.14 0.79 27.54	25CpxC 64.9 50.87 2.33 11.78	24Opx( 52.9 50.50 1.02 27.87
re203 Mg0 Mn0 TiO2 Cr2O3 Na2O Ca0 K2O NiO Za0	17.45 0.88 0.08 0.03 0.00 0.72 0.01 0.00	0.00 0.00 0.02 0.71 0.03 15.89 0.04	10.47 0.20 2.13 0.29 1.11 11.87 2.25 0.00	10.62 0.13 1.40 0.17 0.83 11.57 2.13 0.06	16.89 0.90 0.09 0.07 0.01 0.83 0.02 0.04	0.00 0.03 0.00 1.56 17.62 0.07 0.00	14.90 0.10 3.72 0.18 0.04 0.04 9.99 0.05	0.00 0.03 0.03 1.57 17.76 0.04 0.00	14.17 0.09 3.99 0.27 0.04 0.00 9.94 0.01	- 11.85 0.57 0.29 0.06 0.27 21.80 0.01 0.07	11.60 0.34 0.35 0.10 0.30 22.09 0.00 0.03	17.20 0.86 0.11 0.07 0.03 0.67 0.00 0.10	17.27 0.97 0.07 0.06 0.00 0.69 0.00 0.02	17.49 0.99 0.08 0.11 0.02 0.92 0.00 0.00	12.44 0.57 0.20 0.16 0.26 20.48 0.00 0.04	17.70 0.98 0.10 0.03 0.02 0.78 0.00 0.02	17.94 0.88 0.03 0.06 0.00 0.69 0.00 0.00	12.65 0.38 0.13 0.21 0.22 22.98 0.01 0.00	12.48 0.36 0.16 0.10 0.23 22.51 0.01 0.01	12.40 0.54 0.11 0.16 0.24 22.40 0.02 0.02	18.22 0.96 0.04 0.10 0.00 0.80 0.00 0.01	17.54 1.03 0.10 0.13 0.01 0.78 0.00 0.00	12.51 0.39 0.17 0.15 0.20 22.61 0.01 0.03	17.49 0.93 0.09 0.00 0.02 1.03 0.00 0.05	12.06 0.37 0.21 0.06 0.26 22.56 0.01 0.00	12.22 0.40 0.17 0.10 0.26 21.97 0.01 0.04	17.55 1.05 0.07 0.11 0.02 0.74 0.00 0.05	12.22 0.52 0.19 0.22 0.24 21.59 0.00 0.06	17.59 0.98 0.10 0.08 0.00 0.91 0.00 0.04
Totals	99.24	99.67	96.35	95.03	99.12	99.50	94.58	100.37	94.35	99.85	99.54	98.50	99.21	98.69	- 99.78	98.83	98.44	100.35	99.80	- 99.69	100.02	99.41	99.52	99.15	99.41	- 99.90	99.06	100.02	99.09

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Mg N° SiO2 Ai2O2 FeO Fe2O3 MgO MgO MgO Cr2O3 Na2O Cr2O3 Na2O CaO K2O NiO ZnO Totals	Mc Kaskle 29Ksp.r2 	Hiths, M6 30.0px 53.7 49.18 3.63 27.32 0.00 17.75 0.99 0.06 0.14 0.02 0.03 - 99.25	Opx 53.6 49.68 3.32 27.26 0.00 17.66 0.79 0.05 0.10 0.05 0.10 0.01 0.01 0.04 99.07	8.10.91 33Phi 59.6 36.74 14.67 16.62 0.00 13.78 0.00 13.78 0.00 2.49 0.07 0.02 0.04 9.92 0.08	35Ph1 61.5 36.89 15.10 15.99 0.00 14.34 0.00 2.36 0.19 0.04 0.13 9.80 0.00 -	370px 53.5 49.09 3.56 27.46 0.00 17.74 1.22 0.06 0.12 0.00 0.15 0.00 0.03	380px 53.5 49.60 3.37 27.49 0.00 17.73 1.08 0.01 0.12 0.01 0.11 0.01 0.07 - 99.64	P1.adj 57.16 27.11 0.21 0.00 0.03 0.00 0.01 0.00 6.15 9.17 0.09 0.00	40Ph1 61.4 36.13 15.29 15.44 0.00 13.80 0.04 2.95 0.22 0.04 0.03 10.08 0.04 - 94.06	410px 54.1 48.88 5.37 26.89 0.00 17.78 0.94 0.94 0.94 0.14 0.00 0.10 0.00 - 100.16	42P1 57.14 27.20 0.18 0.00 0.07 0.02 0.00 6.10 9.02 0.17 0.00 99.90	44Kfs 65.04 18.70 0.25 0.00 0.05 0.00 0.01 0.02 1.54 1.45 12.25 0.00 - 99.31	45Phi 58.7 36.65 14.93 16.27 0.00 12.98 0.00 3.83 0.03 9.81 0.05 9.81 0.10									Ţ				
	Reinbolt	Hills, 76, 7	2020														Reinbolt H	ills. 12A						Reinbolt Hil	lls. 12b	
	Grt	Орх	Ph	i I	PI	Kfs	llm -	Opx 13	P1.r3	Grt	Opx.a	tj (	Grt	Орх	P1.adj		Срх	Ilm	Pl	Орх	Phl	Орх	Сря	Scap	Pl	Pl
Mg N°	34.7	60.4	68.	.5	-	•	7.8	57.9	•	33.5	60.8	3:	5.0	57.8	•		60.5	2.5	•	48.7	55.1	47.4	62.0	-	•	-
SiO2	39.21	50.86	5 35.6	66 56	.47	64.23	•	50.64	57.50	38.88	51.09	39	1.45	50.67	58.01		51.08	•	57.30	52.47	37.14	50.59	51.75	39.15	43.90	44.31
A12O3	22.23	3.50	12.8	85 27	.61	18.58	•	3.95	27.49	22.37	4.00	22	2.27	4.06	27.36		2.02	-	28.40	0.77	13.87	0.84	1.80	15.30	35.67	35.43
FeO	28.04	24.05	5 12.3	36	-	•	43.16	25.58	-	28.60	23.90	) 28	8.04	25.69	•		13.02	41.18	•	32.08	18.15	31.20	12.57	11.48	0.23	0.23
R203	0.15	0.15			•	-	•	-	•	•	-				•			7.82	•			-	-	-	-	-
MgO	8.31	20.63	5 15.	13	•	•	2.03	19.71	-	8.08	20.81	8	.40	19.72	•		11.19	0.00	•	17.08	12.48	15.81	11.49	0.28	0.00	0.00
TiO2	0.74		50	u.	-	051	50 53		· 1	0.05		U			•		0.26	0.41	•	0.58	5 80 ·	0.09	-	0.94	0.00	0.01
Cr203	-		5.0	•	-	-	6.28		-		0.19				:		0.20	47.45	-		3.60		0.22	0.43	0.00	0.01
Na2O		-	0.0	3 5.	25	0.39	-	-	5.94		-				5.60				5.18		-	-	-	-	0.39	0.45
CaO	2.30		-	9.	77	0.24		-	9.22	2.15		2	.20		9.16		21.46		10.34	0.64	-	0.87	22.17	32.63	19.77	20.00
K2O		•	9.7	5 0.	46	15.18		-	0.23	•			•	•	0.45		-	•	0.21	•	9.30	•	•	-	0.02	0.02
NiO	-	-	•		-	•	-	•	-	•			-		•		•	•	•	•	•	-	-	•	-	•
ZnO	-	•	•		-	•	•	•	•	-	-		-	-	•		-	•	•	-	-	•	-	-	-	•
Totals	100.98	99.19	90.8	82 99	.56	99.16	96.00	99.88	100.38	100.73	99.99	10	1.19	100.14	100.58		99.03	97.46	101.43	103.62	96.74	100.00	100.00	100.21	99.97	100.46
	Reinbolt I	Hills, 12b							Reinbolt	Hills, 16																Reinbolt H
	Wol	Wol	Cp	x Spł	hene	Woł	Scheelite		Pl	Срх	Орх	I.	lm	Ph1	Cpx.C	Cpx.Tr	Срх.Тг	Cpx.R	Ph	Pl	Opx.r3	Opx_3				Сря
Mg N°		•	37.	.6	•	•	-		-	64.8	53.9	1	.9	65.7	66.8	65.9	65.6	67.1	65.9	•	54.2	53.8				63.8
SiO2	51.52	51.60	) 50.2	23 29	.79	50.59	0.00		57.56	52.69	52.71		-	38.59	52.72	51.96	52.26	52.33	38.70	57.12	52.56	51.66				52.99
A1203	0.00	0.00	0.8	3.	.66	0.01	0.00		28.45	1.62	0.71		•	12.56	1.81	1.66	1.92	1.64	12.86	28.17	0.39	0.89				0.69
FeO	0.47	0.47	18.1	IS I.	.03	0.66	0.00		•	12.94	28.53	45	6.06	14.27	11.42	11.81	12.27	11.21	14.41	-	28.29	28.31				11.60
re203	•	-			-	-			•				•							•						
Mago		0.62	0.1	4 U. K A	.00	0.01	0.00		•	13.38	18./3	) U	75	15.51	12.90	12.80	13.13	12.54	13.03	•	18.73	18.33				11.40
Tint	0.58	0.02	1.0			0.08	0.00		•		0.58	5	1.03	5.21			0.29	0.19	•	•	0.47	0.53				-
Cr203				29	-0-0 -0-1	0.03	0.00		•	0.20		51		J.21	0.32	0.28	0.29	0.10	5.15	•		•				
Na2O	-			0.	00	0.00	0.00		5 52	-			-	-	0.51	-		-		530	-	-				
CaO	47.43	46.75	23.0	62 28	3.38	47.22	21.77		10.31	19.38	0.68			-	21.04	20.71	20.08	21.85	•	10.20	0.70	0.65				24.21
K2O	•	•	-	0.	.01	0.00	0.00		0.26		•		•	9.71	•	•	-	•	9.86	0.36	-	•				•
NiO	-	-	-		-	•	0.00				-		-	-	-	-		-	-	-	-	-				-
ZnO	•	-			-	•	•		•	•	-		•		-	-	•	-	•	-	-	-				•
i otais	100.00	99,44	100.	.00 92	.41	99.25	21.77		102.10	100.29	101.9	6 97	1.34	95.65	100.52	99.22	100.24	100.05	96.63	101.15	101.16	100.57				100.97

	Reinbolt H	ills, 38										Reinbolt H	ills, 45										
	Pl	Срх	Phi	Орх	Орх	PI	Сря	Срх	Amph	Amph		Орх	Орх	Spl	Spl	Сря	Орх	Срх	Орх	Сря	Amp	Amp	
Mg N°	-	66.6	65.2	53.5	53.2	•	68.0	68.0	59.5	58.2		82.8	82.5	59.6	60.4	87.1	82.6	86.6	83.0	87.2	83.2	81.6	
SiO2	56.52	51.56	39.20	52.51	51.85	56.55	52.11	51.89	44.53	42.25		54.93	54.57	•	-	52.76	54.95	52.49	55.13	52.55	45.22	44.09	
AI2O3	27.97	2.09	12.79	1.01	0.62	27.99	2.83	2.82	10.88	11.91		2.98	3.11	53.97	54.33	3.20	2.87	3.15	3.05	3.10	13.93	14.03	
FeO	-	11.26	14.53	27.95 .	28.53	-	10.95	10.68	14.62	14.68		11.19	11.30	17.76	17.38	4.18	11.35	4.39	0.0	4.28	6.20	6.60	
Fe2O3	•	•	-	-	-	-	•	-	•	-		•	•	5.32	5.06	-	•	•		-	-	-	
MgO	-	12.60	15.26	18.05	18.17	-	13.07	12.73	12.05	11.46		30.31	29.92	14.70	14.91	15.87	30.28	15.95	30.58	16.30	17.17	16.45	
MnO	-	0.26	-	0.55	0.62	-	0.27	•	•	-		-	•	-	•	•	-	•	-	-	-	•	
TiO2	-	0.28	5.30	•	•	•	0.42	0.42	2.64	2.83		-	-	•	•	-	-	-	-	•	0.39	0.40	
Cr2O3	•	•	•	-	-	-	-	•	-	-		0.22	-	8.86	8.58	0.25	-	0.25	-	0.27	0.66	0.67	
Na2O	5.24	-	-	-	•	5.03	0.47	0.51	1.75	1.70		-	-	-	-	-	-	-	-	•	1.89	1.94	
CaO	9.92	21.01	-	0.82	0.70	10.23	21.76	21.59	13.09	11.58		0.28	0.38	•	•	23.76	0.20	23.78	0.25	23.11	12.48	12.25	
K20	0.35	-	9.88	-	-	0.19	-	•	1.37	1.52		•	-	•	-	-	-	-	-	•	0.38	0.47	
NiO	-	-	•	-	•	-	-	-	-	•		-	-	0.69	0.39	-	-	-	-	•	-	•	
ZnO	100.00	-	-	-	-	-	-	-	-			-	-	-	0.34	-	-	-	-	-	-	-	
10(313	100.00	99.00	90.90	100.89	100.49	99.99	101.88	100.04	100.93	97.93		99.91	99.28	101.30	101.00	100.02	99.03	100.01	100.12	99.01	98.32	90.90	
	Reinbolt Hi	ills, 1216														Reinbolt H	ills, 121b						
	Crd	lim	Rt.adj	Kfs	Grt.R	Grt	Phi	Grt	Grt	Grt	Pl	Crd	Pl	Grt		Gri	Grt.Tr	Grt.Tr	Grt.Tr	Grt.Tr	Grt.Tr	llm	Grt.adj
Mg N°	77.9	6.4	•	-	33.7	34.9	76.9	36.8	38.4	-	•	76.1	-	35.4		31.0	30.5	30.5	30.4	29.9	29.3	-	32.1
SiO2	47.88	•	•	65.27	38.43	38.52	39.10	38.71	38.64	39.26	61.28	48.15	61.80	39.16		39.08	38.88	38.83	38.64	38.56	39.05	0.02	37.46
AI203	31.24	-	-	18.86	22.35	22.14	14.45	22.19	22.36	22.89	24.53	27.64	24.39	22.68		21.87	21.95	21.84	21.75	22.08	21.85	0.00	21.82
FeO	4.34	42.85	0.21	•	29.16	28.90	9.48	28.27	27.72	28.19	-	4.06	•	29.21		30.59	31.17	31.07	31.16	31.05	31.53	45.57	30.41
Fe203		-	-	-		-	-	-	<u>.</u>	•	•	-	-	-		0.23	0.15	0.24	0.40	0.00	0.40	0.00	-
MgO	8.56	1.65	-	-	8.31	8.68	17.74	9.23	9.71	9.73	•	7.28	-	8.97		7.76	7.67	7.65	7.63	7.45	7.34	1.12	8.07
MnO	-		-	•	0.95	0.94	-	0.80	0.80	0.77	•	-	-	0.91		0.98	0.93	0.88	1.05	1.04	1.06	0.27	0.98
1102	•	48 87	92.79	0.15	-	•	4.87	-	•	•	-	-	•	-		0.04	0.03	0.03	0.01	0.04	0.05	51.38	0.05
N.30			0.25		-	•	•	· .	•	-		•		•		0.03	0.05	0.02	0.04	0.03	0.04	0.14	0.03
0	-	-	-	1.13	0.70		•			-	8.02	-	7.94			0.01	0.00	0.02	0.00	0.01	0.03	0.02	0.00
K10	-			14 47	0.19	0.81	076	0.60	0.77	0.40	0.02	-	5.72	0.85		0.80	0.90	0.85	0.93	0.93	1.00	0.02	0.67
NiO	-			14.47	-	-	9.70	•	-	•	0.20	-	0.15	-		-	-	-	-	-	-	0.02	0.01
7.0	_	-	-	-	-	-	•	•	•	•	•	•	•	-		-	•	-	-	•	•	-	-
Totals	92.02	93.37	93.25	100.16	99.99	- 99.99	- 95.40	100.00	100.00	101.64	- 99.73	87.13	100.00	101.78		101.44	101.72	101.42	101.60	101.19	102.34	98.54	- 99.72
	Reinbolt Hi	ills, 121c														Reinbolt Hi	lls, 121e						
	GI	lim	Phi	Gd	Kfs	Grt.R	Grt.C	Spł	Spl.symp	Grt.C	Pl	Gđ	Crd	Gd		Grt	Grt	Spi					
Mg Nº	30.2	0.1	65.6	77.8	·	30.0	30.9	41.5	30.4	38.5	•	72.0	73.3	72.9		22.9	22.7	22.1					
5102	38.27	-	38.42	50.42	65.44	39.14	38.50	0.00	0.01	39.26	62.20	49.06	48.88	49.02		37.21	37.30	0.00					
AI203	22.24	0.27	14.53	33.93	19.34	22.53	22.02	56.67	55.72	22.89	24.91	32.65	32.62	32.07		21.15	21.08	54.96					
re0 E-202	30.57	41.42	13.79	5.27	-	31.24	30.34	20.78	24.74	27.80	-	6.83	6.50	6.51		32.82	32.70	25.75					
MaO	7 17	1.50			-			3.44	3.90	0.43	-	-	-	•		•	-	5.87					
MgO MgO	1.42	1.52	14./8	10.33	-	7.52	7.60	8.28	6.04	9.73	•	9.80	10.03	9.84		5.46	5.39	4.09					
500	0.71	0.50		-	-	0.68	0.69	0.10	0.10	0.77	•	-	-	-		1.22	1.22	0.14					
6201	-	0.04	3.38	-	-	•	-	0.00	0.03	-	•	-	0.01	0.01		0.00	0.67	0.01					
Nan	•	0.23	-	•		-	-	1.18	0.23	-	•	-	-	-		0.00	0.00	0.19					
C10	0.70	•	•	•	2.38	-	-	-	•		7.93	0.18	0.16	0.16		0.01	0.01	0.00					
K10	0.77	•		-	0.52	0.83	0.85	•	•	0.80	5.74	0.01	0.02	0.01		1.18	0.97	0.00					
NiO	-		9.04	•	12.55	•	•	•	-	•	0.18	0.05	0.05	0.06		0.02	0.04	0.00					
7n0	-	-	-	•	•	-	•	-		-	•	•	•	-		•	•	0.06					
Totals	100.00	98.95	96.91	00 05	100.01	101.04	100.00	1.20	0.22	101 69	-	-	-				· · ·	9.36					
			70.74	77.75	100.01	101.94	100.00	97.71	97.00	101.08	100.96	98.58	98.27	97.67		99.06	99.38	100.43					