DOLERITE INTRUSION
HOBART DISTRICT TASMANIA

by

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for the degree of
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This thesis contains no material which has been accepted for the award of any other degree or diploma in any University and, to the best of my knowledge and belief, contains no copy or paraphrase of material previously published or written by another person, except where due reference is made in the text of the thesis.

D. E. Leaman

D. E. LEAMAN,
University of Tasmania,
February, 1970.

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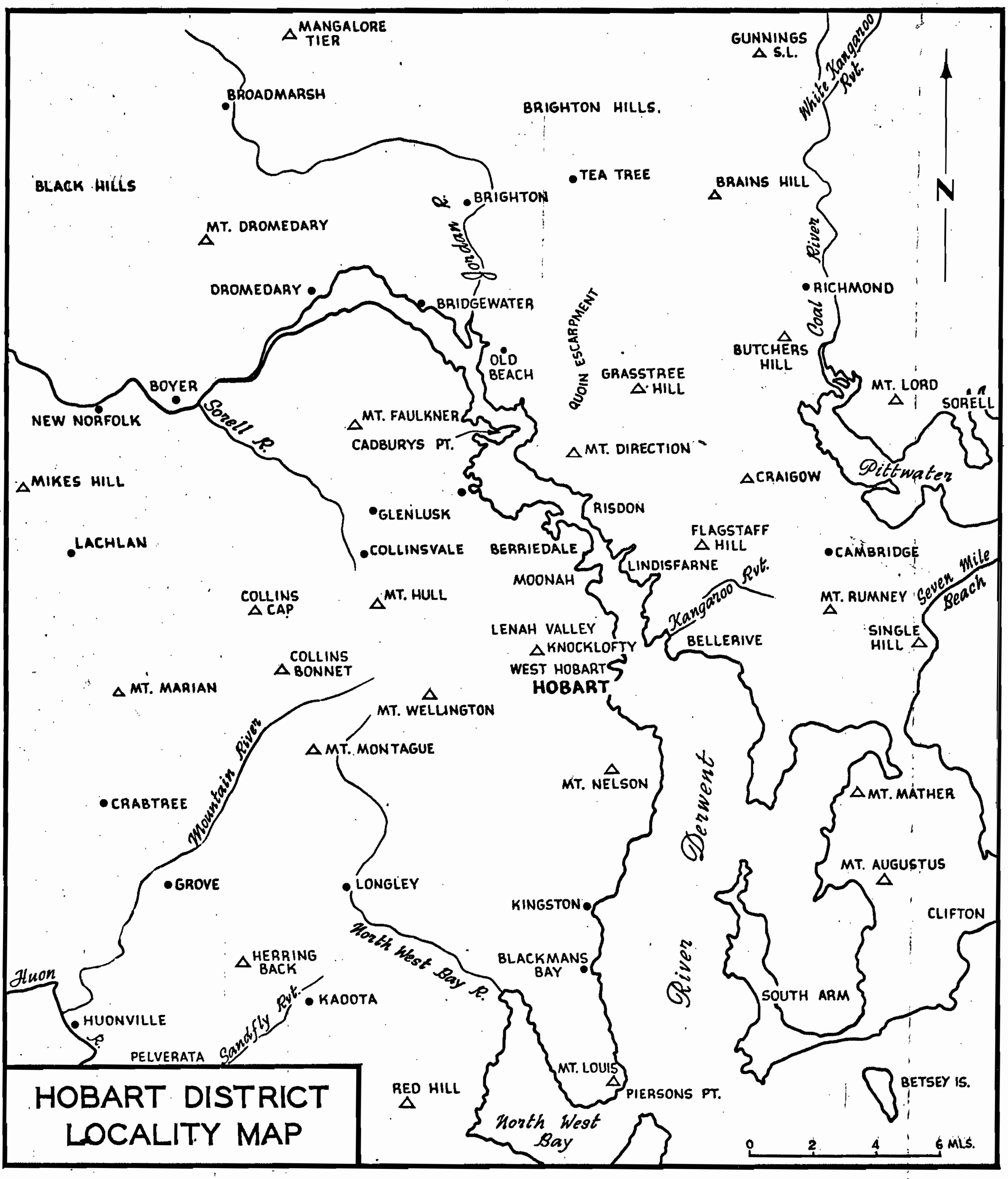
"..... the Eternal shall rejoice in his works. He looketh on the earth, and it trembleth: he toucheth the hills and they smoke."

Psalm 104: 31-32



HOBART DISTRICT LOCALITY MAP

ABSTRACT

Jurassic dolerite intrusions of the Hobart district, Tasmania, have been examined geologically and gravimetrically in order to determine their form. The dolerite intrudes flat-lying shallow marine Permian and continental Triassic rocks. A major problem was the resolution of more recent faulting superimposed upon Jurassic structures.

The intrusions are the result of a limited series of injections (four or five). Each individual intrusion has an irregular flattened trumpet shape. Synchronous intrusions have interconnected to produce a cross-wave pattern in which each hollow represents the site of one or more massive feeders. The feeders are basically dykes up to a mile across, although some are pipe-like extensions or wedges from dykes, and most are related to pre-existing faults.

Sheets have been initiated above feeder wedges at a point where effective intrusion pressure (about $7x10^5 gm/cm^2$) has exceeded the load pressure. Dislocation by fracturing was followed by hydrostatic intrusion. The actual form of the sheets, termed chonoliths, is determined at any place by any previous and concomitant fracturing. Fractures are controlled by rock heterogeneities, plastic confining beds, fluid content and distance from the feeder, or proximity of the free surface. Each sheet is about 1,000-1,500 feet thick.

Initial intrusions are normally placed low in the sedimentary column, while later intrusions generally found a higher level. Ultimately a lava plateau could be produced if the magma supply was adequate, although no evidence exists for this feature in Tasmania.

Extreme products of differentiation are to be found only in those parts of the intrusion adjacent to, or above, a feeder. There is no evidence of assimilation within the area.

1. INTRODUCTION

1.1 General

The Hobart district, an area of 1,000 square miles, is centred on Hobart in southeastern Tasmania. Although geologically typical of eastern Tasmania, it has the best outcrop and access. Dolerite outcrops over about half the area, and possibly underlies much of the remainder. Structural configurations typical of the Tasmanian dolerites are found, these being dykes, sills and sheets at various scales and attitudes.

The geology of the district is complicated by two superimposed systems of faulting. One Jurassic in age, and probably partly contemporaneous with the dolerite intrusion, and the other mainly Tertiary in age. Fault rejuvenation has made study of the intrusions difficult, due to uncertainties in age and structural relations. In addition, as also noted by Carey (1958a, p.131), the detailed complexities of the intrusions have fogged first order examinations. Previous workers have attempted to resolve this problem using only geological methods. Little of general value was derived. Failure was often due to the smallness of area chosen, and inability of geological methods to provide a unique solution. Gravity surveys have only recently been employed, although the possibilities have long been obvious. Three surveys have been directed at this problem in Tasmania; McDougall and

Stott (1961); Jones et al (1966); Leaman and Naqvi (1967). All dealt with small areas. They indicated that with a detailed survey of large scale the form of the intrusions, as a whole, could be resolved. A detailed geological study by the interpreter of the gravity survey was also shown to be essential. With application of both geological and geophysical methods a sense of uniqueness can be approached in interpretation. It is impossible without drill control to fully specify the parameters of intrusive bodies.

The basic approach has been to map and survey in detail a significant, accessible and varied area. The range of structures present, both intrusive and epeirogenic, and the great topographic relief were key factors in the choice of area. The district has one distinct disadvantage in that many structures related to, or concealed by, the Derwent estuary cannot be examined.

1.2 Geomorphology

Two features dominate the Hobart district, the Mt. Wellington-Mt. Marian plateau and the Derwent lowlands. Relief is generally moderate to high. Without exception, elevated country is dominated by dolerite bodies which give protection against erosion.

In detail, the topography is marked by fault-controlled features, such as escarpments and straight narrow valleys. The Derwent lowlands are fault-controlled and represent, with the Coal River valley and Pittwater, a graben some 20 miles (32km) across. Step faulting within the graben has produced linear blocks at various elevations. The Mt. Direction and South Arm blocks represent a central zone elevated with respect to the eastern escarpment and downthrown compared with the western escarpment. Topographic regimes are generally north-south. Few streams of any magnitude cut across this grain. The River Derwent is an exception, trending west-east from New Norfolk to Bridgewater across the main north-south range. The river follows fault trends in the lower and middle reaches of the valley and there is no obvious structural control for such a course change. Several streams show meander incision and quite possibly the course change of the River Derwent is an incised feature dating from Mesozoic times, as the Lower and Middle Derwent faulting is rejuvenated Jurassic faulting.

In the elevated plateau regions where frost action is common, and where periglacial conditions prevailed in Pleistocene times, there is much evidence of solifluction and congelifraction deposits. Substantial deposits of talus, probably related to this time, are in places overlain by more recent scree fields (Davies, 1958).

The coastal regions are marked by the presence of higher shoreline levels. These are particularly evident in the South Arm-Seven Mile Beach region, and occur between 2 and 6 feet (0.6-2 m) above the present sea level (Davies, 1959). There is also much evidence for variation of erosion and river base in the complex of depositional and erosional terraces in the valleys of the Coal and Derwent Rivers. The coastline is generally one of submergence with inter-island bar connection at South Arm.

1.3 Acknowledgments

I should like particularly to express my gratitude to Prof. S. W. Carey for his guidance, discussion and criticism throughout all stages of the work. My gratitude is also extended to Mr. M. R. Banks, Mr. J. E. Shirley, Dr. R. Varne, Dr. E. Williams, Dr. W. D. Parkinson and Mr. I. B. Jennings for their general interest and help. I am also grateful to the State of Tasmania (per the Department of Mines) for enabling me to undertake this project.

1.4 Previous literature

Although Hobart was first settled in 1803, it was not until 1864 that the first geological work was published (Harrison, 1864). He referred briefly to the dolerites of the city site and classed them as basalts, which flowed down old valleys from which the divides have now been removed. The first major work to appear (Johnson, 1888), following(?) Jukes (1847), regarded the dolerite as 'greenstones' of pre-Carboniferous age and as flows antedating the rocks now known as Permian-Triassic. He ignored the evidence of thermal metamorphism, but was the first to recognise the significance of faulting in the area.

Hills _et al_ (1922), possibly following the sketchy general ideas of Strzelecki (1845); Milligan (1849) and Selwyn (1855), considered the intrusion to be a massive sheet with plugs and dykes pushing into overlying sedimentary rocks. Nye (1922, 1924) also developed this idea. It was not until Edwards (1942) and Lewis (1946) that a reasonable description of petrology and distribution became available. Some of Edwards' conclusions concerning mechanism of differentiation are based on Lewis' erroneous interpretations of the structure, and should be considered with reserve (p. 76). Many of the errors in Lewis' published work, which is a monument to tireless and generally first rate observation, persist because of his death prior to publication. Most errors are restricted to his map. He noted the particular importance of Tertiary faulting and the Wellington uplift. Although generous in indicating faults on his map, he often omitted reference to Jurassic structures. He considered the dolerite to be intruded in the form of thick and subsequently faulted sheets. No attempt was made to relate the parts of the intrusion. He considered the intrusions to be the result of a hydrostatic and non-forcible process.

Subsequent workers have generally done detailed geological mapping of small sections of the area. No great interest was shown, nor was it possible with the areas involved, to adduce much of comprehensive value concerning the dolerite, e.g. Mather (1955), Rodger (1957), Woolley (1959), McDougall (1959b), Hastie (1961), Moore (1965, 1968) and Gatehouse (1968). However, Green (1961) mapped sufficient area to suggest sill repetition by Tertiary faulting across South Arm. McDougall (1962), and Sutherland (1964) also mapped areas dominated by large dolerite bodies, which led both to significant comments on intrusion mechanism and form. The validity of their conclusions is discussed later (p. 58, 75).

Literature on the Tasmanian dolerites has been predominantly of a petrological character. However, the Dolerite Symposium (1958) contained some papers dealing with possible mechanisms of intrusion and descriptions of the intrusion form in this and other provinces (Carey, 1958a, b; Walker, 1958). Carey (1958a) postulated that the dolerite was intruded as massive cone sheets emanating from many centres. This idea was followed by Spry (1958) and Sutherland (1964, 1966). Carey's postulate was based on use of contact-stratigraphic structure contours termed isostrats, which have since been criticised (Leaman and Naqvi, 1967). Work in this district shows that while the isostrat principle is not invalid it gives only a partial solution.

Other than the examination of the Red Hill intrusion by McDougall (1961, 1962) and McDougall and Stott (1961) no other detailed geological-geophysical work had been undertaken

Addendum resulting from examiner's reports:

Some unpublished gravity work was in existence prior to the survey. It is presented by Cameron (1967) and included the small Sorell survey of Shalley (1964) (Honours Thesis, Univ. Tasm.), and exercise surveys by geophysics students. Its quality is variable and coverage is sparse and irregular.

Sill: An intrusive body of igneous rock of approximately uniform thickness and relatively thin compared with its lateral extent, which has been emplaced parallel to the bedding of the intruded rocks. (Note use of adjective 'transgressive' where the angle between the plane of the intrusion and the bedding is small, and the noun 'transgression' which is a departure from concordancy or sub-concordancy.)

<u>Sheet</u>: A tabular mass of igneous rock, either a flow, sill or dyke. (In the context of this thesis it will be taken to be a generally sub-horizontal body on the broad scale.)

<u>Boss</u>: (<u>Plug</u>) A steep-sided protrusion from a major body (sill or sheet) into overlying intruded rocks (writer's defn.). The word plug is used interchangeably with boss throughout the text, although some would restrict the term to volcanic vents containing glass. Many such protrusions may well be true vents. Certainly they are plugs in that they stop a hole produced by uplift forces, and which was not stoped. In view of their possible vent character the term plug is not improper although, in the context of lack of proof, boss is the more technically accurate term. Local usage supports the term plug.

<u>Dyke</u>: A tabular body which cuts across the structure of the intruded rocks.

<u>Feeder</u>: The pipe or dyke-like body, in the crust, by which the magma was intruded (writer's definition).

It should be commented that the term "sheet" will also be taken to include combinations of sills, transgressions and dykes, where the whole system is substantially wide-angle and predominantly sub-concordant in broad scale.

2. GEOLOGY

2.1 Introduction

Detailed geological fieldwork, extending over a period of more than three years, is summarised in Map 1 (folder). As much of the area had been mapped previously most of the present work took the form of revision and checking. About one quarter of the map is original work. No previous workers have had the advantage of an accurate area-wide topographic basemap.

Previous mapping by McDougall (1959b, 1962), Green (1961) and Moore (1965) was found to be reliable. Insofar as the map of Banks et al (1965) includes such work, and some other unpublished Mines Department work, it is also accurate. Considerable revision was undertaken of work by Mather (1955), Gatehouse (1968) and especially Woolley (1959). Some simplification of mapping by Sutherland (1964) was found necessary as neither exposure nor map scale justified the detail shown by him.

In a study of this kind, knowledge of all aspects of the geology is essential in order to sort out the structures involved. A brief summary of basic geological information follows. More detailed particulars are given as required in Section 3.4.4.

2.2 Stratigraphy

PERMIAN:

The total thickness of exposed Permian rocks is some 2,000 feet(600m). The base of the system is not exposed within this district, although by analogy with the adjacent Woodbridge, Cygnet and Maydena regions there could be a further 500 feet(150m) of glacigene rocks. All formations are conformable.

i) Lower Permian:

The rocks designated Lower Permian consist of a monotonous mudstone-siltstone sequence, with occasional sandstone units, in excess of 400 feet(120m) thick. The only exposures are in the Collinsvale-Glenlusk-Berriedale region (see also Sutherland, 1964). The group may be equivalent to the Quamby Group of Northern Tasmania (see also Banks, 1962). It is possible that these rocks are in fact Carboniferous (Gulline, 1967; M. Clarke, Tas. Dept. Mines, pers. comm).

ii) Bundella Mudstone:

A formation of fossiliferous and somewhat pebbly mudstone, also containing calcareous mudstone and limestone units, about 250 feet(75m) thick. Complete sections through this formation are rare because dolerite commonly intrudes this horizon.

iii) Faulkner Group:

Rocks of this group are variable in thickness, facies and lithology. They consist of sandstone, mudstone and conglomerate. With the exception of the Cygnet Coal Measures, the only non-marine Permian rocks occur in this group. Thickness varies from 60 to 100 feet(18 to 30m)(see also Banks and Hale, 1957).

iv) Cascades Group: (Banks and Hale, 1957)

This group consists of very fossiliferous mudstone, siltstone and limestone. The Berriedale Limestone has its greatest thickness on Mt. Dromedary and thins to the southwest. The dominant unit over the southern half of the district is Grange Mudstone. The group has a thickness of 300-330 feet (90-100m). Due to the common occurrence of sills in this horizon few total thickness estimates are possible.

v) Malbina Formation: (Banks and Read, 1962)

The Malbina Formation is composed mainly of unfossiliferous siliceous siltstone, with a pebbly fossiliferous sandstone at the base and a very fossiliferous mudstone at the top. Variation in thickness does occur, 220 to 300 feet(65-90m), with the greatest thickness developed near New Norfolk. It thins markedly to the southwest.

vi) Ferntree Group:

The base of the group is marked by a pebbly feldspathic sandstone about 20 feet(6m) thick. The remainder consists of 550 feet(170m) of fissile and non-fissile generally unfossiliferous siltstone with occasional sand and grit beds.

vii) Cygnet Coal Measures:

This formation is that non-marine material, consisting of coal, carbonaceous mudstone and shale and(or) feldspathic sandstone containing carbonaceous fragments, which usually disconformably overlies the Ferntree Group. Thickness varies from 0 to 100 feet(0 to 30m).

TRIASSIC:

Triassic rocks may be divided into two associations; a sequence of quartz sandstone, mudstone and shale of Lower and Middle Triassic age overlain by a sequence of lithic feldspathic sandstone and mudstone of Upper Triassic-Rhaetic age (Hale, 1962; Townrow, 1962). All rocks are of freshwater origin.

The base of the Triassic rocks is marked by the appearance of pure siliceous rocks (compare Cygnet Coal Measures), a topographic bench and occasionally a quartz grit. The Lower Triassic rocks have a maximum thickness of 1,300-1,500 feet(400-450m), and show a change in composition and texture throughout the sequence. The basal rocks are nearly always dominated by a massive medium-coarse sandstone while the overlying rocks are more fine-grained, more feldspathic (approx. 10-15%) and micaceous. The proportion of lutite increases upward, from minor dark shale occurrences near the base to units of thick massive mudstone near the top. A succession of massive mudstone units, often with red beds, normally precedes occurrences of Upper Triassic rocks. There is some interdigitation of the two associations.

The lithic sequence has a higher proportion of fine-grained rocks than does the quartz sequence. Thin coal seams are also present. Its thickness is unknown but at least 500 feet(150m) was proven by drilling at Richmond.

TERTIARY:

Non-marine clay and sand has been deposited in fault-drainage-erosion troughs in the Coal and Derwent valleys. The maximum thickness known exceeds 670 feet (drilling at "Carrington", Richmond). The deposits conform to the shape of the wedge-shaped fault troughs, although the influence of erosion channels within these is very important. The basin north of Richmond contains much lignite.

QUATERNARY:

Alluvial deposits are associated with most streams, and are generally only 10-20 feet(3-6m) thick. Thick deposits of windblown sand are found at Seven Mile Beach and South Arm. Gravels occur at up to 50 feet(15m) above present river level in the Derwent valley west of Bridgewater. These deposits are probably related to greater river flows, or higher sea levels of Pleistocene times.

2.3 Igneous geology

JURASSIC:

Tholeiitic dolerite, dated at about 167×10^6 years (McDougall, 1961), outcrops over about half the district. Two major petrological studies have been made of bodies within this area; those of Edwards in 1942 (Mt. Wellington, Mt. Nelson, Gunnings Sugar Loaf) and McDougall in 1962 (Red Hill). Both studies were directed at differentiation sequences. No significant attempts have been made to relate type, or stage of differentiation to the form of the intrusion. The above-mentioned authors, Joplin (1957, 1964) and Spry (1962) have stated that the magma was very uniform in composition and intruded close to the liquidus temperature. This conclusion is based on chilled margin studies which may be open to some doubt (see p. 107). These authors have concluded that the intrusion took place in one major pulse but the general work done is hardly sufficient to be definitive. There is little petrological evidence available to suggest that the intrusion occurred in more than one pulse. Detailed work has not yet been undertaken on adjacent intrusions to examine such variations as may often be readily observed to be present. A minor second pulse, at least, is definitely represented by small dykes, e.g., Mt. Nelson (Edwards, 1942), Hickmans Hill (McDougall, 1962) and Single Hill (Plate 2-extreme example).

TERTIARY:

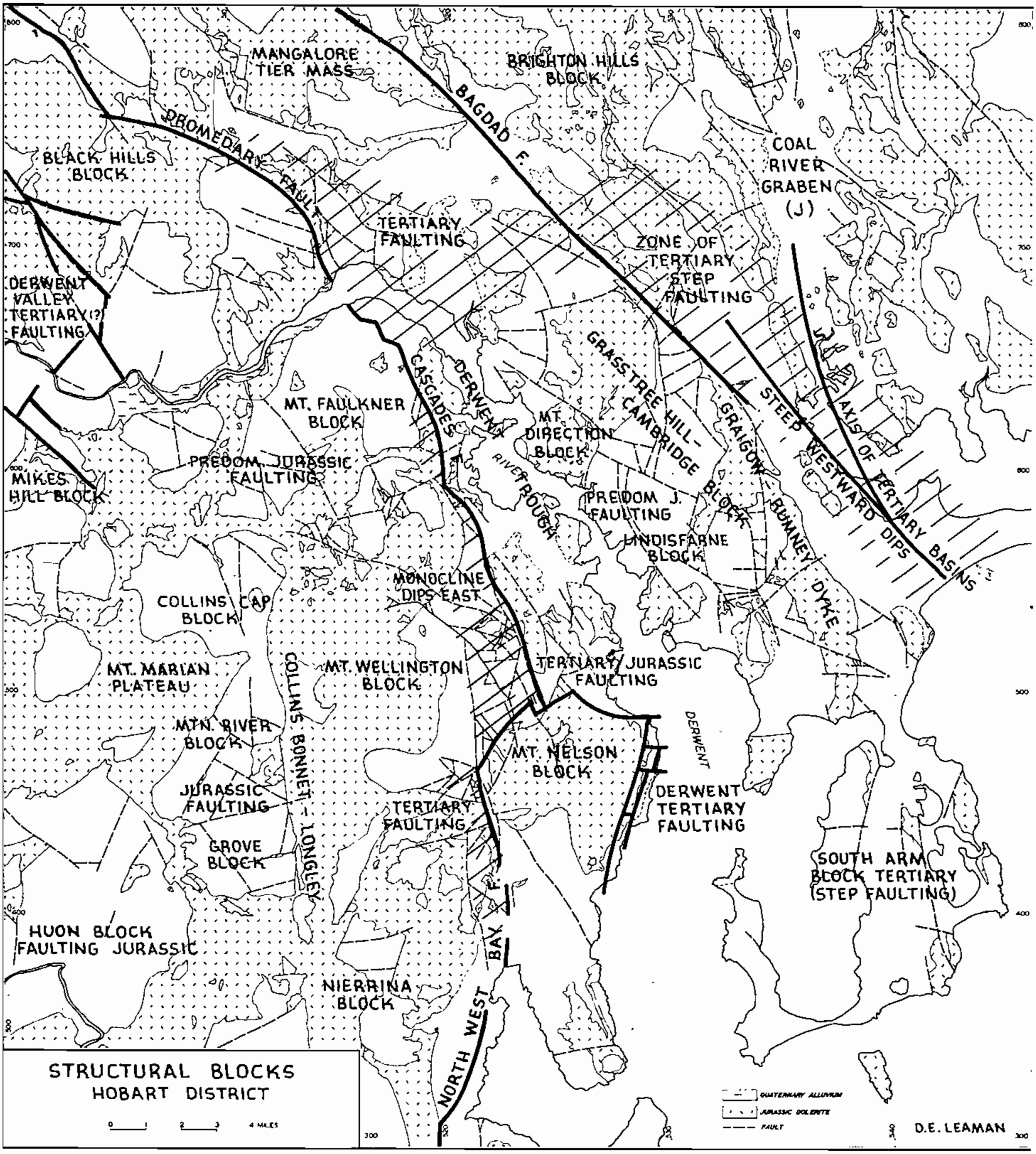
Tholeiitic and alkali basalts occur in the valleys of the Coal, Jordan and Derwent rivers. The thickest flows are in the Jordan valley near Brighton, where the thickness exceeds 150 feet(45m). Petrological studies have been undertaken of the Brighton basalts (McDougall, 1959a).

2.4 Structural geology

The location and general relationships of major structural features are shown in fig. 2, p. 16.

i) Attitude of sedimentary rocks:

With the exception of a narrow belt immediately east of the Mt. Wellington-Mt. Faulkner block, all rocks dip west.



MANGALORE TIER MASS
BRIGHTON HILLS BLOCK
BAGDAD F.
DROMEDARY FAULT
BLACK HILLS BLOCK
COAL RIVER GRABEN (J)
TERTIARY FAULTING
ZONE OF TERTIARY STEP FAULTING
DERWENT VALLEY TERTIARY(?) FAULTING
GRASSTREE HILL-CAMBRIDGE BLOCK
GRAIGOW-BUMNEY DYKE
STEEP WESTWARD DIPS
AXIS OF TERTIARY BASINS
CASCADES F.
DERWENT RIVER TROUGH
MT. FAULKNER BLOCK
MT. DIRECTION BLOCK
PREDOM. JURASSIC FAULTING
MIKES HILL BLOCK
PREDOM J. FAULTING
LINDISFARNE BLOCK
MONOCLINE DIPS EAST
COLLINS CAP BLOCK
MT. MARIAN PLATEAU
COLLINS BONNET - LONGLEY
MT. WELLINGTON BLOCK
TERTIARY/JURASSIC FAULTING
MTN. RIVER BLOCK
MT. NELSON BLOCK
DERWENT
JURASSIC FAULTING
TERTIARY FAULTING
DERWENT TERTIARY FAULTING
GROVE BLOCK
SOUTH ARM BLOCK TERTIARY (STEP FAULTING)
HUON BLOCK FAULTING JURASSIC
NORTH WEST BAY F.
NIERRINA BLOCK
STRUCTURAL BLOCKS
HOBART DISTRICT
0 1 2 3 4 MILES
QUATERNARY ALLUVIUM
JURASSIC DOLERITE
FAULT
D.E. LEAMAN

Fig. 2

Dips are normally of the order of 5-10°, although 15-25° is typical in the Coal River valley and estuary in association with Tertiary step faulting. Dips are east at about 10° in the crushed warp-monocline flanking Mt. Wellington and extending southward to Kingston.

ii) Faulting:

Normal faulting of Jurassic and Tertiary age has greatly contributed to the complexity of the district. Jurassic faulting includes all faulting directly associated with, or immediately preceding, the dolerite intrusions. Such faults are indicated by many sharp intrusive boundaries, or by faults containing dykes and plugs in the slip surface. The younger faults are indicated by disruption of such intrusions. The age of the later movements may be impossible to date however, if there is more than one pulse of intrusion, as each pulse may activate or re-activate faults. There is commonly insufficient evidence to show that a fault disrupts one intrusion and not another. Jurassic faulting has produced north-south-trending horst and graben structures. The Coal and Derwent Rivers occupy such grabens for part of their lower courses. The central trough widths are often less than 0.5 miles(c 1 km), as at Richmond and Grass Tree Hill, and the structures have an overall wavelength of 40 miles(60km). The release of magma was probably indirectly caused by the stresses producing these structures. It is not known why the stress was developed in mid-Jurassic times, but forces related to the break-up of Gondwana would account for it, e.g., King (1953), see also page 107.

Superimposed on the Jurassic structures is Tertiary step faulting, which consistently downthrows to the east, with a trend slightly west of north. A Tertiary age is ascribed to the later faulting on circumstantial evidence based on its relationships to basalts and sediments of known Tertiary age. Although there have been rejuvenations throughout the Cainozoic, the major post-dolerite movements appear to have been Eocene(?) (Solomon, 1962). Such faulting is pronounced only in the Coal River region, and adjacent to the Mt. Nelson and Mt. Wellington blocks. In many cases Tertiary movements have been deflected about major Jurassic structures, e.g., Mt. Nelson, Mikes Hill. A shallow rotational origin is indicated by the fault-dip relationship in the Coal River region.

iii) Igneous emplacement:

The matter of dolerite emplacement forms the bulk of the content of this thesis and will therefore be discussed fully later. However, it may be noted that the most massive dolerite bodies occur in the Grass Tree Hill-Cambridge and Black Hills-Collins Bonnet-Longley regions. Sills and sheets of dolerite are often prominent but are no more common than large dykes in exposure.

One particular aspect of value in structure reduction of dolerite intrusions is that of dilation. While both horizontal and vertical dilation may be present, the vertical aspect is that usually noted, for example, where a dolerite sill terminates at a fault, and the intruded side is uplifted by the thickness of the sill. This simple estimate of intrusion thickness may be affected slightly by dip or transgressive angle reduction effects. Dilation is fully discussed in Section 4.6, p. 86, fig. 5.

Small dykes of dolerite have been seen intrusive into major bodies in several places, e.g., Mt. Nelson and Hickmans Hill. These are 3-20 feet(1-6m) across and always chilled.

Basalt centres are usually small dykes 6-50 feet(2-15m) wide associated with Tertiary faults or fault junctions and large Jurassic structures, e.g., Craigow-Mt. Rumney dyke intrusions.

3. GRAVITY FIELD

3.1 Introduction

The use of gravity surveys for assessing emplacement of basic intrusions is well known. Its effectiveness depends upon any non-gravimetric restrictions on interpretation available and the density contrast with the intruded rocks.

Addendum resulting from examiner's reports:

The work presented by Cameron (1967), comprising various small surveys, was limited in scope, reliability and accuracy, and in order to obtain uniformity of results the entire area was resurveyed.

(Hinch, 1965; Longman and Leaman, 1967). Only the survey of Longman and Leaman (1967) covered sufficient area to permit broad scale deduction. The limitations of earlier work in other areas precluded collection of useful general information.

3.2 Survey details and accuracy

Approximately 2,000 stations have been installed with a station spacing of about 0.5 miles(0.8km). The base station for the survey, at Hobart Airport (reference 6491.0161), was originally installed by the Bureau of Mineral Resources, Canberra, as part of an Australian network. It has a datum value of 980448.91 mgal and a terrain-corrected Bouguer anomaly of 15.45 mgal. The station distribution is shown in

Map 2 (in folder).

The meter used throughout the survey was Worden 273 with scale constant of 0.1008 mgal/division. Drift characteristics of the meter were excellent, approx. ± 0.02(max) mgal/hour.

Traverses on loop segments were made on a 2-3 hour base interval. Although most loops contain more than 20 stations, loop errors were normally less than 0.05 mgals, and in many cases were nil. As a result many adjustments were made simply to tie stations in the loops. Where groups of adjacent loops had significant errors a least squares adjustment was made (Gibson, 1941). No specific corrections have been made for tides and such as may be necessary are incorporated within the drift correction. The precision of individual gravity measurements is considered better than ± 0.02 mgal.

Stations have been sited, where possible, on State Permanent Marks, or Lands Department survey spot heights. The former are rare outside the Hobart Metropolitan Area, whilst the latter are scattered across the district in various topographic positions. Most elevations have been determined barometrically, using a Mechanisms micro-barometer, with respect to various survey points as ties. Many stations have been tied to high water level in the estuary, with a foot(0.3m) subtracted to approximate mean sea level, as used for survey standard in Tasmania (M.S.L. Hobart).

As a result of the use of different sources for elevations, there is some variation in standards of accuracy. Most stations are accurate to only 3-5 feet(1-1.5m). This results in an inaccuracy of some 0.30 mgal in the observed Bouguer gravity.

All stations have been terrain-corrected using the method of Hammer (1939) to a radius of 12 miles(19km). At this radius the effects of the earth's curvature become significant and the attraction in outer zones becomes constant for large blocks of stations. As a result no further calculation is worthwhile and any errors present are constant over the whole survey, as the dimensions of the area covered become small compared with distances to significant features such as the continental shelf. The accuracy of the correction made is estimated at 5% or less, resulting in an error of 0.05-0.10 mgal at most stations. This accuracy is consistent with the precision claimed by Hammer.

Availability of accurate survey maps has enabled station locations to be stated to within 100-250 feet(30-75m). This results in a maximum error of 0.05 mgal in the latitude correction.

The RMS accuracy of the observations is about 0.33 mgal, and values have been contoured with interval of 1 mgal (Map 3, folder).

3.3 Bouguer anomalies

3.3.1 SPECIFICATION AND PRESENTATION

The results of the survey have been expressed in terms of the extended Bouguer anomaly, since this is the most direct and useful form of preliminary treatment, leading to an interpretation of near surface crustal structures.

A density value of 2.67 gm/cc has been used throughout the reduction. Although no pre-Permian rocks are exposed in the Hobart district, and it is therefore not possible to state the density of such rocks, shallow crustal seismic surveys indicate a value of 2.65-2.67 gm/cc (Johnson, University of Tasmania Ph.D. thesis in preparation). In addition, examination of those rocks considered most likely to occur have a density range of about 2.60-2.70 gm/cc. The upper and lower figures represent Cambrian rocks and Devonian granites respectively. Ordovician, Silurian and Precambrian rocks generally have average values close to 2.67 gm/cc. The choice of a value of 2.67 gm/cc presumes that all anomalies would be related to density variations in the readily examinable post-Carboniferous rocks including the dolerite. The possibility of a heterogeneous basement is further discussed on page 31.

Contoured total Bouguer anomalies are presented in Map 3 (folder), with a contour interval of 1 mgal. All data and observations from which this map was drawn are available at the University of Tasmania, Geology Department.

3.3.2 REGIONAL SEPARATION

The total Bouguer anomalies (Map 3) show that the gravity field decreases significantly to the northwest as a result of the Central Tasmanian plateau. The Hobart district is placed midway between the root of continental Tasmania and the continental shelf. It is thus situated close to the zone of steepest gradients.

The character of the regional gradient in Tasmania, and it should be noted here that regional is taken to mean that component of the field derived from the core, mantle and lower crust, has been examined (Johnson, Ph.D. thesis in prep). On the limited information available the gradient was shown to be about -1 mgal/mile (0.6 mgal/km) to the north-west. The information provided by this previous work could have been considered adequate for the specification of the regional gradient. However,it was decided, in view of the increased data, to adopt an averaging procedure over this survey area and compare results. The initial averaging was based on squares with sides of 2 miles(3km). Each square included, with few exceptions, 8-16 stations. The averages obtained were then recalculated with squares of 16 and 25

<u>Addendum resulting from examiner's reports</u>:

The filter has a section in the wave number domain of sinc (kx), where k represents the wave number as applied in two horizontal directions and x is the width of the window used in the averaging process. A uniform distribution of points is desirable for the most effective filtering. The major problem is the selection of the length scale factor (x) in view of the range and continuity of wave numbers.

of the area. It was however, distorted in the eastern portion due to the presence of a large positive anomaly with area approximating 100 square miles ($256km^2$). The area of this zone of steepest gradients.

The character of the regional gradient in Tasmania, and it should be noted here that regional is taken to mean that component of the field derived from the core, mantle and lower crust, has been examined (Johnson, Ph.D. thesis in prep). On the limited information available the gradient was shown to be about -1 mgal/mile (0.6 mgal/km) to the north-west. The information provided by this previous work could have been considered adequate for the specification of the regional gradient. However,it was decided, in view of the increased data, to adopt an averaging procedure over this survey area and compare results. The initial averaging was based on squares with sides of 2 miles(3km). Each square included, with few exceptions, 8-16 stations. The averages obtained were then recalculated with squares of 16 and 25 times the area. The separation is mathematically analogous to filtering in electrical circuitry - in this case a sinc(x) function (St. John, 1967). For such a filter to be effective a uniform distribution of points is required, and an appropriate frequency chosen. The latter factor is diff-icult to prescribe due to great variation in anomaly wavelengths.

Bulk filtering was found to produce a fairly consistent gradient across the northern, western and southeastern parts of the area. It was however, distorted in the eastern portion due to the presence of a large positive anomaly with area approximating 100 square miles (256km^2). The area of this anomaly is greater than the bulk area assumption used in the filter, and hence the breakdown. Bulk averaging on the scale required by this anomaly is impossible on an area as small as this district. The general gradient was shown to agree closely with that obtained by Johnson (op. cit.), although the contours are offset to the north as his data did not include terrain corrections. The final gradient, as shown in Map 3, was produced by eye-smoothing of contours, based on the averages obtained by the method described above and with the trend and absolute values indicated in the western half of the area carried through the positive anomaly which dominates part of the eastern half.

Edge effects were minimised, during averaging, by considering such information as is available outside the area (north, east, south only) and suitably weighted elsewhere. It should be noted that such data is in no way comparable in station density with the present survey and it is likely that some edge effects persist.

3.3.3 DESCRIPTION OF RESIDUAL ANOMALIES

Map 4 (folder) presents the residual Bouguer anomaly field as obtained from Map 3 by removal of the gradient indicated. This map shows that most anomalies are nearly equidimensional, and have a range of +10 to -12 mgals.

One anomaly approaches the requirements of two-dimensionality, i.e., has a length more than 20 times its width (Grant and West, 1965). It is that associated with the Tertiary basin faulting and the eastern margin of the

TABLE 1: BULK WET DENSITIES

		range, gm/cc	av. gm/cc
TERTIARY:	clay, sandy clay (0-500 feet from surface)	1.82 - 2.00	1.92
	volcanics(solid basalt)	2.90 - 3.00	
JURASSIC:	dolerite	2.75 - 2.95	
	(average for sill, Jaeger, 1964)		2.90
TRIASSIC:	upper lithic sequence		
	sandstone	2.36 - 2.48	2.43 *2.47
	mudstone	2.49 - 2.52	2.51
	lower quartz sequence		
	sandstone	2.30+- 2.43	2.37 *2.45
	mudstone	2.44 - 2.54	2.49
PERMIAN:	Ferntree Group	2.37+ - 2.58	2.50-2.52
	Malbina Formation	2.46 - 2.54	
	Cascades Group,		
	weathered	2.10 - 2.14	
	unweathered	2.49 - 2.54	2.53
	metamorphosed	2.64 - 2.68	
	Faulkner Group, sandstone	2.37	
	Bundella Mudstone,		
	mudstone	2.55 - 2.61	2.59
	limestone	2.63	
	Lower Permian		
	mudstone, siltstone	2.58 - 2.60	
	tillite matrix	2.59	
	tillite bulk	2.66	
	Average - total Permian		2.57
PRE-PERMIAN:	See discussion Section 3.3.1		2.67

+weathered; *average based on rock weighting of sequence.

Craigow-Rumney intrusion.

Significant positive anomalies are associated with the Mangalore Tier and Craigow-Lindisfarne blocks (+10 mgal), and lesser anomalies are related to the Huonville, Boyer, Lachlan, Dromedary and Mt. Nelson blocks (+5 to +8 mgal). Large tracts of the district have anomalies between -2 and +2 mgal. Moderate negative anomalies are associated with the Lenah Valley-Berriedale, and Coal River graben faulting (-5 to -8 mgal). Lagge negative anomalies show a correlation with deep outlet(?) channels for Tertiary basins. Tertiary basins generally show a maximum negative anomaly of around -4 mgal.

3.4 Interpretation

3.4.1 ROCK DENSITIES

The results of density determinations upon rock formations occurring throughout the district are presented in table 1. Each average is based on 10-20 samples. Determinations have been made on fresh samples, unless otherwise indicated, of 1-2 kgm which had been water saturated. Results are to British Density Standard Specifications. Most samples were taken from recent drill cores.

3.4.2 METHODS OF INTERPRETATION

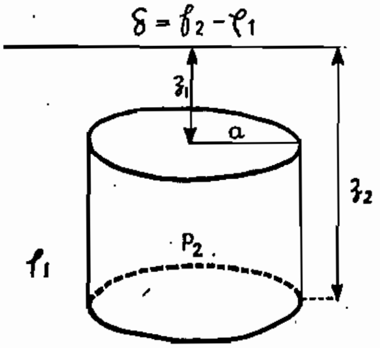
Only indirect, comparative interpretation methods have been employed, as direct methods entail more complexity of calculation, precision and detail of specification of anomalies than is possible with this survey.

As most anomalies are nearly equidimensional, three-dimensional interpretation methods should be employed if a reasonably precise interpretation is required. There are, however, considerable problems associated with such methods. For example, calculations are invariably lengthy and even with the facilities available for rapid computing (Elliott 503 automatic computer) corrective iterations are difficult to prescribe and time consuming to make. These difficulties notwithstanding it has been found fruitful to make such interpretation in parts of the area. In this way a greater understanding of aspects of the intrusion complex is gained although the general structural outline can be deduced from a qualitative study of the anomalies.

The attraction of slices of a vertical cylinder may be used to estimate values in many of the blocks. In addition calculations on the attraction of cylinders can give an indication of the scale of simple feeder systems. The attraction of a cylinder is shown in fig. 3, p. 29.

Minimum limits on the mass requirements of various anomalies can also be set by considering the anomaly produced by a two-dimensional structure composed of horizontal slabs. As dolerite is, for all practical purposes, the only positively attracting material present compared with the basic density assumption used in the Bouguer reductions, an anomaly of nil or greater implies dolerite in the column. The actual amount estimated is governed by the magnitude of the anomaly and the amount of negatively attracting materials

Cylinder



Parasnis (1961)

$$\Delta g = 2\pi G\delta\left[z_2 - z_1 + \sqrt{z_1^2+a^2} - \sqrt{z_2^2+a^2}\right]$$

(point on axis)

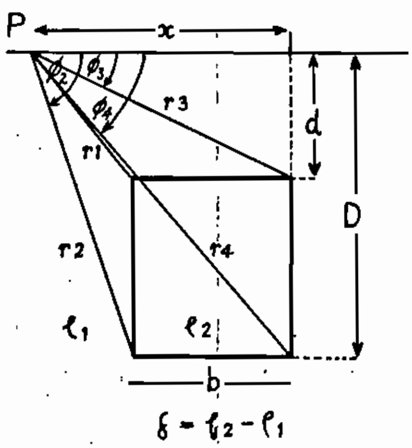
If $z_2 \to \infty$, $\Delta g = 2\pi G\delta\left[\sqrt{z_1^2+a^2} - z_1\right]$

If $\left.\begin{matrix} z_1 \to 0 \\ z_2 \to \infty \end{matrix}\right\} \Delta g = 2\pi G\delta a$

$$\Delta g = \frac{a}{4x}\left(2\pi G\delta\left[z_2 - z_1 + \sqrt{z_1^2+a^2} - \sqrt{z_2^2+a^2}\right]\right)$$

(point off axis, estimation valid if $x \geq a$)

2-D Rectangular Prism



$$\Delta g_p = 2G\delta\left[x \ln\frac{r_1 r_4}{r_2 r_3} + b \ln\frac{r_2}{r_1} + D(\phi_2 - \phi_4) - d(\phi_1 - \phi_3)\right]$$

Parasnis (1962)

GRAVITATIONAL ATTRACTION OF REGULAR BODIES

Fig. 3

present. Small negative anomalies are possible where the sedimentary sequence is thick, even though several hundred metres of dolerite may be present. An example of this qualitative usage may be shown where basal Triassic rocks are exposed, and there is a positive anomaly of 1 mgal. This implies about 450 metres of dolerite present, i.e.,

750 metres Permian rocks at -0.10 gm/cc	= -3.14 mgal
450 metres dolerite at +0.23 gm/cc	= $\underline{+4.26}$ mgal
	+1.12 mgal

This kind of usage is more accurate than is immediately obvious, provided the surface dimensions of the slab anomaly is much greater than the depth to anomaly base (basement). The relative reliability of this method is derived from the addition of positive and negative terms at variable depths in thin slices. This reduces the total mass two-dimensional end effects that would otherwise be incurred.

Such an approach may be regarded as preliminary to use of more detailed methods. It provides much information about the structure, quickly revealing those blocks where much, little or no dolerite is present. It can give no indication of the magnitude of vertical bodies or feeders, and always understates the positively attracting material of a residual anomaly, and conversely, where anomalies are equidimensional. The degree of understatement has been found to be small.

The equation used for all such qualitative (and also complete where applicable) two-dimensional interpretation is stated in fig. 3.

All interpretation has been made from the ground surface and is thus a two-part process since the base level is sea level.

3.4.3 LIMITATIONS INHERENT IN INTERPRETATION

As indicated above, many conclusions of direct value are possible, although interpretations of the gravity field are basically ambiguous. Care must be taken however, not to overinterpret the field in this district on account of the following considerations.

<u>Basement problems</u>

It is possible that the basement rocks are not uniform in density, and also that their bulk average is not 2.67 gm/cc. The effect of the former property would be to produce, i) anomaly patches of low amplitude and long wavelength, which would not be readily discernible in an area where anomalies correlate closely with obvious near-surface structures, or ii) anomaly trends. The latter would cause total variations in the regional anomaly, making all parts of the residual gravity in error, although by a constant amount. The presence of feeder systems in the pre-Permian rocks may also add broad scale positive effects to residual anomalies. The mass requirements of most feeder systems can be estimated (Sect. 3.4.4), but the actual distribution of mass in detail is another matter. Deep carry-over effects may be present in many anomalies but are virtually impossible to recognize or estimate. Thus any interpretation made of the residual anomalies, neglecting the possibility of such side effects, is open to a margin of doubt.

A thickness of 750 metres of Permian rocks has been assumed in all calculations, but only 600 metres are proven in this district (p. 11). Variations in thickness of tillitic rocks, if present, could produce variations of up to 0.3-0.5 mgal by varying the bulk Permian average which includes this material.

Regional assumptions

It is assumed that the regional gradient indicated in Map 3 is valid across the area. Since interpretation is undertaken upon the residual anomalies, any deficiencies in this gradient would invalidate any interpretation in detail. The maximum variation considered likely is less than 1 mgal, but lacking a grid of deep bore holes by which to anchor fully some part of the interpretation, and the residual anomalies, its possible existence should be noted.

Density assumptions

The validity of the density values stated in Table 1 is assumed. The variations noted may be significant. Dolerite densities change with form, size and position of(or in) the body. In all interpretation the density of dolerite has been taken at 2.90 gm/cc, which in many cases would cause understatement of the anomalous body. Ferntree Group values are proportional to pyrite or siderite content. The averages stated for the Triassic sequences are variable, depending on the actual proportions of rock members. The average value of the Permian rocks, as a group, increases with depth and thus a partial sequence is denser than a total sequence.

<u>Interpretation difficulties</u>

Realism of structure and anomaly distribution may not be approached, particularly in regard to the difficulties inherent in specification and treatment of vertical bodies and feeder systems, where geologic control is minimal.

As a consequence of the above factors unambiguous interpretation is impossible, and indeed the magnitude of features included may be inexact. The station spacing used for the survey is adequate for a first order investigation such as this, although many small areas require a detailed coverage beyond the scope of this study.

Irrespective of the above deficiencies, this survey permits indications and size estimates of masses producing particular anomalies. The information it provides on the distribution of dolerite, and the order of its thickness, is sufficient to remove most of the uncertainties and ambiguities that have dogged purely geological studies. Feeders may be unambiguously located by magnitude of anomaly, although their exact form is not necessarily deducible.

3.4.4 INTERPRETATION OF STRUCTURE

Structure reduction has been basically geological, with application of gravimetric tests to check scale and sign of anomalies. Simple comparison of Maps 1 and 4 precludes many of the structural possibilities. The nature of the tests used have been outlined on pages 28-30. Some direct profile-model comparisons have been made and these are indicated where appropriate.

Each section appearing in fig. 4 (folder) is discussed briefly below. In order to avoid repetition, as many structures appear across several sections, the sections are outlined from north to south and only at the first appearance is a particular structural feature discussed in detail. Further comments may be given in subsequent sections, but these are subsidiary and specialized to the particular section. For ease of reference, letter or number symbols have been used to refer to blocks of each section. The key aspects of each profile only, are outlined as a comparative review of the residual Bouguer anomalies (Map 4) and the geology (Map 1) make more detailed comments unnecessary. *

Section 800:

This section is typical of those areas where dolerite

* The reader is advised that the following 40 pages (to page 74) contain factual details and concise discussion difficult to assimilate. A first reading of the thesis might well skim this section in order that a clearer view of the concepts outlined be obtained.

Lower Triassic sandstone outcrops in block A1. The anomaly here is about 0 mgal and hence 400-450 m of dolerite is present. This figure often recurs in anomaly estimates and dilation studies and has thus been used throughout the interpretation. There is no real proof that such a thickness could not be composed of two smaller bodies, but for simplicity a single body has been indicated. Also, in many cases significant exposures of sheet bodies show thicknesses approaching this figure (e.g. Mt. Dromedary). The presence of small plugs and dykes in A1 imply that the sheet is not at any great depth. The hills to the north and south of this section show the base of a further higher body and this is indicated in the section.

B1 shows a decreasing anomaly to the east. Its absolute magnitude indicates the presence of a sheet, and the dilated block supports this conclusion. No exact figure can be given to this dilation. The eastern boundary of B1 is a fault-igneous margin feature. It is likely that the dolerite in block C is related to the body falling transgressively east in B1, since it is a sheet base, and the anomaly shows conclusively that there is no deeper intrusion. A centre is implied, and the presence of a series of anomaly swells to the south along this line, supports this implication. A source (S1) has been indicated. The magnitude of the anomaly, and its shape, suggests that in this section it is the northern end of a narrow dyke wedge.

The major anomaly in the section falls in D. The margins of +5 mgal imply a very thick intrusion (approx. 800 m if concordant) and the peak value of +10 mgal suggests a very substantial dyke or pipe extending well into the crust. A pipe 1,500 metres in diameter extending through the crust with effective contrast for 11-12 km will not produce this anomaly! This centre (S2) appears to have a basic "Y" shape but further details are unobtainable. The great thickness of dolerite, indicated in the section, is based on the above estimates. It is likely that there are several closely associated bodies present (p. 39).

Fault f3, known as the Bagdad Fault, passes about the eastern margin of the Mangalore Tier mass. The steep gradient and negative anomaly to the east, suggests that the feeder system and associated sheets(?) dip westward and that little dolerite is present to the east. One sheet, at least, is suggested in E by the presence of bosses and the moderate residual anomaly. The value of the anomaly and the thickness of sedimentary rocks known to be present show that this sheet is about 400 m thick. Since the increasing negative anomaly reflects less dolerite and more sedimentary rocks this sheet must also transgress steeply eastward. A fault at the point of transgression is also suggested, both gravimetrically and dilationally, as lack of such a feature would imply too little Triassic in F, and the sheet would then expose Permian rocks, which it does not.

Block F is typified generally by an irregularly roofed series of intrusions. Immediately south of this section is a substantial positive anomaly and the structure shown is regarded as a sheet arm rising away from that feature (S5 - Sect. 775).

Blocks G1, G2 are essentially devoid of dolerite except for the surface exposures of sill bases. The sharp, narrow, elongate positive anomaly, on the western side of Gunnings Sugarloaf, shows that the dyke boundary is in fact the edge of a feeder and not part of a transgressing sheet since no dolerite can be present at depth in G1.

G3 is a little understood graben block which contains 100-200 m(?) of Upper Triassic rocks. For the most part it is probably devoid of dolerite bodies. The very narrowness of

G3 makes definitive interpretation difficult, even though it is an easily calculable two-dimensional feature. The bounding faults were in existence prior to the intrusion. Field evidence suggests that they have been moved subsequently. The scale of later movement on the western fault is inferred to be small on the basis of comparative elevations of a fragment of sheet base east of Gunnings Sugarloaf which is thought to be part of the same body. The eastern boundary fault has many plug and dyke intrusions along its length. All are reflected by a series of positive anomalies. The amount of subsequent movement on this fault is unknown.

H1 may contain one or two major sheets, or alternatively the anomaly could be affected by the feeder system (S25) to the south. This cannot be directly resolved in this section, but a lower sheet is inferred in Sections 725, 750, 775. This sheet may account for the transgression apparent near 800N, 5395E. Alternatively, the transgression could represent the base of the sheet from S25 passing northward. Another possibility is that the two bodies link at the line of White Kangaroo Rivulet; the lower sheet in rising to the north between Sections 775, 800 has been cut off by a sheet from S25. The occurrence of dolerite north of the section (lower sheet continued) supports this possibility, and also accounts for the tendency of the anomaly pattern to trend along the line of the rivulet. Extensive, abnormal thermal metamorphism is apparent in H1.

The anomalies drop sharply in H2, I and show that the dolerite of the hills and escarpment in I is only a capping, and that no intrusions of consequence occur at depth.

Section 775:

Many comments made in regard to Section 800 apply here. Block A1 shows the high level capping of the Black Hills range. The anomaly over this part of Black Hills shows that a further major sheet, probably in Lower Triassic rocks, is present. This is also demonstrated by the outcrop about Black Hills. The sheet present in A2 is part of the inclined western arm of S1. The eastern side of this body has intruded along a fault which is indicated by drag phenomena. The western side has been faulted subsequently, and there is a similar possibility on the eastern side. A dilational block, B1, is also apparent. The anomaly due to S1 in this section is about +4 mgal, and suggests quite a substantial feeder. Rocks within B1 and east of the fault above the feeder S1 are intensely metamorphosed. C must be generally devoid of dolerite in depth, since the anomaly is so strongly negative. The dolerite at the surface can be shown to be a sheet base which dips steeply west to S1. A dyke in C may in depth be part of the Mangalore Tier feeder system (S2), as it certainly appears to be connected to it north of the section. It cannot be related to other dolerites since C is deficient in dolerite.

The section cuts obliquely across the northern tip of the uplifted block of Permian rocks at Mangalore. These are completely surrounded by dolerite, probably one sheet 400-500 m thick, with the displacement about the southern and western portions of block D essentially dilational, being roughly equal to the excess mass of dolerite calculated as present. However, on the slope of Mangalore Tier there is a suggestion of an overlying body which is reflected by topography and included blocks (see p. 83). Interpretation is impossible here due to the unknown depth effects of S2. One arm of the feeder system extends southeast along the Bagdad Fault. Many intrusions are present in this zone, and two ("c" and "d") are indicated in the section. The sheet "d" is transgressive through both sedimentary rocks and sheet "c" and the relationships are clearly visible in the western part of the uplifted Mangalore block. The great variety of boundary phenomena led to this conclusion, and only detailed petrological work could separate them and thus either prove or disprove this hypothesis.

Block E, as exposed in this section, is the western part of F in Section 800 and is composed of Permian and Lower Triassic rocks with minor occurrences of the Upper Triassic lithic sequence. The gravity anomaly is about -1 to -3 mgal in this section, but is wedged between two large positive anomalies. The separation and gradients do suggest that this is close to the true attraction, and that a moderate-sized sheet is probably present and rising northward. The small plugs present suggest dolerite below. The presence of steep dips near the line of upward transgression of this body to the east is another significant feature. The roof boundary is very irregular, e.g., at 7600N, 5240E, but is partly concordant. It is believed to be a remnant of a different intrusion which has been sliced through. (See also comments, Sections 700, 725). S5 must be a substantial pipe. The anomaly of +4 mgal is localized in an area where the exposed Triassic rocks are estimated to be more than 300 m thick. The presence of roof pendants and disruptions in F, with the general gentle anomaly reduction, shows a transgressing eastern limb. More than one intrusion may be present here, judging on the number and distribution of sedimentary fragments.

Blocks G1, G2, and G3 are essentially as in Section 800, with one notable exception. G1 contains a large basalt centre and the anomalies are considerably distorted about it. While not a great volume of basalt remains, either as a flow or pipe (which is relatively small), there is considerable thermal metamorphism. The problem of G3 was described in the previous section.

H is shown to contain the northern part of feeder S25 and a sheet transgressing from the west. The size of the positive anomaly (+3 to +4 mgal) implies a minimum mass requirement equivalent to two large sheets. The shape and termination of the anomaly does not support such a conclusion. There is also extensive thermal metamorphism in this region. The anomalies west of S25 suggest only one intrusion is possible, although possibly more than 200 metres of Triassic rocks are present. All igneous boundaries in this locality are irregular, commonly discordant and very suggestive of disrupted roof effects.

Block I is as described for Section 800.

Section 750:

The western half of this section is structurally similar to 775, 800, while the eastern half is characteristic of the step-faulted Derwent and Coal River grabens. A1 is basically similar to Section 775 and the transgression of the Black Hills capping sheet from the west is clearly seen. The presence of a deeper body is indicated by the dykes and plugs emanating just south of the western end of the section and by the general gravity anomaly.

On the eastern side of the Black Hills massif is a block (B) of Lower Triassic sandstone completely surrounded by dolerite. It lies over the southern end of S1 at a point where dolerite rising from the south joins material from S1 (Section 725) and is intruded again by part of the higher cap dolerites. The actual distribution of the various intrusions is indicated in fig. 8, p. 94. The gravity pattern is not a great help at this point, but the conclusion based on study of all outcrop phenomena as shown in the section is compatible with the anomalies. The dolerite from S6 (Sect. 725) transgresses steeply northwest in the large dyke at 7450N, 5085E and meets that from S1. It then passes over the enclosed block. The structure of S1 also appears a little different here, a vertical western margin being indicated. The dilational effect of the S1 intrusion has elevated this block, since without dilation Upper Triassic rocks would be expected to outcrop.

C1, C2 and C3 are blocks showing a sheet base only and the anomaly of -4 mgal shows that deeper dolerites are unlikely. The section across D appears a little odd due to obliquity. The dolerite is rising consistently southward although showing crenulation. A concealed fault of some magnitude is shown to pass beneath the western arm of the Mangalore structure and a feature not unlike a cauldron subsidence is produced. North of the section a wedge of Ferntree Group has been caught between the dolerite and a pre- intrusion fault.

Block E shows the presence of three sheets. The upper sheet is clearly exposed as a fragment at 7550N, 5230E, and across the hills to the south, where it can be shown to be relatively thin (200-250m). A sheet from the west rises steeply through the upper body to form the steep (dip slope?) slopes of the Brighton Hills. The general level of the gravity anomalies, and the presence of dykes suggest a deeper dolerite about 400-500 metres thick. Correlation with other sections suggests that it is probably equivalent to the dolerite from feeder S5, although some cross-faulting is suspected to account for absolute differences in altitude. There is evidence for subsidiary feeders at Brains Hill (S7) and S8, both south of the section. The faulting east of f3 is consistently down to the east and throws are generally small.

G3, comprising the central Coal River graben, is virtually impossible to interpret. The cover of Tertiary basalt and sediment of unknown thickness provides the source of doubt. South of this section this material is known to be in excess of 670 feet(200m) thick. Precise estimates of structure or dolerite content are impossible especially as a whole Triassic sequence, of unknown quantity, is probably present as well. A possible solution satisfying the gravity

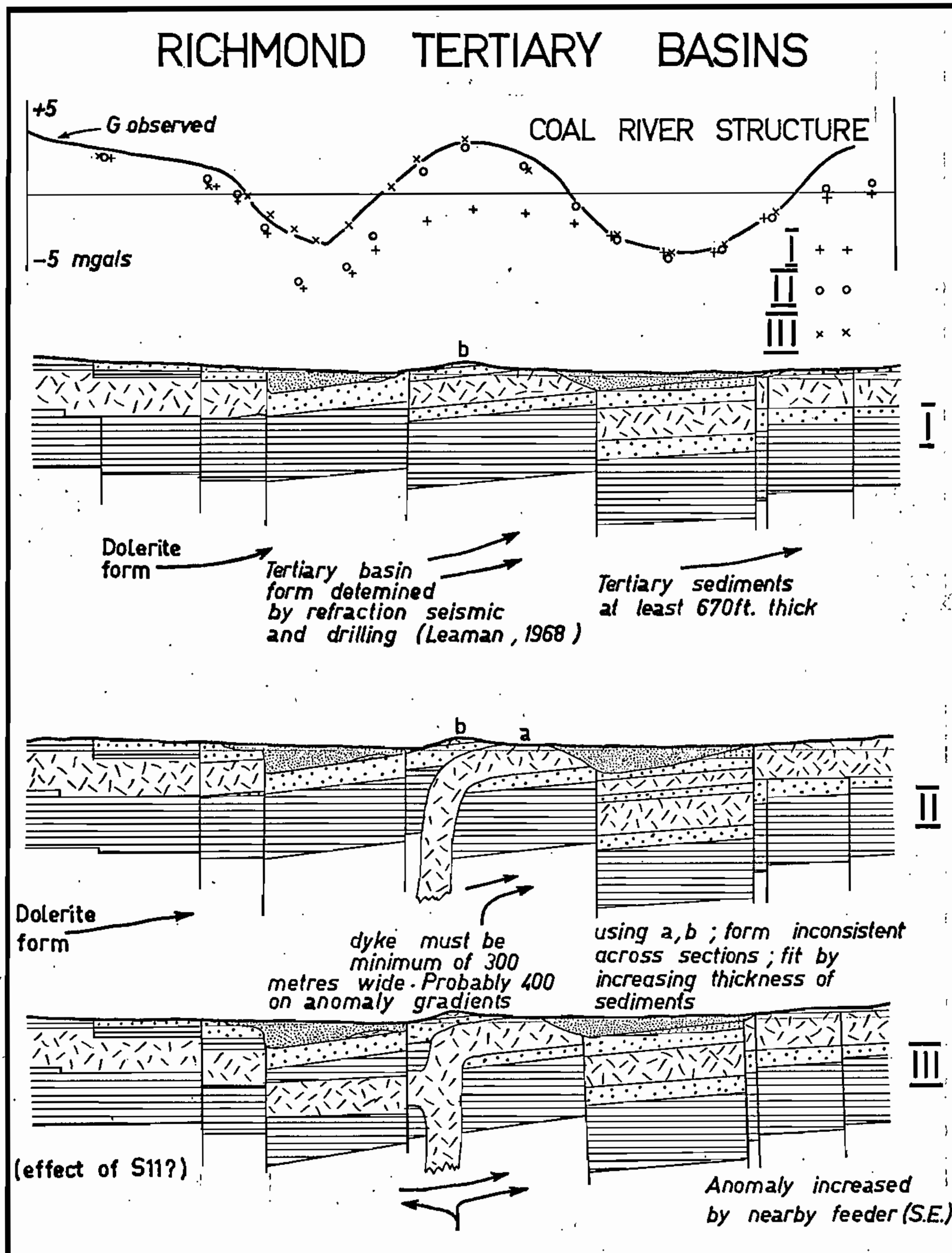

RICHMOND TERTIARY BASINS
+5
G observed
COAL RIVER STRUCTURE
-5 mgals
I
II
III
b
Dolerite form
Tertiary basin form detemined by refraction seismic and drilling (Leaman, 1968)
Tertiary sediments at least 670ft. thick
b
a
Dolerite form
dyke must be minimum of 300 metres wide. Probably 400 on anomaly gradients
using a, b ; form inconsistent across sections ; fit by increasing thickness of sediments
(effect of S11?)
Anomaly increased by nearby feeder (S.E.)

Fig. 5

requirements is indicated in fig. 5, p. 43.

Block H is as described in Sections 775, 800, except that this section passes over the anomaly peak related to S25. The gradients to east and south indicate a marked transgression of the related sheet, and its base is clearly seen in the small escarpment along the valley to the immediate south.

The structure in I is quite confused and the two intrusive bodies seen in H interfere. Thus there are a large number of included blocks and contacts of all types. In addition, the gravity anomalies show that the interference occurs wholly in Triassic rocks near the surface and that there is no deeper intrusion.

Section 725:

In A1 the upper capping dolerite is thicker and this is reflected in higher anomaly values. Fault f1, which is one of a pair of faults concealed beneath the dolerite of Black Hills, clearly shows pre-intrusion movement. Both faults appear to have suffered minor subsequent movement. A2 is marked by a substantial north-south anomaly (S6) suggesting that it has been produced by a dyke at depth. The anomaly trend carries northward toward Mangalore Tier (S2), and the two features may be inter-connected. The reduction in anomaly northward may reflect a depth effect since the Dromedary Fault(f2) is crossed between them. Around the entire eastern flank of Mt. Dromedary dolerite appears at about the Bundella Mudstone horizon. Thus the feeder and sheet must form a 'T' junction. This sheet passes to f1 at about the same level. Its thickness is estimated at 400-500 metres since the entire column, including the thickness of the capping dolerite, is well known.

The composition of B is difficult to assess due to the shadowing effect of the nearby S6 anomaly. A thin sill outcrops, and it is considered unlikely that there is a deeper dolerite. There is evidence that f2 is in part Jurassic in age, and that the sheet from S6 was terminated upon it. There has been 500-600 metres of subsequent movement. C is probably devoid of dolerite; the value of -3 mgals is not as low as might be anticipated but then there are many additive effects about C. Certainly no thick intrusion can be present.

D and E are simple step-faulted blocks with one complete sheet in Lower Triassic rocks and the base of a further sheet some 100-200 metres higher (compare E, F, Section 750). Southeast of Brighton, at fault f2A, there is a rise in the anomaly of about 2 mgals which cannot be accounted for in any other way than a further deeper intrusion. This conclusion is reinforced by the occurrence of stratigraphically higher rocks to the south, which would increase the negative component of the anomaly, and a cross fault approximating the axis of the basalt-filled Jordan valley is implied. Examination of Sections 625-700 also shows the consistency of this, and that f2A represents the source limit to the west of any such lower body. Such a source is indicated in the axis of the Derwent trough (Sections 600, 625 esp).

In F a dyke shows the contact relations and dilation of the previously mentioned upper dolerite. This reflects a a transgression of a sheet rising from the west. Two concealed sheets are present to the west and only one to the east (note grade in anomaly). The simplest coherent explanation is indicated in the section.

Block G shows the asymmetrical lower sheet and source S7. The symmetry of this intrusion increases northward (Sect. 750). The eastern limb is exposed as the lower sheet on the east side of Brains Hill. The western limb is inferred to be in the Permian rocks, as seismic work and drilling has shown the Triassic rocks to be devoid of dolerite. The presence of a dolerite body here is not obvious from a study of the anomalies south of the section, but these are complicated by the presence of Tertiary sediments. The sheet limb is proven in fig. 5, p. 43.

The structure of the Coal River Graben is uncertain and the comments on Section 750 apply here also. Block H in this section shows part of a very irregularly roofed intrusion. The anomalies show that these intrusions are roof effects and that a thick sheet is present below. The anomalies here reflect a single sheet only, being between the effects of S25, S26 (Sect. 700). In I, a sheet rising southward from S25 is considered to cut the previously mentioned sheet. This conclusion is based on depth and thickness requirements.

<u>Section 700</u>:

Blocks A1, A2 show that the dolerite sheet derived from S6 (Sect. 725) is rising westward. The arch, at about 5020E, is based on intrusion levels and suggests a merger with another body rising from the west(?). Fault f1 is associated with the major upstep, and some rejuvenation is also indicated resulting in a present-day escarpment. There is a possibility of a small Jurassic fault under the Dromedary plateau. Comments on B, f2 are as for Section 725.

Centred south of C in the section is a further centre (S9). The transgressing sheet arms are indicated in BB1, BB2. Their character, at least on the eastern side, is seen north of Bridgewater, which is less than a mile from the centre of the intrusion. The sheet in BB1 is inferred from the gravity. C is as in Section 725, but due to the irregular nature of pre-intrusion(?) faulting the symmetry of S9 is disrupted. Such faults have also been reactivated. The intrusion "c" in D, E and F in the Lower Triassic rocks of Sections 700 and 725 arises from this source.

The requirement of a further deeper sheet east of f2A and its subsequent transgression was discussed in Section 725. The slope of the transgressive step in F must be steep, since there is a marked gravity gradient at this point. The Brains Hill structure has been partially outlined in Section 725(also Sect. 675). The structure in G, H and I is similar to previous sections, except that in the far east of I a further centre is inferred. The anomaly in this region is too high for simple sheet structures, and only one such body is suggested anyway. The irregular pattern of the intrusion, the dilation associated with cross faults at 7050N, 5400E and eastwards, and the very substantial positive anomaly in an area where the sedimentary sequence is thick, supports this contention.

Section 675:

A sheet outcrops in Cascades Group rocks in A1 and A2. The minor variations in residual anomalies north of New Norfolk are due to variations in the amounts of Triassic rocks present in the various fault blocks. This section passes directly through the plug intrusion(S6') on the southern slope of Mt. Dromedary. At this point an offshoot from the sheet rises vertically and terminates with this plug in a pipe type of structure.

C1 and C2 are essentially lacking in dolerite as indicated by moderate negative anomalies. The north-south anomaly trend (S9) passing through C1 appears to be related to a plug on Mt. Faulkner, and probably represents the continuation in depth of a feeding dyke between the two major features.

C3, D, E, F and G are as for Section 700 except that blocks D to F are upfaulted by 500-600 metres. The northern part of the Quoin escarpment represents most of the movement. Fault f2A corresponds with an anomaly gradient and probable source S8 continued. Two interpretations are possible for C3. Alternative to that indicated in the section, and inconsistent with the terminal requirements of this sheet (e.g., Sections 600, 625, 725), the sheet could transgress to the west. The area is basalt covered and the gravity cannot distinguish between these possibilities. In E the inflection of the upper sheet represents the scoop base of a sheet radiating north and west from S10 (Section 650).

The structure in F to G is crucial to several sections. The need of the sheet in Permian rocks is clearly shown in fig. 5, p. 43. Drilling and seismic work shows that it is not in Triassic rocks. S7 is also fixed in form.

Blocks H and I are as in Sections 700, 725 with a feeder S27 suggested on the east margin of the Coal River structure. Some plug-like intrusions are present at the surface. The single sheet emphasized in previous sections is demonstrable by the large areas of 0 mgal anomalies in the Triassic rocks. The sheet tongues of S26 are discordant and rise through the hills in this region giving an irregular outcrop pattern.

Section 650:

The anomalies in A1 and A2 indicate a sheet of about 450 metres thickness which is known to occur in Cascades Group rocks. Faulting in these blocks is the southern extension of the Middle Derwent trough. There is evidence for an included block east of f1 in A3 where the dolerite is much thinner. The enclosing faults subsequently occupied by dolerite and plug S6' are difficult to represent in section. On the southwest side of A3 (see map) is a small wedge of Triassic rocks. It is left due to dilation effect, being overlooked by intrusion even though surrounded by concomitant fracturing. The dolerite passes under and round A3 if only as a thinner, more irregular body.

The Faulkner block (B) is essentially devoid of dolerite. A thin body (<200m) may occur. The assumptions of Section 3.4.3 are to be noted, as this is doubtful and possibly within the interpretive errors. Small dolerite bodies have been located on the north face of Mt. Faulkner suggesting that a small sill is not unreasonable. The plug northeast of Mt. Faulkner and its associated anomaly is distinctive and it probably dips southeast. The apparent plug at 6400N, 5130E is deduced to be a basal step in a sheet rising south from S6 as no anomaly is associated with it.

In Sections 600-675 the Cascades Fault(f2) has a throw of about 600 metres. Block C is lacking in dolerite (anomaly -4 to -5 mgal) except for the irregular sheet base exposed. This block is more faulted than the map or section shows, but the positions of the faults are difficult to specify. There are zones of steeper dips as well, and these structures combined probably account for the obviously "irregular" base of the sheet.

S8, D and E are as for Section 675, although the end of feeder dyke S10 is clearly developed (+7 mgal). The lower sheet is dilationally lifted to the east and is now not generally exposed although apparent chilled margins and fine-jointing is present over much of this area. The ribbon wedge of sediments between the sheets is noted round Mt. Direction on all sides.

Block F is characterized by a very large anomaly (+9 mgal) which has a sharp eastern margin. The broad swell of anomaly west of f3 can be accounted for by S10, which could imply a consistent forked-sheet structure. The dolerite which outcrops in F has an intrusive, but subsequently faulted eastern margin (f3), and a moderately dipping western boundary. The termination of this body shows that the roof is present and that it is hinged southward. The anomaly is not compatible with a single sheet arm (as clearly seen in Sects. 575-625 where two anomalies separate). The sheet arm present conceals what must be a large dyke-plug which dips steeply(?) westward, as implied by gravity gradients and total anomaly values west of f3. A single body is most unlikely in any event. The particular problem of excess mass exists throughout the Rumney ridge to the south and a dyke of this trend is seen at Cambridge. The mass requirements there are less and the dyke seen is related to a sheet offset from the main plug system.

The sheet in blocks G1, G2 and G3 and its southward extension is clearly necessary as shown in fig. 5, p. 43. In this region the thickness of Tertiary rocks, and the nature and composition of basin base is well known from drilling and seismic studies.

East of the Brains Hill feature (S7) is a narrow channel about 500 feet(150m) deep filled with Tertiary sediment. The gravity shows only a slight dip here, due to the presence of two sizeable positive anomalies nearby, but drilling has proven the structure and the channel is eroded along the line of the western graben fault.

H and I are as described in previous sections, with the addition of a high level sheet on Mt. Lord. S27 is shown to be unrelated to that sheet, although the plug and outcrop indications of Section 675 could suggest relation. S27 is considered to be associated with the disrupted general sheet at shallow depth in this region.

Section 625:

The anomaly at A0, which is related to the uplifted fault block of Lower Permian rocks (dilation 300-400m), is clearly due to a feeder. Any sheet producing such an amount of dilation could not provide more than about +2 to +3 mgals. The structure is difficult to indicate in section. The dolerite appears to rise southward onto Mikes Hill, and be terminated by, or be a very thin dyke in, f1 which extends northwest into the Derwent valley (Alwar, 1960). This fault was probably pre-intrusion. The Lachlan intrusion is also bounded by it although this is by no means clear in the section. In A1 there is an unusual effect of a sheet from the south arching over. The effect is merely a contraction of that structure in A1-A2, Section 600. Dolerite from S13, S14 (Sect. 600, 575) join near 6200N, 5040E as a closed structure, and in a definite arch (see A2, Sect. 600). The sheet from S13 persists for some miles to A3, and then transgresses steeply eastward upon the same trend as dolerite rising from S6. The eastern part of A3 is devoid of any major intrusions as indicated by the -4 mgal anomaly.

The Faulkner block(B) with capping sheet was described on page 49. C1, C2 and C3 are monoclinal drag blocks west of the Cascades Fault (f2). They are lacking in dolerite and persist to Mt. Nelson in the south. There are some plug intrusions present which produce the small closed irregularities in the anomaly pattern.

S8 is clearly seen as the Cadbury's Point dyke. It is the definite termination, or source of the lower Direction sheet, which is observed to plunge westward on outcrop occurrences. The dyke in this locality is probably aligned along a major fault in this part of the valley. The fault is possibly of Jurassic age and the east side of the graben structure which dominates the valley. The present line of the river appears to occupy the trend of such an implied fault and the anomalies are consistent with such a structure.

D, E, F1, F2, G1, G2 and G3 are as for Section 650. A separation of anomaly sources is clearly seen in F1-2. The peak of the anomaly lies close to f3, whereas the known dipping body is well away and completely exposed. The need for more mass near f3 is apparent and the sheets, as drawn leading to S10, cannot produce the +5 mgals which is the base value in the whole Lindisfarne block. Much of the broad swell of internal anomaly (2 mgals?) must be contributed by the feeder system S10 which has a north-south axis. The axis of the centres comprising S10 is the narrow graben extending from Grass Tree Hill to Bellerive and offset at Risdon. Fault f2A forms the eastern boundary of this graben.

H1 is as described in previous sections. However, H2 and I show a sheet rising from the south and which upsteps onto Mt. Lord enclosing the Permian block at its southern end. The amount of dilation indicated is more than 200 metres. That it is an intrusion separate from S27, is implied by the fact that material from S27 is not faulted to juxtaposition, since one body could not produce the sheet in both H1, H2 and I.

Section 600:

In A1 the dolerite capping Mikes Hill rises from the northwest whereas the Lachlan body is rising northward. On the north and east sides of Mikes Hill it appears as though the upper body has cut through the lower. This is the only structure compatible with dilation and anomaly distribution. The dilation could be explained with a vertical body comprising the bulk of the hill but this would not account for the low and high level dolerites, nor their dips and concordances. A2 shows coalescence of two dolerites and in this zone of arching and consequently thinner dolerite exposure there is a decrease in anomaly. A3 shows the uplifted, inner zone above a sheet from S13(+5 mgal). The dilation, and hence sheet thickness, is about 450 metres. A4 is lacking in intrusions (-4 mgal).

B1 and B2 contain a sheet, low in Permian rocks, which is transgressing northward from the Collinsvale structure. In B1 there is an apparent excess in dolerite thickness, but this is due to the angle of the section and the twisted northward transgression. The thickness of the Collinsvale body is a minimum of 300 metres, as shown by the dilation across the dyke limb on the east side of Mt. Faulkner (6100N, 5170E). However, as there is known to be 150-200 metres of dolerite present in the Faulkner block, this thickness is increased to about 500 metres. The general anomaly values are consistent with this figure. There is a smaller abrupt positive anomaly high on Mt. Faulkner which may represent a feeder to the Collinsvale body or the upper Faulkner sheet (S28a).

Apart from small plugs, C is lacking in intrusions. Any anomaly of -7 mgal can only be produced by the complete thickness of the Permian and Lower Triassic rocks being present. No sheet is possible. There is the suggestion that f2 is in part concomitant or pre-intrusion and that the Collinsvale body terminated upon it or rose up it.

D, E, F, S10 and S11 are described in Sections 625-650. Transgression of the sheet from S8 is clearly seen on the face of Mt. Direction and the dilational effects of the sheets above S10 are most marked. The continuous dyke from Grass Tree Hill to Risdon represents the margin of the sheets from S10. The extra mass of the Craigow body (S11: +10 mgal) is also noted. The anomaly is far too great over the whole area to have been produced by inclined sheets alone as that would require an impossible 1,000 metre sheet. A feeder must be postulated to explain the anomaly. Fault f3 causes some offset of the anomalies to the west and shows that the eastern dyke boundary dips west.

FF is sandwiched between S11 and S12. S12 is a localized anomaly, the magnitude of which upon a small dolerite body in a thick sedimentary sequence, implies a feeder structure. The anomaly spread from the two features blankets FF and the anomaly of 0 mgal suggests no dolerite between the two bodies. This is supported by the sharpness of the S11 anomaly implying a mass deficient zone.

East of S12 lies Pittwater with a faulted Triassic sandstone platform covered by Tertiary sediments. The precise structure is indeterminate. A study of the anomalies about the water-covered areas suggests that the Lower Triassic rocks which outcrop in the area, or more likely the Permian rocks below, are intruded by a single large sheet as at Single Hill (Section 525).

Section 575:

S14, a centre for the Lachlan body, is indicated by a +6 mgal northwest-trending anomaly in A1. The sheet of more than 400 metres thickness trasngresses east and west. A2 shows windows of dilationally lower rocks as sheets from S13 and S14 pass over them. B1 and B2 show the thick Collinsvale sheet. There is a further complication in B2, where the higher level sill caps the Mt. Hull ridge and is clearly observed at its eastern end. C1 and C2 are as in previous sections.

Block D covers the main Derwent lowlands which lack dolerite sheets of any significance at depth. There are some small plugs and sills near the Cascades Fault margin and material intruded along it may have squeezed into this block. The course of the old Derwent River and the sediment fill and lava capping is indicated west of the present course. Drilling has shown that basalts are intercalated with the sediments. The thickness of the deposits probably exceeds 100 metres.

S10 and associated structures are detailed on pages 60, 97. The graben block inferred to lack dolerite further north may contain dolerite here. F1 needs comment. The inclined sheet from S10 crops out as a dyke arm which is terminated on f2A. At about the same point the anomaly is increased. In addition a dolerite sheet of considerable thickness must persist under F1-2. The S10 sheet is observed to rise and flatten into the Lower Triassic rocks and cap Craigow. The lower intrusion rises steeply east via the Cambridge dyke. The point anomaly at 5600N, 5310E and much of the anomaly increase in F1-2 is probably due to an extension of S11 and that the second sheet derived from it closes round and reconnects via the dyke limb in the east. There is also a pronounced step in the intrusion at depth indicated by the anomaly upstep at the east-west faults which bound the southern edge of F1-2. Two sheets are conclusively necessary, as a study of the dilation requirements will reveal. A vertical dyke and horizontal limb cannot produce this pattern, nor account for the upper Craigow concordancy.

Comments on FF apply as in Section 600. The structure of G is adequately discussed in Section 525 where exposure permits its full evaluation. In this section all structure is obscured by Tertiary sediments. Further east toward Pittwater the anomalies do indicate a lower sheet (compare Sect. 600) and which, by analogy with Single Hill (Sect. 525) upsteps about the line of splay faulting from f3, is considered to pass through the region of S12.

Section 550:

In A1 and A2 dolerite rises transgressively from S14. The fault between A1 and A2 has been indicated as post-intrusion. This may not be so, and in view of the size of the anomaly over the Lachlan block, the sheet may be thicker than indicated with a change in thickness at this point. The structure at 5450N, 5024E shows some post-intrusion movement whereas that at 5330N, 5025E does not. The ages may be purely relative. The roof form of the Lachlan intrusion to the south is quite complex and irregular although showing an overall transgression southward. The larger anomaly over this intrusion (compare Boyer structure, S13) may be explained in three ways. The feeder could be larger and more trumpet-shaped; the sheet could be thicker although dilation estimates do not support this; or a further dolerite intrusion could be present deeper in the section. The first is the most likely.

The feeder S14, a transgressive limb and small fault (f1), probably pre-intrusion, meet in this section. A structure of the form suggested is necessary to preserve the approximate dilationary balance between intrusions from east and west. Blocks A3 and A4 which contain thick successions must also contain a large sheet to balance anomaly requirements. Study of the windows to the north shows that it rises steeply around A3. Feeder S15 is indicated by the marked increase in anomaly, which occurs over the small dolerite tongue exposed at 5600N, 5095E. Metamorphism is more intense than usual here. These blocks also contain a higher level dolerite south of the section, at Collins Cap.

Block B shows the structure proposed for the Collinsvale intrusion. It is not dissimilar to that of Sutherland (1964) which was based partly on petrological evidence. The anomalies suggest a sheet 500-550 metres thick. The Mt. Hull rise is exceptional and stands as a dyke projecting from the sheet roof. A small source is inferred beneath this zone on the small increase in anomaly (S16). Dolerite transgresses westward and rises to meet material from S15. This relationship and the necessity of two separate bodies meeting is seen from comparison of the requirements of adjacent sections (esp. 500 and 525), and also from structure dips. The occurrence of Lower Triassic rocks at 5450N, 5130E is a result of the transgression of the sheet being steeper than the topography at this point. (Compare B1, Sect. 575). There is also the possibility of a small fault, the only demonstrable outcrop of which is at 5100N, 5140E. To the east the Collinsvale sheet rises steeply and the blocks C are devoid of any major dolerite. Similarly D contains only a sheet base (also Sections 575, 600), and f2 here has a throw of 800(?) metres. The anomaly pattern in D shows that the sheet base is repeated by faulting, although some arching and cross transgression is indicated from both east and west.

The structure beneath the river cannot be outlined, but it is likely that it is comparable to the structure of the Coal River valley at Richmond. Available drilling information supports this conclusion. The circular anomaly (+7 mgal) at Lindisfarne on f2AA is a finger(?) from the S10 feeder system. The dolerite bodies around this area show dips radial to S10.

Dolerite outcrops in E as a coarse grained, irregularly roofed sheet; probably the sheet derived from S10. While faults f2AA and f2A can be shown further north to be Jurassic in age, at this point post-dolerite movements are indicated. It is not clear whether this graben block contains dolerite north of Kangaroo Rivulet. The thickness of this body is estimated from the anomaly requirements of this block further south, and away from the effects of S10 and S11. Weighing all considerations and remembering the position and termination of the Flagstaff Hill intrusion, which has been deduced to be related to S10 also, only one conclusion is possible. It appears likely that the sheet in E passes southward, but is terminated at about the line of the valley of Kangaroo Rivulet by a cross fault, with the same alignment as the Flagstaff intrusion. Thus the entire S10 structure is a large ovate funnel with a sheet centred on it. Its southern end has been broken by reactivation of the graben faulting, thereby depressing the associated sheet which had risen into Triassic rocks at this point. The inconsistency of throws on the graben faults in this region, allied to the known presence of sheets, is compatible with the presence of cross faulting and (or) upstepping of the sheet as envisaged.

Throughout F1, F2 and F3 a thick body of dolerite intrudes the Permian rocks. It is either an east-west dyke limb upstepping to the north from S11 or a change in thickness structure. It is probably a combination of the two. The dyke limb is indicated by the arc of higher anomaly around blocks F1 to F3 from the Flagstaff intrusion which it underlies structurally but overrides gravitationally.

In F4 there is no evidence for dolerite in the Permian rocks, but a body does intrude Triassic rocks. Much metamorphism is present. The patch of Triassic sandstone atop Mt. Rumney is considered to be on the roof of this sheet. It is difficult to specify all forms of the movement on the faults in F1 to F4. Many of the faults appear to be rejuvenated concomitant or pre-intrusion structures. F4 in this section also shows the special mass requirements for the Rumney ridge as were necessary for Craigow (Sects. 600-650). The residual anomaly produced by a 500 metre sheet at the base of the Triassic system would be about +1.5 mgal. Both sides of the intrusion are discordant, and comparisons with Sections 500-525 show that the sheet alone cannot produce the boundary phenomena or the +4 to +5 mgal anomalies. A partly concealed (?) dyke mass (S17), is added to compensate and provide the extra mass. As there can be no dolerite in depth in FF, S17 is indicated as a vertical intrusion with a plug-dyke character.

The structure in G is implied from Section 525, as there is total concealment in this section.

<u>Section 525</u>:

A1 is dilationally lower than A1 and A2 of Section 550 by at least 300 metres. It is comparable with A2 this section, however. As the anomaly on A1 suggests absence of any major bodies, while that on A2 shows one cap dolerite (clearly seen), and one body (from S15) at depth, the sheets from sources S14 and S15 must rise and meet in f1. Consistent with comments in Section 550, f1 must also have a pre-intrusion throw of about 250-300 metres. The mass, dip and dilation requirements can be explained in no other way. The sheet from S15 is transgressive to east, south and west.

B1 consists of a dolerite cap from S16 (Collinsvale). The anomaly distribution over the whole Mt. Wellington block shows only one body can be present and that it is on the top. Dolerite from S16 and S15 meet in the Collins Bonnet ridge. The sheet-dyke separation is clearly seen south of the section.

B2 is similar to B1, but contains a plug intrusion which is aligned with S18, as the anomaly trend clearly shows.

C1 and C2 are monoclinal or warp blocks intruded by a thin irregular sheet from S18. The intrusions are more discordant than concordant. Many of the faults contain dolerite dykes. The faults are thus dated, in part at least, although some have been rejuvenated. The anomalies suggest the presence of S18 as a partly injected plug. There are probably many small offshoots, e.g. 5060N, 5214E and also that drilled at depth in South Hobart (Johnson, 1888).

D1 and D2 are difficult to interpret. North of the section they are clearly devoid of dolerite at depth, whereas south of it there is an implied sheet. It is possible that a deep carry-over effect from the Nelson mass is complicating the anomaly pattern. The problem of whether there is a deeper sheet, or whether the feeder anomaly carries over cannot be solved at present. The need to terminate abruptly any such lower body of sheet form makes that possibility unlikely. The dolerite of Knocklofty appears more than a simple sheet base although its form can be explained by a sheet rising from the southwest and, as indicated, this would provide the discordant east margin.

E is as described in Section 550 except that here the anomalies are sufficiently separated to be sure that the sheet is present. The intrusions in F1, F2 and F3 are as in Section 550, but in F3 the separation of the two bodies clearly shows the need for a major accessory plug system. The small patch of Triassic rocks forms a window to the sheet rising steeply from the west. FF is as for previous sections.

The structure of Single Hill has been referred to earlier. The outcrop and gravity pattern show it to be an elbow in a sheet rising from the east. Some of the associated faulting appears concomitant. On the coast a sill in Cascades Group rocks is disrupted by later faulting. The deficiency of mass to the west confirms the field observations.

Section 500:

A1 and A2 are as for Section 525. The fault (f1) is again implied marginal to the intrusion. Its throw cannot be determined precisely due to lack of outcrop of any specific horizons. The anomalies in the region immediately south of the section imply a further massive intrusion concealed by the capping dolerite. In A3 the Collins Bonnet dyke is seen at a much lower level. It is likely that the sheet from S15, indicated in Permian rocks, is not as thick in this part of the region. Examination of the anomalies in the Grove-Mountain River region suggests that a sheet is present with marked thickness variations. Dolerite occurs below this region, as indicated by numerous small plugs and other irregular intrusions. As described in Section 425, a thin sheet rises to the southwest from this region. It is possible that the faulting is simply in the roof, above the intrusion, and thereby reflects variable sheet thicknesses.

All the anomalies south of this section in the region of Mountain River appear more negative than might be expected. This cannot be directly accounted for (see page 103). The anomalies in A3 show that no major sheet can be present to the west. The range of dolerite hills form no part of a dyke complex here. The anomalies over the Mt. Wellington-Mountain River blocks are about two or three mgals more negative than can be accounted for with the known rocks. While this precludes the possibility of deeper intrusions little else may be stated. In B, the Mt. Wellington block, the maximum anomaly that can be obtained with the observed geology is -4.5 to -5.5 mgals. The deficient area is too large and the topography too varied for this to be the result of short radius terrain corrections.

C1 and C2 are the severely faulted monoclinal blocks of South Hobart. The anomaly indicates a general lack of dolerite although plug feeders such as S18 are present. Blocks D1 and D2 expose dolerite but its exact relationship to the Nelson intrusion is unclear due to faulting and discordancy, although it may represent an offshoot sill with a discordant northwest arm. The thickness of Tertiary sediments in D2 exceeds 200 metres. No other details are known and no further interpretation is possible until the thickness of such sediments is known. The thicker the overlying cover, the thicker the dolerite body required beneath it.

F1, F2, F3 and FF are as for Section 525. A large pipe in F3 is implied by the anomaly of +6 mgals. The sheet in F1, F2 cannot provide this anomaly, although it is transgressing eastward at an angle of about 30° in this region.

<u>Section 475:</u>

A1, A2, A3, B and f1 are as described in Section 500 with the specific exceptions that a pipe is present in fl and that the western transgression from the lower intrusion in A2 and A3 is probably to the west of the included Triassic block at Crabtree (4750N, 5055E). The anomaly over this block is too high for it to be deficient in dolerite although a feeder zone is nearby (S19).

The limitations on the reconstruction in A2 and B are as for Section 500, although south of the core of the Mt. Wellington block it does become possible to explain the anomaly with known materials.

Blocks C comprise the faulted South Hobart monocline, which is intruded by an irregular transgressive sheet with many discordant basal upstep edges. The anomaly distribution shows that little intrusive material is present in these blocks away from the Nelson feeder zone in D. All outcrops in D show that sill initiation has taken place in the Cascades Group.

Blocks F2, F3, FF and G are as for Sections 500, 525. In F1 the increasing anomaly toward the river, outcrop distribution of Permian rocks and the transgressive character of the dolerite thereby implied suggests a source equivalent to S11(?)(Sect. 525). The eastern coastline of the South Arm peninsula (G) is intruded by a sill in Cascades Group rocks.

Section 450:

The Permian rocks in A1 contain a thick sheet emanating from centres S20a and b. It transgresses east and north but only in the narrow dyke to the east is the transgression observed, as dolerite from S19 conceals it to the north. The relationship of intrusions from east and west in A2 is clearly seen further south (Section 425). A2 and A3 appear to contain dolerite in a patchy(?) intrusion which also transgresses east into or through(?) or under(?) a steep pipe intrusion which is partly dyke-like to the northeast. This is shown by the dyke in the North West Bay River at Wellington Falls and Mt. Montague.

In B2 dolerite rises as a transgressive wall (hence the apparent thickness) from the Nierrina intrusion to the south. This body is about 500 metres thick based on the general +4 mgal anomaly over the large region where the sheet is concordant in Cascades Group rocks.

C and D are as in Section 475. A series of fault blocks tangential to the Nelson intrusion form the western side of the Derwent trough and comprise DD. Tertiary sediments fill the basin so produced.

F3, FF and G are as in Sections 475, 500. The diminishing positive anomaly in F3 for which a plug-dyke feeder system is proposed along strike suggests a size reduction or greater depth. No surface dolerite features can be correlated.

Section 425:

A1 is composed basically of a feeder-sheet system for which few details can be adduced due to the magnitude and breadth of the anomaly. It does appear to be a two part system which upsteps gently to the east and steeply to the west along the line of pre-intrusion structures. The upstep at the west end of the section is in fact a complex wedge-shaped intrusion which has lifted a large triangular piece of roof from the sheet arm to the west (Mather, 1955).

At A2 the major sheet from S20a and b rises steeply east and south. In the narrow dyke trending northwest from Grove there is sufficient exposure to show that two bodies are in fact involved. The small wedges of sedimentary rock at 4150N, 5085E are below both. The eastern intrusion, which in previous sections (450-500) has been regarded as patchy and variable in thickness, is about 100-150 metres thick. Exposures further east are consistent with this conclusion and such a value of thickness is also compatible with the general spread of anomaly values in the Grove-Mountain River block.

The Triassic sedimentary block at Longley (B1) must be devoid of dolerite as indicated by the low anomalies of -4 to -6 mgal. A dilationary step can be seen at the NNE trending fault-boundary structure at Longley (4200N, 5160E). B2 contains the thick Nierrina sheet. Only the top of this body with various roof pendants is visible. It is seen to rise gently northward over the whole area with an anomaly of +4 mgal. The implied thickness, accepting this anomaly value, is 550-600 metres which seems very thick. The dilation indicated at Longley is 400-500 metres, and this figure may represent either the true thickness of the sheet and a 100 metre pre-intrusion fault at Longley, or overall residual value elevation.

West of f2, which is the Tertiary component of the Cascades Fault zone movement offset around the Nelson block, the Nierrina sheet is faulted and generally concealed. f2 also shows itself to have been a basic fault at the time of intrusion since no major sheet intrusion can be ascribed to the Triassic capped block east of it. There is some confusion here in interpretation since the Nelson anomaly trend appears to continue into the Kingston-Blackmans Bay region and cause a slight elevation in values.

f2A is the line of the Jurassic movement of the Cascades Fault. The shape of the intrusions in its vicinity show its importance. In addition it shows more than one age of movement. Small dykes of younger dolerite are intruded into the fault zone at 4340N, 5255E and contact phenomena with the major body are visible. Some basalt necks of Tertiary age also occur adjacent to this structure.

D contains the squared transgressive southern end of the Nelsom block rising to the south.

F1 and F3 are as in Sections 450, 475. In F4 the Rumney dyke-plug system indicated in other sections is offset about two km to the east. Although little dolerite is obvious here, comparison with the features of the Rumney dyke and the relative sharpness of the anomaly generally would indicate that this is a dolerite structure and not a pre-Permian basement influence. It is possibly a small feeding dyke, or just the plug in F3 offset. The nature of any connection of the plug-dyke system and the sheet is totally unknown. The sheet passing beneath this area is shown to rise to the east in F5. The structure in F6 cannot be detailed as there are too many unknowns, the most critical of which is the thickness of less dense sedimentary cover. G is as in Section 450.

Section 400:

Block A1 is as described in Section 425 except that a fault (f1) west of Mountain River is crossed. The anomaly associated with this fault implies a thickness variation in the sill rather than just a change in depth on the east side. This sheet transgresses east and south and its base is repeated at the deep gully in A2 (4050N, 5105E). The structure in A3 reflects dolerite rising from the Nierrina intrusion to the southeast and does not represent dolerite from either east or west. The Triassic rocks on the surface are clearly a roof as examination of the neighbouring areas shows.

B1, B2, f2, C1 and C2 are as in Section 425. Block D is probably not dissimilar to the western margin of the Mt. Nelson intrusion. Along the coast south of Kingston part of a dyke, which has the same trend as f2A, is visible. Comparison with Sections 375, 350 suggest that this is merely the west wall of a transgressive upstep from the east.

Blocks F1 to F5 and G are essentially as for Section 425 except that the anomalies present can be adequately accounted for by the simple sheet in mid-Permian rocks. Little evidence of the plug trends of previous sections persists. It is not possible to correlate structures in F5 or G due to the deep Tertiary basin at Clifton, which is believed to be a filled fault wedge at least 200-300 metres deep (anomaly max, -12 mgal!).

Section 375:

Blocks A1 and A2 are basically as in Section 400 except that the structures of A1, A2, A3 and B1 of that section are compressed here. The nature of the contacts on the Herring Back are indicated and the small patches of Upper and Lower Triassic rocks are either small roof capping remnants or windows to one or other of the intrusions. Dolerite rises into the Herring Back from the southeast, south and west; any northern contribution being negligible. Between A1 and A2 the situation is more complex. The gravity field indicates the necessity of a second dyke and subsidiary feeder system northwest of the main transgressive boundary (3800N, 5060E) but cannot resolve the structure completely. Mather (1955) suggested a structure not unlike that proposed, and which is based on the occurrence of a trapped wedge block being of such stratigraphic elevation as to indicate dilation. This is consistent with the boundary phenomena and the requirements of the sheet from S20 to north and south. A detailed petrologic study would be necessary to sort out the entire story at this point since all the bodies merge to one great mass of dolerite over much of the ridge and it is only where included blocks are present that any separation can be made. Gravity anomalies are generally 0 to -4 mgal and indicate the amount of capping dolerite. The anomaly range would be -1 to +3 mgal if a deeper sheet was present.

Blocks B1 and B2 are dominated by the massive Nierrina body which is essentially a large dyke with uplifted roof over the central feeding zone (S21 - esp. in Red Hill region). Fault f2 appears to have little Tertiary movement in this section, although further south such movement is indicated at the dyke boundary (Sect. 300). Further north the younger movements are offset into many small fault blocks. Most of the surface displacement of 500+ metres is thus dilational since the gravity field on C2 indicates little or no dolerite. Indeed, with a slightly thinner Permian succession the anomalies would be totally accounted for. The illusion of a very thick Nierrina sheet can also be reduced slightly in this way.

D, F1, F3, F4, F5, F6 and G are as in previous sections, although a junction between the eastern and western sheets of South Arm exists at F5 where a number of discordant boundaries occur. It is not possible to determine whether this is a true merger or whether one body cuts another.

Section 350:

Block AA cannot be described totally due to lack of gravity coverage. The hilltops southwest of Huonville are capped with a sill. It is not clear whether the dyke to the river is connected as the one body, or whether it has been cut through by a later intrusive sheet. The anomalies of one to two mgal at Huonville and north in AA suggest that the dolerite from S20a rises southward in this dyke. This is clearly indicated in A1 east of the Huon River. The structure suggested for A2 is only one of two possible. There must be a dolerite rising south from S20a and a dolerite rising north from the region of Grey Mountain (out of area - see Leaman and Naqvi, 1967). This second structure is shown by the upstep in Sandfly Rivulet and the gravity anomalies over the Pelverata-Kaoota block (A2). Where the two bodies merge, the section would imply Upper Triassic rocks at shallow depth.

In fact, the outcropping rocks adjacent to this section are Lower Triassic. It is likely that a concealed dilation of the type suggested in Section 375 would provide the solution. Faulting is an unsupported possibility.

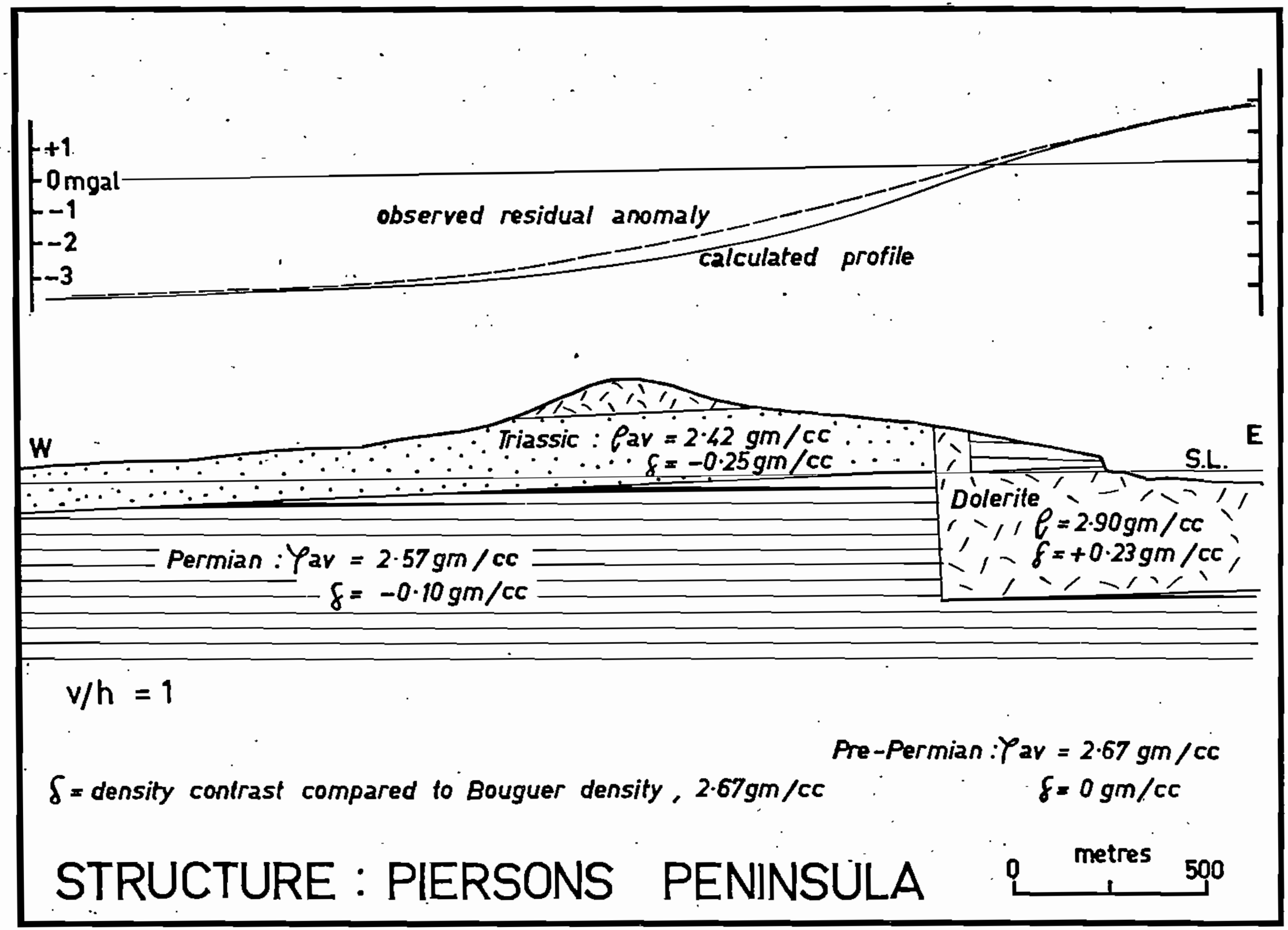
Dolerites from the Nierrina and Grey Mountain sources merge in A3. Contact phenomena and petrographic variations are present. Block B with S21 and C2 are as in previous sections but with f2 showing little displacement other than can be accounted for by dilationary effects.

The structure of D is clearly shown in coastal exposures to be a sheet transgressing steeply westward by a narrow dyke limb to cap the hills of Piersons Peninsula. A dilation of about 350 metres is indicated across this dyke and the anomaly of more than -3 mgal on the Triassic rocks of North West Bay precludes much dolerite continuing under the peninsula. As mentioned in Section 375 a slight thinning of the Permian succession would account completely for the anomaly and no dolerite would be necessary. The structure of Piersons Peninsula is shown in fig. 6, p. 73. Fl and F2 are as for previous sections. The Tertiary trough is fairly symmetrical (graben?) and of unknown depth, but probably more than 200 metres assuming a structure as indicated in the section.

<u>Section 325</u>:

The Red Hill dyke with obvious roof uplift is shown in B. There is no evidence that the dyke extends in depth beyond the base of the sheet produced by S21 (see also McDougall and Stott, 1961). Cl and C2 are as in Section 350 although there is a clear requirement for some faulting of

Fig. 6



+1
0 mgal
−1
−2
−3
observed residual anomaly
calculated profile
W
E
S.L.
Triassic : ρav = 2·42 gm/cc
δ = −0·25 gm/cc
Dolerite
ρ = 2·90 gm/cc
δ = +0·23 gm/cc
Permian : ρav = 2·57 gm/cc
δ = −0·10 gm/cc
v/h = 1
Pre-Permian : ρav = 2·67 gm/cc
δ = 0 gm/cc
δ = density contrast compared to Bouguer density, 2·67 gm/cc
STRUCTURE : PIERSONS PENINSULA
metres
0
500

(or warping) of rocks in North West Bay. At Piersons Point the coastal sheet is faulted down to the east but the north-west transgression is seen around Mt. Louis.

Betsey Island (H) has an unknown structure. The presence of Triassic rocks on the island and Permian rocks on the reefs between it and the mainland suggest some form of dilation or east-west faulting in the channels between the island and the mainland.

Section 300:

As for Section 325. Clear Tertiary or post-dolerite movements are observed on the dyke wall at B although the stratigraphic and dilational requirements suggest that the throw must be small.

Structural Summary:

Some general comments may be made of the structure, as it exists, without much regard to the emplacement of the intrusions which is fully discussed in Section 5, p. 90.

The Derwent, Mt. Faulkner and Mt. Wellington blocks contain no dolerite sheets below the level of 200-300 metres above the Permo-Triassic boundary. Dolerite feeders are fairly regularly spread over the district.

The effects of Tertiary, or certainly post-dolerite faulting, have been basic to the structural confusion experienced by earlier workers and may be fully appreciated, particularly when the results show many localities in which different dolerite bodies can be placed adjacent to one another. Tertiary faulting is most pronounced east of f2

(Dromedary-Cascades Fault). f2 extended as the North West Bay Fault shows surprisingly little Tertiary movement over much of its length. These three faults were key structures at the time of the intrusion as many intrusions terminate or upstep near them. Whether they then formed one fault system is not clear. It is likely that Tertiary reactivation and block cross-breaking, as near Dromedary and Mt. Nelson, combined to produce one crush zone. The monoclinal or warp blocks about the Mt. Wellington block are probably related to this reactivation.

The Bagdad Fault (f3) and its southern extension has a similar history although the later movements show a hinging southward. Tertiary faulting dominates the present structure of the Derwent lowlands, the Coal River lowlands, the Brighton-Tea Tree region and South Arm. The southern part of the Middle Derwent faulting is observed near New Norfolk but much of the movement is terminated on one or two cross faults. Few features between New Norfolk, Huonville and Mt. Wellington are of this age (see also fig. 2, p. 16).

Some structural conclusions made by previous workers may also be discussed here. The structure proposed for South Arm by Green (1961) has been proven basically correct. The 'cone' structure proposed for the Collinsvale region by Sutherland (1964) has also been verified. There is a problem providing a feeder for this structure, and the only conclusion is that several small sources are involved, e.g. S28a, b. The two sheet structure of Mt. Dromedary (McDougall, 1959b) and the dyke-sheet structure of Red Hill (McDougall and

Stott, 1961; McDougall, 1962) have been verified. The present results on Red Hill are minimum estimates because a uniform density value has been used whereas McDougall and Stott allowed different values across the dyke but did not terrain correct their observations. They also had a problem accounting for the amount of granophyre present, but their survey did not extend far enough north to locate the Nierrina feeder. The concept of a massive feeder system of upturned "V" shape for the Craigow-Rumney dyke (Hastie, 1960) is partly supported geophysically, but modified to the extent of demonstrating that more than one body is present.

The structure proposed for Gunnings Sugarloaf differs considerably from the wide dyke of Edwards (1942). The narrow dyke feeder to the west of the Sugarloaf would provide a "bottomless" body in part, at least. This body needs re-examination regarding the differentiation process.

The association of a major feeder with the Nelson sill would also affect the acid content of the material and comparisons of the Nelson and Wellington sills may not be valid (see Edwards, 1942).

4. PHYSICAL AND STRUCTURAL ASPECTS OF DOLERITE INTRUSIONS

4.1 Thermal characteristics

Petrological evidence suggests that the magma intruded close to its liquidus temperature of about 1100°C (Edwards, 1942; McDougall, 1962). Jaeger (1958) has shown, under reasonable assumptions, that a sheet of the scale common to this area will solidify in about 1,000 years from this temperature. The rate of temperature fall is very rapid late in the crystallization process but probably only changes by 20-50° while the dominant minerals are crystallizing. The time to cool to less than 100° is considered by Jaeger to be 10^4-10^5 years. He also showed that a second intrusion into a solidified but incompletely cooled sheet is unlikely to form a chilled margin if the first has not cooled below 300°C. This would be expected to take of the order of 10^4 years. In addition, Jaeger (1961) has shown that if there is a dyke-sheet junction then the time of cooling is increased at the junction and is greater than the cooling time in either dyke or sheet.

A further aspect concerns the heating capacity of the feeding pipes. Such features had a direct connection to the heat source and also passed a large volume of material through a small cross-section. The effect of this is to increase the wall temperatures, reduce the efficiency of heat transfer by decreasing the temperature gradient and thereby increase the time of cooling of the material in the pipe. No realistic estimates on the time of cooling involved are possible due to the variety of assumptions necessary.

4.2 Intrusion margins

Intrusion margins are invariably crisp, sharp features. While they may, on occasion, have a blocky irregular character there is no evidence of assimilation. The intrusions have produced slight thermal metamorphism of the sedimentary rocks with marginal chilling of the dolerite itself. The chilled margin is rarely more than a few feet thick near the roofs of sills, or walls of dykes. Near the base of large sub-concordant bodies the grain size can grade imperceptibly over large distances and fine-grained material persists through many tens of feet. Contact phenomena in the intruded rocks are variable, and marked thermal effects can only be seen within a very few feet of the intrusion margin. This applies particularly to the siliceous formations (e.g. Ferntree Group, Lower Triassic sequence). Those formations which have a high calcareous content (e.g. Bundella Mudstone, Cascades Group) show thermal metamorphic effects over a greater area, but even then it is rarely more than 20-30 feet(6-10m). The above comments apply to obvious changes. Hamilton (1965) has suggested that the whole intruded sequence in Antarctica has undergone changes of some sort, often very minor, as a result of the intrusions within it. Whether this is in fact so in Tasmania cannot be judged as yet since insufficient study of the textures of the intruded rocks has been made. The carbonisation of spores would suggest that thermal changes have occurred. The narrowness of the obvious effect indicates a low heat capacity or that few hydrous phases were possessed by the magma.

Metamorphic effects are more extreme where the material is over the roof of a major body, e.g. Collinsvale, or a feeder. Metamorphism is especially severe in the case of included blocks.

Dolerite at intrusion margins is always finely jointed and it is not uncommon for two sets of joints to be formed perpendicular to the contact surface. Columns of four, five or six sides are often produced and these may extend well into the intrusive body becoming larger and more continuous away from the margin (e.g. Mt. Wellington -'organ pipes'). The attitude of such columns gives a reliable indication of the dip of the body.

Internal boundaries between dolerite bodies are more difficult to assess. Where a definite chilled dyke of younger dolerite can be observed such boundaries are quite sharp. They are rarely found by surface mapping and cuttings and quarries are the usual sources of information. The difficulties are compounded when trying to locate boundaries between large dolerite intrusions suspected of being a little different in age. Firstly, unless the time is long, no chilled margin will develop (p. 77) and there may only be subtle changes in grain size. Secondly, as any dolerite boundary is very susceptible to weathering and erosion, such junctions may be difficult to determine directly in the field. These problems have been noted elsewhere (Blignaut, 1952), but better outcrop and less vegetation helps considerably in South Africa and Antarctica (e.g. Hamilton and Hayes, 1963, pp. 9-10).

There is also an incomplete understanding, at the present time, of the pattern of petrological and grain size variations in dykes or dyke limbs of inclined sheets. Any changes that may appear out of sequence could be misinterpreted when it is realised that most information comes from road or creek sections which may not give a three-dimensionally consistent picture due to a relative paucity of traversing. Cross country traverse information is often patchy and unreliable due to rock drift and soil creep effects. Some changes may even reflect injection by pulses to produce the dykes and sills. A complete systematic petrological study is long overdue.

Variations that are compatible with the sections and structure suggested in Section 3.4.4 have been found on some structures. Some others can only be implied, as deep weathering occurs at the points where contacts were expected.

4.3 Density and viscosity

The density of solid dolerite is well known (p. 26). The liquid density is not so well known but Dane (1942, p. 36) has given results of 2.60-2.64 gm/cc at 1200°C. This value would be altered by volatile content and consequent changes in compressibility. In near surface conditions this effect is considered negligible (Birch, 1942), although its effect at depth is unknown. Hamilton (1965) concurs with the above stated density range.

Viscosity determinations suffer from similar deficiencies. Dolerite at 1400°C has a viscosity of 15-400 poises, whereas Hawaiian olivine basalt has a viscosity of 127 poises at that temperature, and 4×10^4 poises at 1150°C. Figures after Ramberg (1967, p. 127). Consideration of these results would suggest that a viscosity of 10^5 poises would be a realistic figure for dolerite at 1100°C, as at the time of intrusion.

4.4 Included blocks and their implication

"Inclusions" of sedimentary blocks are commonly noted in dolerite intrusions. In most cases such blocks are small, perhaps 100-200 cubic feet or less, and are normally found within inches, or in the case of large intrusions about 20 feet(6m), of the upper junction or roof of the body. A large inclusion more than 100 feet by 20 feet (30x6m) in section can be seen within about 20 feet of a sill roof in a road cutting at Sorell River (6310N, 5091E).

An examination of the geological map (Map 1), and sections (fig. 4), will show that quite large bodies, apparently "inclusions", occur centrally disposed within dolerite masses. Examples may be seen in the Brighton-Tea Tree Hills and at Mt. Direction. The apparent enigma of such blocks either at the margin or hundreds of feet from it prompted consideration of the forces acting on an included block in a large body of fluid.

Any slab of sedimentary rock of the type intruded is less dense than the surrounding magma. Hence, as soon as it is broken away from the base of the body, and fluid surrounds it, buoyant forces become active and lift it upward.

If h_o is the distance from the roof of the intrusion, A is the area of the block and hence the cross section of the fluid to be displaced, η is the viscosity of fluid and Fb is the buoyant force then the time taken for the block to rise to a height h from the roof is given by

$$t = \frac{A \eta h_o}{Fb} \left(\frac{1}{h} - \frac{1}{h_o} \right) \quad , Fb = f(\rho_1, \rho_2, \text{block volume}) = g\,v\,(\rho_1 - \rho_2)$$

ρ_1 = density of fluid, ρ_2 = density of block, v = volume, g = acceleration due to gravity. (Scott Blair, 1949)

This equation gives the time for a very loosely fitting piston to compress a fluid and should ideally be used for regular bodies with circular section. It assumes a true fluid at constant temperature and ample room for fluid escape - a required assumption in the circumstances. The effect of changing temperature is discussed below.

e.g. If h_o = 500 feet(150m), $\rho_1 - \rho_2$ = 0.2 gm/cc, h = 100 feet(30m), volume = 5,000 x 10,000 x 300 cu feet (1,500 x 3,000 x 90 cu m), $\eta = 10^8$ poises; then time = (approx) 2.3×10^2 seconds.

In view of some of the assumptions made, the value of η is greater than might be expected in order to give a margin for error. If the viscosity is 10^{10} poises near the roof, due to cooling effects at the margin, the time for the body to reach 20 feet(6m) is about 2×10^5 seconds. This would allow a maximum of about a week for this block to lift close to the roof - a very small fraction of the total crystallization time. It is possible that these times are $10^2 - 10^3$ times a true figure, considering the viscosity assumptions.

As the block rises through the fluid there is condensation effected about it, and crystallization will take place. In effect, the size of the block will increase with time and decrease the density differential. With a large block this effect will be negligible. As the block nears the roof, its rate of ascent is decreased systematically by the increasing viscosity resulting from cooling across the narrowing gap. While the calculation above assumes static conditions it will still overestimate the time involved.

On the basis of buoyancy, no blocks, regardless of size, should be found anywhere other than the upper margins of intrusive bodies. The time taken is proportional to the area compressed and inverse to the volume of the body. Hence the more massive the body, the more rapid the approach. A factor of two makes a 66% difference in time.

The direct conclusion from such observations on "inclusions" infers that such blocks in major dolerite masses reflect boundaries, or near boundaries with later intrusions. The field evidence, when reinterpreted in this light, supports its consistency. In fact, they are probably part of the roof in which subsequent intrusion has taken place. These situations rarely have the clarity of exposure seen in Antarctica or Skye, where definite slivers between sills are visible and where there are clear contact features between sills

(Hamilton and Hayes, 1963). An example of this situation, which is common to other provinces, is at Mt. Direction.

Alternatively, this conclusion may be derived from consideration of the hydraulics of a multiple system. Two fluid sheets, one above the other, in a sedimentary pile form an hydraulically unstable system. If both are connected, however indirectly by pipes, dykes or other such features, the upper body will load the lower and since sheet intrusion in this environment is hydrostatic and flotational (p. 122), the magma will be transferred from the lower to the upper shortly after initiation of the second intrusion which can never be lower than the first. The transfer will not be complete due to chilling effects. This result was also deduced by Bradley (1965, p. 39).

This process is best understood by considering two newly formed offshoots from a feeding dyke. After a time, the load of the upper intrusion will become such that the system does less work lifting the roof above the upper offshoot than the lower which is lifting extra sediment plus the upper intrusion. Intrusion can continue at the higher level since the magma pressure must have been sufficient to raise the magma to it in the first instance. An analogy is given by Bradley (1965) of slabs of wood in water. Such slabs will either float as a unit or only one will float. There will not be a series of floating pieces irrespective of where a wedge of fluid has penetrated.

As a corollary it will be observed that major sill initiation can only take place at one level for a given intrusion and that the presence of more than one major body per column implies multiple intrusion with a separation at least equivalent to the crystallization time.

The presence of minor intrusions in association with major intrusions implies either

i) trapped fluid in a fracture unable to grow as a result of the process outline above, or

ii) intrusion by pulses, where the minor intrusion represents one pulse. Under this hypothesis major bodies would be built up of many spurts of magma separated by only a short time interval. If concordancy of pulses is disrupted an included block could be produced. They would however, remain marginal as a result of the special conditions of this environment.

Probably both processes occur. The larger of the minor intrusions are possibly produced by the latter mechanism (e.g. Pl. 4, Hamilton, 1965). The validity of the latter hypothesis remains to be seen, although several authors now believe that major bodies are so built up (e.g. Walker, 1969).

It might be argued that sheets from different sources could be contemporaneously intruded in the one column and not affect one another. However, the sheets show upward transgressions and as soon as they joined the comments on page 84 would apply. The presence of many faults makes complete separation impossible for any time as blocks of intruded rocks will be moved during intrusion and hydraulic connection could be readily established.

4.5 Form and scale

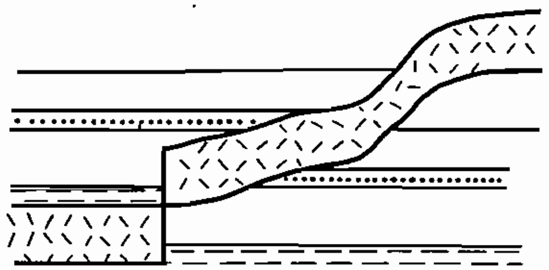
Three main types of structure are represented in the intrusions of this district - sills, dykes and bosses(plugs). An examination of the sections (fig. 4) will show that many of the sills and dykes are connected to form, in overall section, an inclined (stepped) sheet. Such sheets form at two scales only; very small or very large. Although there is a considerable range in thickness of the dyke limbs in such sheets, depending on their angle and any horizontal dilation, the sill limbs are either within the range 1,000-1,500 feet (300-450m) or one inch to six feet(<2m). Unlike some other provinces, e.g. South Africa, there is no intermediate size distribution. The large bodies present are very large and two to five times the average size of the intrusions in many other provinces. Plug-like bodies are usually one half mile (0.8km) square or larger.

4.6 Dilation

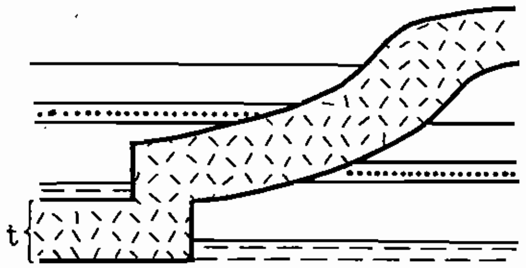
The topic of dilation was briefly mentioned in Section 2.3 where the general principles were enunciated. Examination of the geological map will show many likely examples (e.g. Longley, 4380N, 5170E; Blackmans Bay, 3600N, 5270E; Mangalore) which have been supported in the structural reduction. In every case vertical dilation is the dominant characteristic although some discordant bodies appear far wider than their angle of dip and vertical component would suggest. Examples of such a situation are at Mt. Rumney and Craigow where possible dyke wedges are involved. Dilationary components may be affected by dips in intruded rocks and faulting, and by interference of uplift asymmetries. All aspects of dilation are outlined by Leaman and Naqvi (1967) and a revised summary figure is reproduced here (fig. 7, p. 88). If the fracture and intrusion is three-dimensional a closed funnel block will be uplifted as in the case of cone-sheets. A small scale example is shown in Plate 1.

4.7 Fault relationships

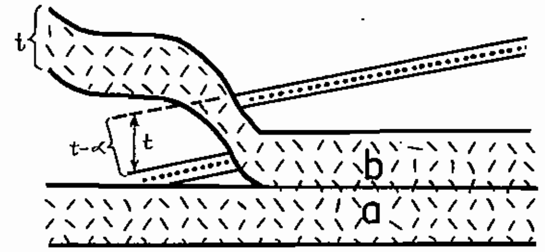
With respect to the dolerite intrusions, faults may be classified as pre-intrusion, concomitant or post-intrusion. On many occasions it is difficult to separate the former pair. If a displacement can be proven or directly implied beneath an intrusion then the fault is clearly pre-intrusion. In many cases this is impossible to show and a minimum age of concomitance may be indicated. A throw above an intrusion may represent a change in thickness of the intrusion below (e.g. McDougall, 1962, p. 282; implication Section 400, Huonville). Concomitant faulting represents the fracturing and general disturbance accompanying the intrusions while the pre-intrusion faults reflect the stress environment leading to activity. In the case of concomitant features there is always an occupation of the fracture as a dyke or as one side of an intrusion. The key observation concerning either type of fault is that intrusions rise steeply along them, examples being the Collinsvale intrusion on the Cascades



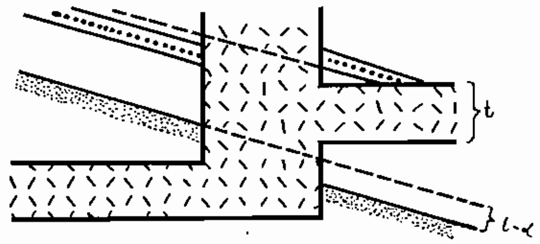
FLAT LYING STRATA VERTICAL DILATION ONLY
LONGLEY



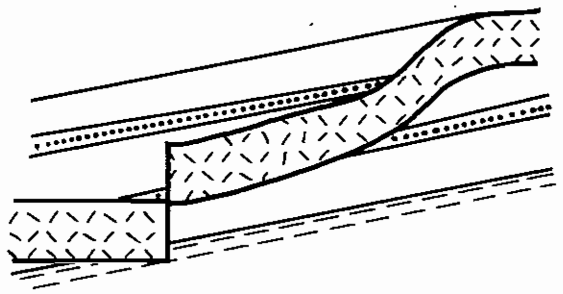
FLAT LYING STRATA OBLIQUE DILATION H = V



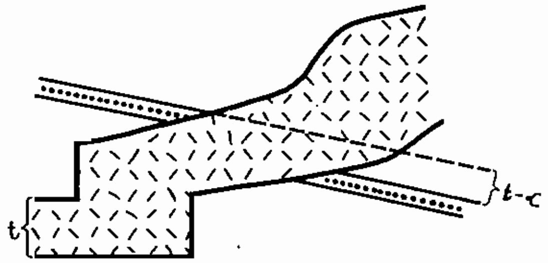
VERTICAL DILATION ONLY
Mt. DIRECTION



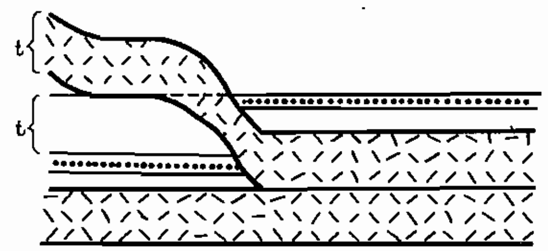
H = 2V



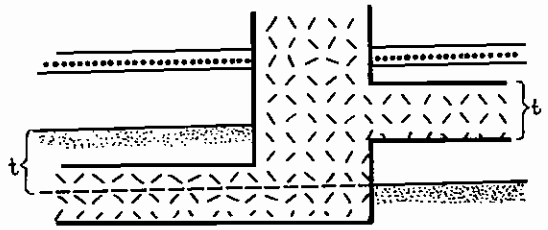
DIPPING STRATA VERTICAL DILATION



$\alpha = 1/3$ H=2V



VERTICAL DILATION ONLY

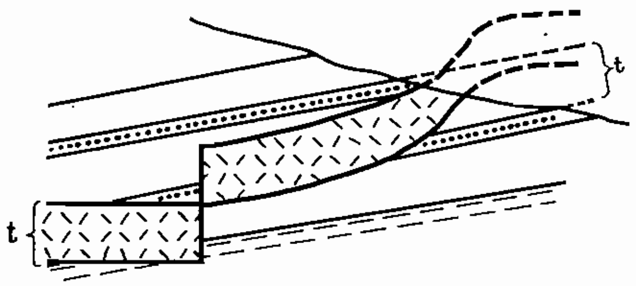


H=2V
Mt. DROMEDARY

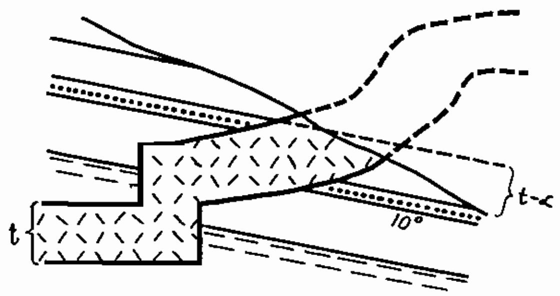
(iii) (iv)

(DIP EFFECTS ARE NEGLIGIBLE IN HOBART DISTRICT)
HORIZONTAL DISPLACEMENT OF SMALL ORDER IS IMPLIED, IN MOST STRUCTURES

REFER ALSO WILLIAMS & GROVES (1967)



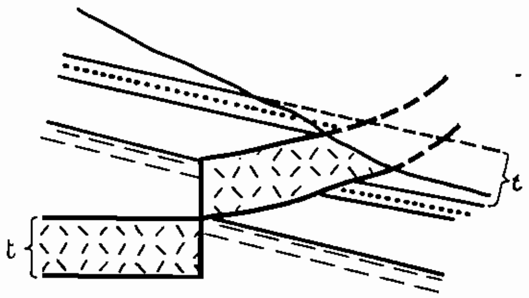
AFTER EROSION



AFTER EROSION OF DIPPING STRATA OBLIQUE DILATION

OBLIQUE DILATION IS V=H
$\alpha = 1/6$

(ii)



(i)

α = REDUCTION BY OBLIQUITY

DEPARTMENT OF MINES — TASMANIA

FORM OF DILATION ASSOCIATED WITH DOLERITE BODIES

DATE:— *OCTOBER 1966*	REPRODUCED FROM LEAMAN & NAQVI (1967) REVISED NOV. 1969
GEOLOGIST:— *D. LEAMAN*	
DRAUGHTSMAN:— *R. J. VOSS*	MAP SHEET & No:- *MECH.*
REVISIONS:-	FILE No:— 2941

Fault; Dromedary intrusion on Dromedary Fault, Magra Fault (fl, Sect. 700). Some intrusions terminate upon concomitant faults, as south of Mt. Dromedary and on the North West Bay Fault (fig. 4; fig. 8, p. 94).

Some difficulty has been encountered with interpretation of post-intrusion faults. Firstly, they may be inter-intrusional and thus their character will not be totally post-intrusion. Secondly, they may be rejuvenations of earlier faulting. As commonly happens, these faults show both contact phenomena and contact dislocation. If the former movement also produced crushing and dragging of the intruded rocks any post-intrusion character may be impossible to deduce.

5. FORM OF DOLERITE EMPLACEMENT

5.1 General

Examination of the geological map and structural sections (Map 1; fig. 4) shows that the intrusions within this area have the form of sub-circular inclined sheets, each sheet being related to a source at its deepest point in the intruded rocks. The actual shape of each intrusion is quite variable and ranges from a Y- to T- shape at its heart. Classification of centres with respect to the basic variations in form is shown in fig. 11, p. 118. The sheets are composed predominantly of concordant or sub-concordant limbs with abrupt transgressions between such limbs. In the Permian rocks concordant bodies are restricted to Bundella Mudstone and Cascades Group horizons and in the Triassic rocks to those parts where much mudstone is present. The condition of the roof is much more irregular and disrupted at, or above, the boundary with Upper Triassic rocks.

In the third dimension each intrusion ranges from a crude circular outline to a sheet trough. In extreme cases, such as the inferred Craigow and Rumney-Augustus plug-dyke systems, the trough reduces to a dyke. The general shape of some of these intrusions was predicted by Carey (1958a) although none of the examples described by him were in this area. The form predicted, based on a mechanistic "punch" process, is valid and the S1, S10 and S15 intrusions may be cited. This intrusion shape has been called a cone-sheet. This term is confusing and not strictly accurate, since none of the intrusions is conical, and most are a flattened and distorted Y shape. Some are even asymmetrical and only half a T in form (e.g. S8, S11?, fig. 11). Such asymmetrical forms have also been noted in Guyana (Hawkes, 1966b).

In view of the irregular form of the intrusions it is proposed to refer to each by the general term chonolith defined by Daly (1933) as:

> "A discordant igneous body (a) injected into dislocated rock of any kind, stratified or not; (b) of shape and relations irregular; and (c) composed of magma passively squeezed into a subterranean chamber or actively forcing apart the country rocks (p. 106)."

The concept is one of the filling of an actual or potential cavity, and aspect (c) is supported later in this thesis (p. 114). Chonolith is a general term etymologically referring to a mould. Each component of the intrusion (sills, dykes, etc), and the whole, will be shown to have filled a mould. As such it includes the term cone-sheet but avoids the special connotation that term implies.

Apart from the descriptive aspects of the form of each individual intrusion (chonolith), the most important single observation is the recognition of up to three large intrusive sheets in one column over substantial areas. This leads to the corollary that at least three pulses of intrusion are represented (see Section 4.4, p. 83). Previous workers have regarded the intrusive stockwork as a single phase intrusion and a rebuttal of the reasoning leading to this conclusion appears in Section 6.9, p. 128 and Section 4.4, p. 81.

Normally only one sheet appears as a sill in the Permian rocks and then only in one or other of the horizons mentioned above. Such a sheet transgresses sharply into middle Lower Triassic rocks (e.g., S6, S8, S13, S15, S16, S20, and S21). It is not uncommon, however, to find two sheets in the Lower Triassic rocks which are much thinner as a group. The availability of intrusion horizons is a key factor in this (Sect. 6.5, p. 114). Sills in the Triassic rocks are, with few exceptions, much more extensive than in Permian rocks.

A further general observation is possible regarding the source localities. Many are related to graben faulting which was at least concomitant with the intrusion (e.g. S10 and S11). Others are related to single faults of the same age (e.g. S1, S13, S19 and S20). The implication is that these faults were (and still are?) major fractures in the crust, since the anomalies suggest bodies extending to great depth. There is nothing to imply that the dolerite fortuitously occupies them at shallow depth only. Since the magma was probably derived from a depth of at least 35km any association of centres with faults implies use of a major fracture from that depth. Normal faults pass to shallow angles at depth (65-70° or less, De Sitter, 1956, p. 147) and in most cases would not reach that depth. This suggests that many of the occupied faults, as observed now, are normal rejuvenations of major crustal fractures which at one time may have had some transcurrent movement. Many other faults act as terminators to the intrusion or as initiators of transgression. This clearly implies either concomitancy or pre-intrusion.

5.2 Specific features of emplacement

A separation of intrusions with respect to age relations is indicated in fig. 8, p. 94. The location of feeders is shown in fig. 9, p. 102. Figure 8 presents the simplest model available and the evidence for it is discussed below. The boundaries between different dolerites are placed as accurately as known. There are few ground contacts observed (Sect. 4.2, p. 79) and most junctions are sited on structural evidence. This study indicates that a detailed petrological investigation of adjacent dolerites is long overdue. It is realised that such work is the only way to confirm the inferences, predictions and conclusions made. The intrusion labelled "c" is taken as a 'marker' due to its extent and easily established continuity, The ages given are relative within parts of the area and obviously a "b" intrusion may be an "a" where there is insufficient evidence to establish a complete ordinal scheme.

A representative of the oldest intrusion "a" occurs beneath the Collins Cap-Grove blocks. As far as can be estimated the feeder and sheet initiation are quite deep (note the breadth of anomaly compared with other feeder systems) and probably close to the pre-Permian unconformity. The sheets from this source (S15) are cut off by sheets from Collinsvale (S28) and Mierrina (S21), and such structures are clearly shown in section (fig. 4). The Grey Mountain-

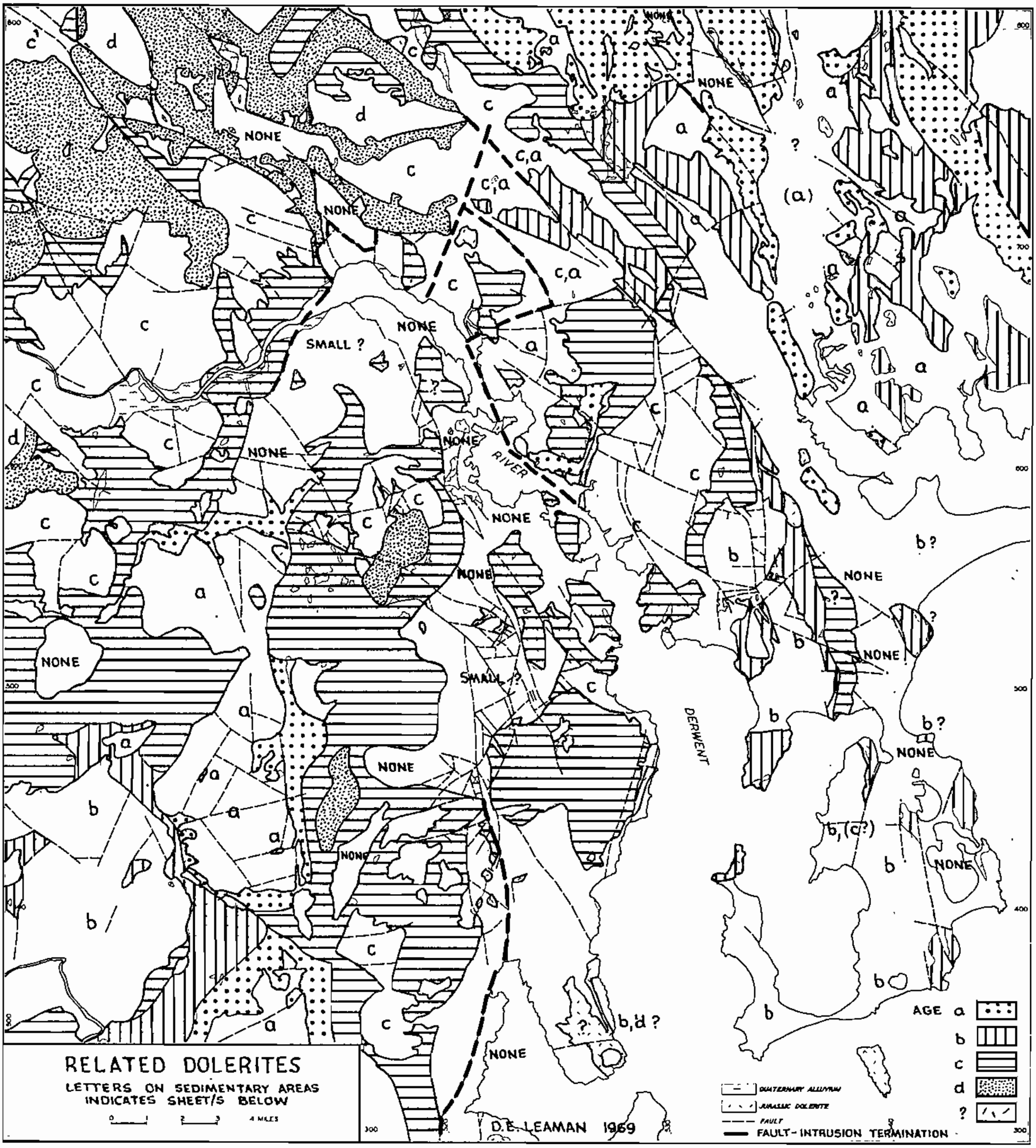

RELATED DOLERITES
LETTERS ON SEDIMENTARY AREAS INDICATES SHEET/S BELOW
D.E. LEAMAN 1969
AGE a
b
c
d
?
FAULT-INTRUSION TERMINATION
NONE
SMALL ?
RIVER
DERWENT

Fig. 8

Pelverata intrusion (S22) and is probably the same age. This is indicated by its relations with the Huonville intrusion "b" in the Herring Back, where the presence of 'included' blocks is crucial to this correlation. Not a great deal is known of the S22 intrusion, being only partly in the area studied. S15 has produced an irregular, elongate intrusion in which the sheet thins significantly to the south (1,500-<500 ft; 450-150 m). No evidence or trace of its high level form is obtainable as dilation by later intrusions has lifted it above the present topography.

The Huonville intrusion (S20) is younger than S15 or S22 but is itself cut off by the Crabtree (S19) and South Huonville (S23) structures. S20 is a massive intrusion with multiple sources and forms the bulk of the Herring Back. In the north the Dromedary (S6), Boyer (S13), Lachlan (S14) and Crabtree (S19) dolerites appear to join and form the high level Mt. Marian-Trestle Mountain-Collins Bonnet massif and plateau. The S20 sheet thus appears at Crabtree only where it passes over the trapped Triassic block above the sheet "a"(=S15) and is itself sliced by the plateau sheet. How far "b" passes to the east is unknown. The intrusive junctions and closures between the S6, S13, S14 and S19 bodies indicate concomitancy (e.g. at 6180N, 5024E; 6330N, 5110E; 5500N, 5050E). There is a slight possibility that S19 is later.

The same age as S19, however, are the Nelson (S24), Collinsvale (S28) and Nierrina (S21) intrusions. These rise onto the Mt. Wellington-Collins Bonnet massif and there join the main plateau sheet from the west, which also caps

Collins Cap. There is no evidence to suggest that these bodies did not merge. Of like age is the S23 intrusion in the far southwest of the area which transgresses through the massive S20 chonolith on the Herring Back. Dolerite from the discordant wall of S6, south of the Derwent River at Dromedary, rises onto Mt. Faulkner where it coalesces with material from the south (S28).

Subsequent intrusions are indicated at Moogara (S4), Mt. Hull (S16) and Mt. Montague (S25). Those of S4 and S16 are indicated by cut-through and double sheet environments whereas S25 and its properties are implied only. It may well blend with intrusions of age "c".

Dolerites of age "c" from Boyer (S13) and Dromedary (S6) rise northwest into the middle Lower Triassic rocks of Black Hills. An interesting feature is the wedge left at a pre-intrusion fault between these intrusions at 6400N, 5107E. This block was probably a wedge between two fault surfaces each of which was later taken up by intrusions from either side. Intrusions of this age also appear to be terminated by the Dromedary Fault, and associated fractures in the north of the district, and by the North West Bay and Cascades Faults in the south. In the latter case the Nierrina chonolith is sealed to the west and the Nelson chonolith to the south. The axis of the Nelson intrusion lies down the Derwent coast to Piersons Point and the dolerite upsteps westward. However, the age of the Piersons Point dolerite is unknown. The Nelson and Nierrina chonoliths are at comparable stratigraphic and structural elevations at Ferntree where they rise to coalesce and upstep onto Mt. Wellington. It should be mentioned that this is the simplest conclusion.

In the step-faulted hills of West Hobart the dolerite sheet can be seen to arch. The source S10 on its bifurcate elongate fracture is thus of age "c" and joins the Nelson, Collinsvale intrusions in the Moonah-West Hobart area. Tertiary movements have produced the elevation differences between Mt. Wellington and Knocklofty.

The large funnel of S10 expands to the east at Flagstaff Hill, Rosny Hill and Craigow, and to the west at the Mt. Direction-Grass Tree Hill rise. The lower sheet on Mt. Direction is clearly older as contact and 'inclusion' phenomena show that its roof is cut through by the S10 body. As far as can be determined "a" is asymmetrical with an axis approximating the river. Its exposure has been terminated by the line of dilation from S10 in the Grass Tree Hill dyke. It is classed as an age "a" intrusion on the relative requirements of the Tea Tree dolerites to the north. Although this intrusion is sliced by S10 the mass requirements suggest that the intrusions "a" are linked to those at Richmond where there is another feeder system (S7). This whole sheet forms a low arch and the dolerite from it does not appear to reach higher than Lower Triassic rocks.

In the Tea Tree region sheet "c", which is faulted and partly concealed northwest of Grass Tree Hill, steps through the repeating sheets ("b") of the Tea Tree Hills. It is therefore younger than them. The evidence for such a conclusion is purely structural. Detailed field considerations indicate that interference of two dolerites is the only way that the distribution of chilled margins, small inclusions and topographic form could be attained. The sheets "b" cannot be the same age as "a" since they appear in the same section. The sequence of events in this region appears to have been a low level injection ("a") causing minor disruption above basal Lower Triassic horizons followed by intrusion of a thin sheet ("b"), possibly from sources to north or east (reactivation of S7?). The major intrusion ("c") from S10 then passed through "a", "b" to intrude the level of the Upper Triassic rocks.

The intrusion S10 is the largest single chonolith in the district with trough length of about 10 miles and width of 4 miles. The closure at the southern end is concealed by the river and broken in the north by later cross faulting which has depressed one segment of the intrusion (Sections 675, 700). The northern sheet from this intrusion overlies much of the Old Beach region and, prior to the Derwent faulting of Tertiary age, probably linked with the high level dolerite on Mt. Faulkner. To the east dolerite rising from the Flagstaff Hill arm of the intrusion becomes concordant onto Craigow and slices the plug(?) intrusion which forms the bulk of the hill. In addition, the peculiar concordant sections of the intrusion on a hill south of Craigow (5790N, 5350E) are explained by the interference of the two dolerites, one of which is discordant, the other concordant. Both intrusions S10 and S11 appear to be centres on the same feeder zone although the incompatibility of age is indicated by the overlap properties shown in Section 575, p. 56. The S11 intrusion has produced a sheet in the Rokeby-South Arm region which rises eastward from an axis on the eastern side of the river into the Rumney ridge.

The age of the plug core of the Rumney ridge and South Arm region is unknown. It shows a north-south lineation with S7 and the Jurassic faulting of the Coal River also has this trend. S12 could be a partially exposed section of such an extended body. Sheet propagation is not necessary from it in this part of the area and it may simply represent the tongue end of an elongate feeding column. It is inferred, from such restricted evidence as is possible to deduce, that this plug system may be equivalent to "c" and may well have linked with the sheet rising from S10.

The intrusion into the eastern part of the South Arm peninsula is thought to be either "b" or "c" in age. The intrusion contacts another at only one point and age relations are uncertain there. West of Single Hill it could rise to join either "b" or "c"(?) in the Rumney ridge.

In the hills northwest of Brighton the order of intrusion is complex. Several intrusions are indicated by the number and distribution of included roof and window fragments and the great variability of intrusion margins. The western boundary of the intrusions in these hills is formed by the upstep of intrusion "c" from both S9 and S10. Also at this boundary are traces of sill "b" which is more clearly represented at Tea Tree. The bulk of the region is composed of an earlier intrusion "a" which shows a general transgression to the northeast, and there joins dolerite rising westward from the S5, S7 feeder systems considered to be of age "a" by their relationship to the Tea Tree intrusions.

Dolerite from S9 persists under the Brighton block and is synchronous with that of S10 which it meets in the arch at Old Beach. It is dislocated by the Mangalore Tier intrusion, which being at a lower stratigraphic level uplifts both Permian rocks and the concealed sheet "c" which now caps Mangalore Tier. It is indicated by the concordancies over the uplifted block, benches and rafted sediments. The Mangalore Tier intrusion (S2) is very massive and is considered to be representative of the youngest phase present. It offsets intrusions of age "c" near Brighton and passes as a thick sheet to the south and west. Some traces of it are probably also present in the Brighton Hills at high level as there are a few boundaries and small blocks which are difficult to explain otherwise. It is upfaulted by the Dromedary Fault (f2) and rises transgressively a little west of the fault to cap the Black Hills region, in which it cuts a further sheet rising from S6. All the visible relationships at Broadmarsh indicate that S1 and S2 are connected and of the same age.

It is not clear what form the intrusion took in crossing the Coal River graben. Subsequent faulting has not aided clarification. A line of feeders occupies the approximate line of the east graben fault. These centres have supplied a sheet which, although disrupted by at least one later phase of intrusion ("b"?), is continuous over the whole region east of the Coal River. This sheet is correlated as age "a", on the ground of its probable equivalence with the eastern arm of the sheet based on S7. No direct correlations are possible, since definitive structural or gravimetric interpretation is impossible across the graben structure, although a suggestion is shown in fig. 5, p. 43.

In summary, it may be stated that the intrusions of each age interconnect to form a rolling cross-wave pattern. This is most clearly seen with regard to "c", as "a" or "b" are too often concealed or eroded to show the gross form.

The presence of a sheet, say age "a", in part of the area has forced subsequent intrusions higher in the section. If the centre for the later intrusion is beneath such a sheet, the sheet propagated will transgress steeply to a level above the previous body.

5.3 Feeders

Feeders have been recognised by the substantial positive anomalies associated with various parts of the district. In almost every case there is a direct relation with an exposed dolerite body. The distribution and nomenclature of feeders is shown in fig. 9, p. 102. The random point distribution precludes shallow basement influences. In addition, the gradients reflect both a shallow and deep-seated source for the anomalies interpreted as feeders.

Several of these bodies are probably related, although in most cases the relation is not apparent. It is considered that the Grass Tree-Risdon-Lindisfarne feeders form one dyke in depth (S10). The Craigow-Mt. Rumney-Mt. Mather trend like-

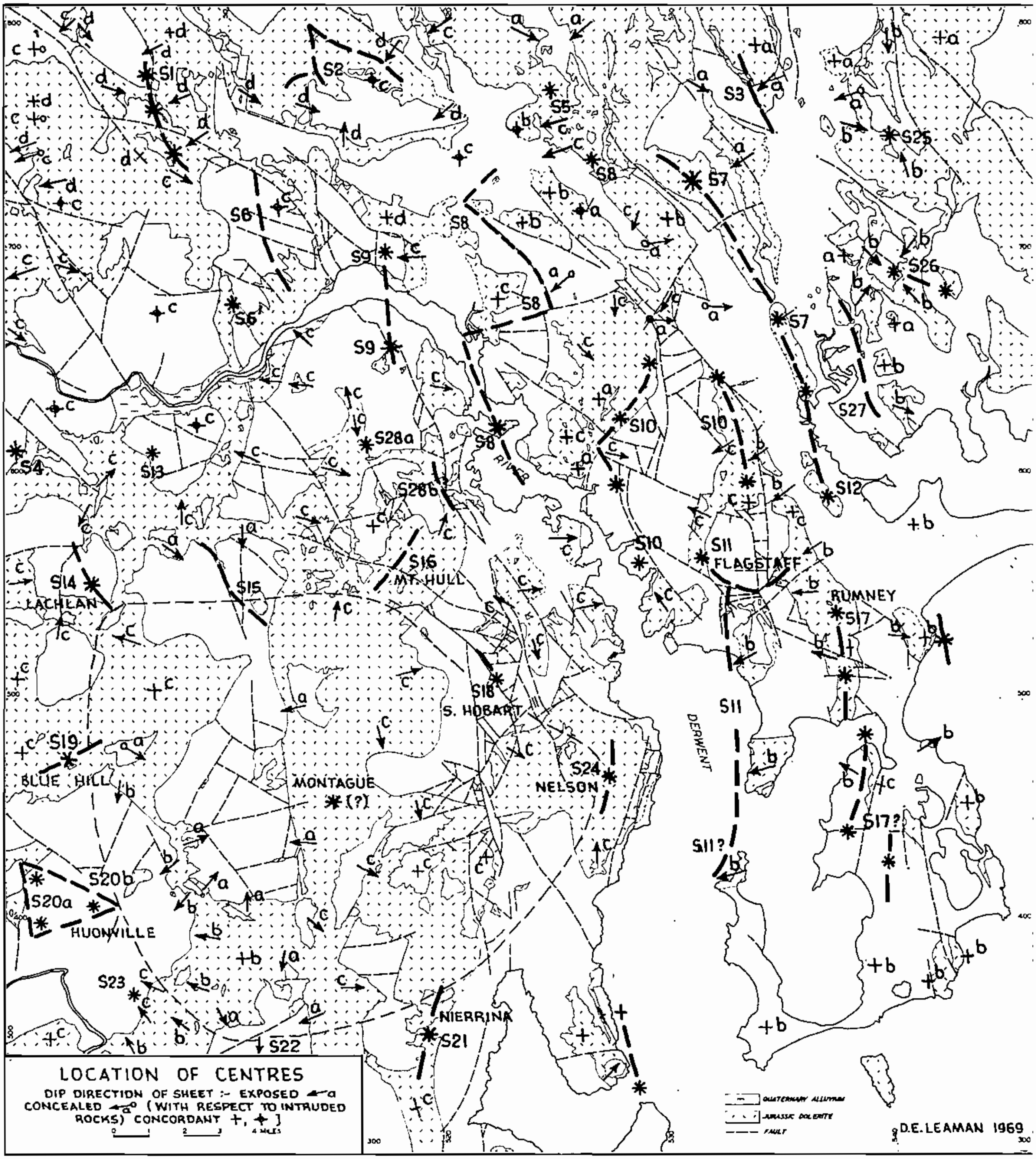

LOCATION OF CENTRES
DIP DIRECTION OF SHEET :- EXPOSED a
CONCEALED a (WITH RESPECT TO INTRUDED ROCKS) CONCORDANT +
0 1 2 3 4 MILES
QUATERNARY ALLUVIUM
JURASSIC DOLERITE
FAULT
D.E. LEAMAN 1969
LACHLAN
BLUE HILL
HUONVILLE
MONTAGUE
MT. HULL
S. HOBART
NELSON
NIERRINA
FLAGSTAFF
RUMNEY
DERWENT
RIVER

Fig. 9

wise also represents a dyke. The actual magnitude of these bodies is unknown, but the anomaly in a number of cases implies either a pipe or dyke up to a mile wide and extending at or near that width well into the crust. When it is realised that the density contrast vanishes in depth, and probably also inverts, an appreciation of the scale of these features and the mass involved is possible. The form of the feeder systems can only be discussed in a very general way.

Most centres appear to be single columns, whereas others show a definite alignment and are probably 'fingers' from a dyke. Examples of fingers are the Grass Tree, Risdon, Lindisfarne sources of S10, the bulges of S1 and the Rumney-Augustus dyke structure. Other sources, such as S7, are clearly dykes. The massive anomalies associated with S20 at Huonville suggest a cluster of pipes in this locality and hence a major crustal weakness.

The distribution map (fig. 9) shows that there is an average separation of 6 to 8 miles(10-13 km). The region enclosed by the broken line possibly contains only one large feeder and that very much smaller than the average. The broad mass deficiency of one or two mgals over large parts of this region, with respect to the regional gravity field assumptions made, suggests that the regional field elsewhere in the district may be too high by this amount due to the cumulative effects of many deep anomaly sources. There is no known reason for the lack of centres in this zone. A small granite stock at depth in the basement would account for the anomaly deficiency and the concentric nature of many other structural features. It could preclude intrusion.

All the feeders indicated in fig. 9 have been located because of their size. Smaller feeding systems may well have been overlooked due to lack of resolution. A further aspect of feeding systems worthy of note is the shape of those structures which have not grossly intruded or disrupted the Permian rocks. Two such features are at South Hobart (S18) and Mt. Augustus (Sect. 425, p. 68), where the anomalies are roughly circular and the gradients imply that the feature is at shallow depth. It is concluded that such structures have a conical termination to a cylindrical pipe, but other mass configurations are obviously possible. Small scale structures of this type are to be seen at Single Hill (fig. 10, p. 113) and Blackmans Bay.

Some pipes or dykes are aligned upon major faults. Such faults are invariably pre-intrusion (Cascades, Coal River east, Lindisfarne graben), and have also been subject to extensive rejuvenation. These faults must reflect fracture systems in the basement rocks. As many feeder dyke orientations show little semblance to the major Jurassic or Tertiary trends, the only possible conclusion is that the bulk of the basement fracturing was slightly oblique to the Jurassic or Tertiary stress field (see also pages 106, 120).

6. PROCESS AND CONTROL OF INTRUSION

6.1 The intrusion environment

Throughout Tasmania dolerite has intruded relatively flat-lying epi-continental sedimentary rocks. At the time of intrusion these formed a large basin some 150 miles by 100 miles(240 x 160 km). The maximum known thickness of Permian and Triassic rocks is about 5,000 feet(1,500 m). It is possible that the actual thickness was of the order of 7,000 feet(2,100m) since it might be expected that any newly deposited, poorly compactdd Lower Jurassic rocks would erode quickly upon uplift. There is a suggestion that, prior to the intrusion underground, basalts existed on the surface. This is inferred from the presence of tuffaceous rocks capping the known succession. The minerals and rock fragments may suggest andesitic volcanism, but this is by no means proven (also Hale, 1962). No deep fault blocks preserve the Upper Triassic-Lower Jurassic succession as far as is known. The block at Richmond has not been bottomed.

The Hobart district appears to have been close to the axis of Permian sedimentation (Banks, 1962, p. 203), but insufficient information about the Triassic rocks is available to determine whether this axis persisted in time. The exposed sequence is among the thickest known in Tasmania.

It is likely that all rocks were flat-lying at the time of intrusion and that the regional and local dips now observed have resulted from Jurassic disruption and Tertiary epeirogeny. At the time of intrusion most of the sedimentary column was subject to brittle fracture. The Permian rocks were probably of comparable density and state of compaction as observed today.

The nature of the basin floor is a key variable determining the basin load and thickness. Relief may exist of 500-2,000 feet(150-600m)(e.g. Maydena, Jago, 1965; Wynyard, Banks, 1962).

Comparison of pre-Permian, Jurassic and Tertiary fault and joint trends throughout eastern Tasmania shows that the same stress field has persisted with time (Williams, 1967, 1969; Marshall, 1968; Legge, 1968). Three main trends are apparent and all appear to have been synchronous; these are NNW-SSE, NE-SW, and E-W with the first the best developed. An examination of many discordant boundaries will show that these trends were occupied by the intrusions (e.g. near 6330N, 5110E).

The environment was in a state of minimum compression and evidence of compressional and transcurrent features is absent. A developing regional continental stress preceded the break-up of Gondwana which presumably occurred in middle Mesozoic times. Some, for example King (1953), have suggested a Middle Jurassic age for this rupture. The overall stress related to this would be NE-SW. Comparable environments exist in other Mesozoic southern hemisphere provinces.

6.2 Magma type and source

Tholeiitic magma is thought to be derived by partial or total melting of more basic material near the Moho junction, or from the upper mantle to depths of up to 100 km; e.g. McDougall, 1962.

The circumstances by which the heat necessary to produce such melting was available during middle Mesozoic times are not known, but as this magma release was global over a restricted period of time (see table 2, p. 148), any explanation must also provide an irreversible global mechanism. Global expansion would provide a pressure release, and in the zones of rupture and stretching, allow isostatic rise of the mantle and associated isotherms. If the hypothesis of global expansion be accepted, a critically irreversible condition relating pressure, temperature, surface accessibility could easily have been reached. Due to the nature of the origin of the magma it might be expected that intrusions would be possible over an extended period. Indeed, the heat flow in Tasmania is still exceptional by normal continental standards (see Gutenberg, 1959, p. 130). Present day remanent stresses are also quite high (Judd, 1964, p. 16).

The composition of the magma has been deduced from examinations of chilled margins which are fairly constant in composition in the few intrusions sampled in Tasmania. From this observation the following assumptions have been made (Edwards, 1942; McDougall, 1962); the magma was very uniform and rapidly intruded as one major pulse. This conclusion ignores the fact that magma derived at different times from the same source region with similar injection rates should have a similar leading tongue, which is all a chilled margin can be taken to represent. Probably, the assumption of rapid intrusion is the only one with validity.

6.3 Magma rise

Dolerite magma is considered to have a maximum density of about 2.65 gm/cc (p. 80), the actual value being determined by water and volatile content. Hence, a density inversion would exist in the upper mantle when magma is present. On pure hydrostatic grounds the excess pressure applied to a magma, as a result of overburden load, is sufficient to lift it to a height of 15-20,000 feet(4.5-6km) above sea level. Standard estimates of present day crustal thicknesses and densities can account for the observed level (Holmes, 1965, p. 251), although it should not be assumed that the same proportions were true at the time of intrusion.

The nature of the melting processes, the general compositional consistency, the conditions of temperature and pressure in the mantle and the massive volume of material required (5-10,000 cu miles for Tasmania alone) militate against there being a magma pool, or that such a convenient pool could exist statically for any time even if it could form. It seems likely, therefore, that the material would be injected as a series of squirts from the one source area, none of which need be very massive. This does not preclude synchronous squirts from different source volumes. This is implied by the semi-interlocking character of the intrusions in this area, some are synchronous while others are not. As this is but a small part of the total province a minor phase here may be more significant elsewhere.

The crustal load presumably acts upon a very large spongy region in the zone of melting since a partial melting process (5-10% by volume) is most likely. Considering the volume required and the area over which the load is applied no isostatic restrictions would apply.

The maximum magmatic pressure will be determined by the load whereas the effective pressure will be controlled by the size of relief passages, viscosity effects and the like.

6.4 Feeders and feeding systems

The distribution of feeders (intrusion centres or axes) is indicated in fig. 9, p. 102. Some alignment of feeders is apparent with regard to observable fault systems. An example is the Grass Tree Hill - Rumney - Mt. Mather axis, to which the Mangalore feature may also be related, parallel to the Bagdad Fault. The string of basalt necks immediately east of this line does imply a major crustal weakness.

It is not possible to state the precise shape of the feeders. Some may be cylindrical or ellipsoidal pipes, and others dykes. All are probably variations on a hand-finger pattern. The dimensions of these structures can only be estimated. Pipe diameters are in excess of one mile(1.6km) and dykes are several miles long. It cannot be stated whether the occupied volume is a fracture or a true pipe, the latter implying ejection of material. There is no conclusive evidence to suggest this might have happened and it can be shown that some feeder systems did not approach the surface directly, as pipes.

Throughout the district, including areas adjacent to centres, there has been no folding or other disruption associated with any part of the intrusions. This property probably reflects the fluidity of the material, in that fracturing and not folding resulted from the applied upward force.

If the feeders are true stoped or explosive vents where has the pre-existing rock material gone? It is possible that many feeders and their high level dykes may have had egress to the surface, in which case all material could be expelled explosively. Other dykes either passed into sheets or terminated at depth (South Hobart, S18; South Arm, S17 ext.). Explosive removal, as a result of gas or fluid pressure, ultimately implies a free vent to the surface and a situation comparable to the diamond pipes of South Africa. In the case of "T" or "Y" intrusions fragments from the pipe would be collected at the roof of the intrusion near the pipe. No evidence of this has been found. It is unlikely that the volume of material removed from pipes of the size envisaged could have passed to the surface by the tortuous fracture routes occupied by most sheets and which probably never reach the surface anyway. In addition, there is no evidence that the dolerite magma was ever rich in volatiles and there is no trace of vesiculation at the higher levels. This suggests that either

1) the gas escaped early and blasted a hole, or

ii) there was little gas present. Metamorphism shows this was not a "wet" magma, or

iii) the roof load was greater than believed and gas confinement occurred.

The first is unlikely as some traces of gas should remain if the material was so enriched. The last possibility cannot be excluded.

Bearing on this problem is the possibility that the Upper Triassic-Rhaetic rocks are tuffs (Hale, 1962). Appraisal of the contained feldspar, mafics and rock fragments is difficult, but if they are indeed tuffs then the implication would be that an extensive period of volcanism preceded the dolerite intrusion. Thus pipe expansion could have occurred. It is unlikely that the vents were situated in the basin since sills would have resulted (see p. 114). A roof load of basalts and andesites could then have been present. This evidence is circumstantial and inadequate but no other explanation of the tuffaceous rocks has been advanced.

However, while it is possible that some feeders were produced in this way many could not have been. How else then, can sub-circular structures be produced? Fracture conditions are unlikely to provide holes of the specification required. A further complication lies in the observation that the scale of tension and fracturing would be Tasmania wide, yet dolerite is rare outside the post-Carboniferous basin. This feature of intrusions has also been noted in South Africa, where it has been suggested that basin extension provides a source of stress release (also Fairbridge, 1949). A genetic relationship between basin and feeders is implied, as those areas outside the basin are generally lacking in dolerite intrusions. Where observed they range in size to one mile by half a mile(1.6x0.8km) and are rarely more elongate than 2:1. In no case is there obvious associated fracturing.

The problem can be resolved if the feeders are fracture fillings, or dykes, at depth but which in plan and section are somewhat bulbous, i.e. they may be lens or cigar-shaped in plan but also have a leading edge of variable amplitude. Fig. 10, p. 113, shows the form of small wedged feeders which have produced no noticeable distortion in the intruded rocks. Thus while strictly sub-circular pipes would not be produced the combinations of these two components could produce the peaking of material and hence anomaly. Active fracturing has then taken place at the peaks of the intrusion - a situation not unlike that proposed for the cone sheets and ring dykes of Scotland (e.g. Anderson, 1935; Richey _et al_, 1961). Such shapes are in accord with a fractured environment (basement) in a state of minimum compression or tension. It does not preclude some wedging of the magma in widening the gaps made available to it.

The nature of the fractures in the basement is unknown. The faults at high level are normal, high angle features. It is likely that most are recent, shallow structures although some of the larger, older faults may represent rejuvenation of concealed basement structures (e.g. Cascades Fault) which may well pass deep into the crust (also p. 92).

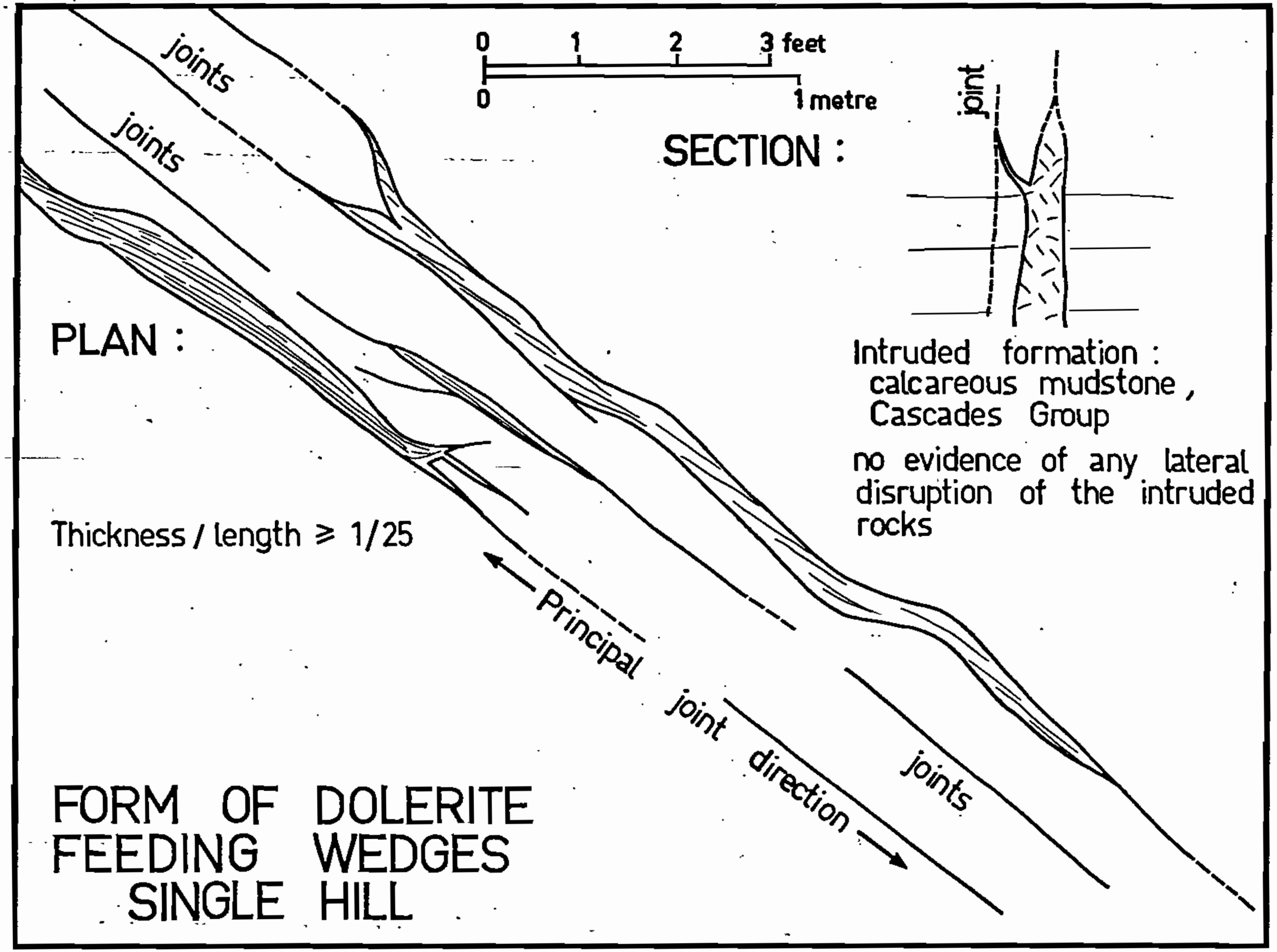

joints
joints
0 1 2 3 feet
0 1 metre
SECTION :
joint
PLAN :
Intruded formation : calcareous mudstone , Cascades Group
no evidence of any lateral disruption of the intruded rocks
Thickness / length ≥ 1/25
Principal joint direction
joints
FORM OF DOLERITE FEEDING WEDGES SINGLE HILL

Fig. 10

As intrusion has taken place in a number of pulses, it might be anticipated that nested feeders would result. The original weakness would be occupied but other weaknesses might be induced nearby.

6.5 Fracturing and consequent intrusion shape

A number of factors may control the fracturing associated with magma injection. These include magma pressure, size and shape of feeding body, overburden load and homogeneity, stress conditions and type of rocks intruded.

Carey (1958a) believed that the dolerite passed through the basement rocks as a pipe, and upon reaching the Permian rocks (or very close to the unconformity) punched out a shear fracture with internal angle of about 45°. This can happen once magma pressure exceeds load plus friction. The precise angle developed depends upon the internal friction of the rock and the whole concept requires transfer of a probable compression, as about the pipe, into a shear. Any heterogeneity, or environmental stresses present, in the fractured materials will also affect the shape of the fracture. It is agreed, however, that the source structure, whether a 'pipe' or dyke, will produce a fracture which will approach the free surface and that the magma will then follow and fill such an opening. He also states (p. 162) that the angle of transgressions flattens from 45° to about 10° in the Triassic rocks. However, Lombaard (1952) would infer that the angle increases as the free surface is approached. Obviously the particular conditions are significant (see also page 119), and although Lombaard is certainly correct in suggesting such behaviour near the free surface the effects at moderate depth (e.g. in mid-Triassic rocks) are unknown.

Once a fracture is produced, by whatever mechanism, it will be followed by the magma since it will be the path of least work done. The region about the unconformity would be very sensitive to vertical stresses, such as the magma would apply, since it is the regime between fractured basement rocks and strongly bedded flat-lying rocks although both are affected by the same tensile stresses.

The concept of a fracture-mould precludes such hypotheses as compensation surfaces (Bradley, 1965), which state that varying load conditions caused the intrusive sheet to rise up and down by a hydrostatic mechanism. This is illogical on three grounds. Firstly, the material must propagate then fill a fracture, and any load or load deficiency of limited extent will cause the fracture to approach the free surface (compare Ramberg, 1967, p. 98-99). Secondly, the fracture will be propagated and its shape determined in advance by stress conditions near the feeder. Thirdly, the forces required to push a magma downward are enormous, as per the compensation hypothesis, particularly in a system as entropic as this. Magma can go downwards if a closed fracture system is present to permit such passage. A variation, of some magnitude, in surface load would cause an immediate upstepping of fracture regardless of concordancy and flotational lift, providing the load exceeds the shear strength across the potential fracture surface to the free surface. If a fracture is already in existence near such a load change, then the intrusion fracture will join it and any intrusion will either pass up it or terminate against it.

Examination of the structures present will show that there has been considerable variation in the fracture form, and that instead of a 45° cone there has generally been a "T" shaped intrusion (see fig. 11, p. 118). This shows that bedding heterogeneity cannot be neglected, and that it exercises considerable control on the fracture system. It may be observed pragmatically that concordant intrusions are of limited extent in the middle-lower Permian rocks, particularly near the feeders. Examples may be seen at Collinsvale (S28), Boyer (S13), Nierrina (S21) and South Arm. In these examples an area four miles by three miles(6.4x4.8km) is the maximum extent of such intrusion before a discordant rising stage is reached. In the Triassic rocks concordancy is more common over larger areas although this is not obvious in this district.

"T" shaped feeder-sheet junctions have been proposed by Mudge (1968). His mechanism requires that a dyke wedge passing upward into heterogeneous sediments reaches a fluid barrier (e.g. a shale; which becomes ductile at depths greater than 3,000 feet (Jones and Pugh, 1948, p. 94; Mudge, 1968)) which prevents passage of the vertical tension fractures and causes parting beneath it. Such a layer may also serve as a vapour barrier confining pressures. It should be noted that intrusion is not a flash process initially and there is a slow build-up of vapour pressure with increasing temperature. Once the pressure is released and fracture commences, the process becomes impulsive. Sill intrusion may then take place provided magma pressures are sufficient and sheathing fluids are present (see also page 126). Mudge in no way specifies the distance the parting fracture will persist parallel to the fluid barrier, and this is difficult to specify mathematically due to the presence of many unknowns. The fluid barriers in the Permian rocks are the calcareous mudstones or limestones. That this process is applicable is undoubted, although the extent of effect is variable (compare Nierrina and Boyer). An additional factor, not included by Mudge, is the effect of sub-parting compression caused by the finite thickness of the feeding wedge away from the tip. Walker (1958, p. 89) has also shown that massive units can prevent vertical dyke penetration and this situation may lead to parting fractures.

All variations between a "Y" and "T" might be expected depending upon the effective presence of partings and fluid barriers. Intrusion base forms within the district are shown in fig. 11, p. 118.

It will also be seen that local controls may affect the shape of the fracture at all points to the surface. The further the fracture is from its source (and closer to the surface), the more likely it is to be controlled by bedding heterogeneity. It would therefore be reasonably expected that the fracture would form a series of steps, and that moderate fracture angles could not be present unless a body of thick homogeneous material were being traversed. The thinner the heterogeneities the more nearly vertical the steps would be.

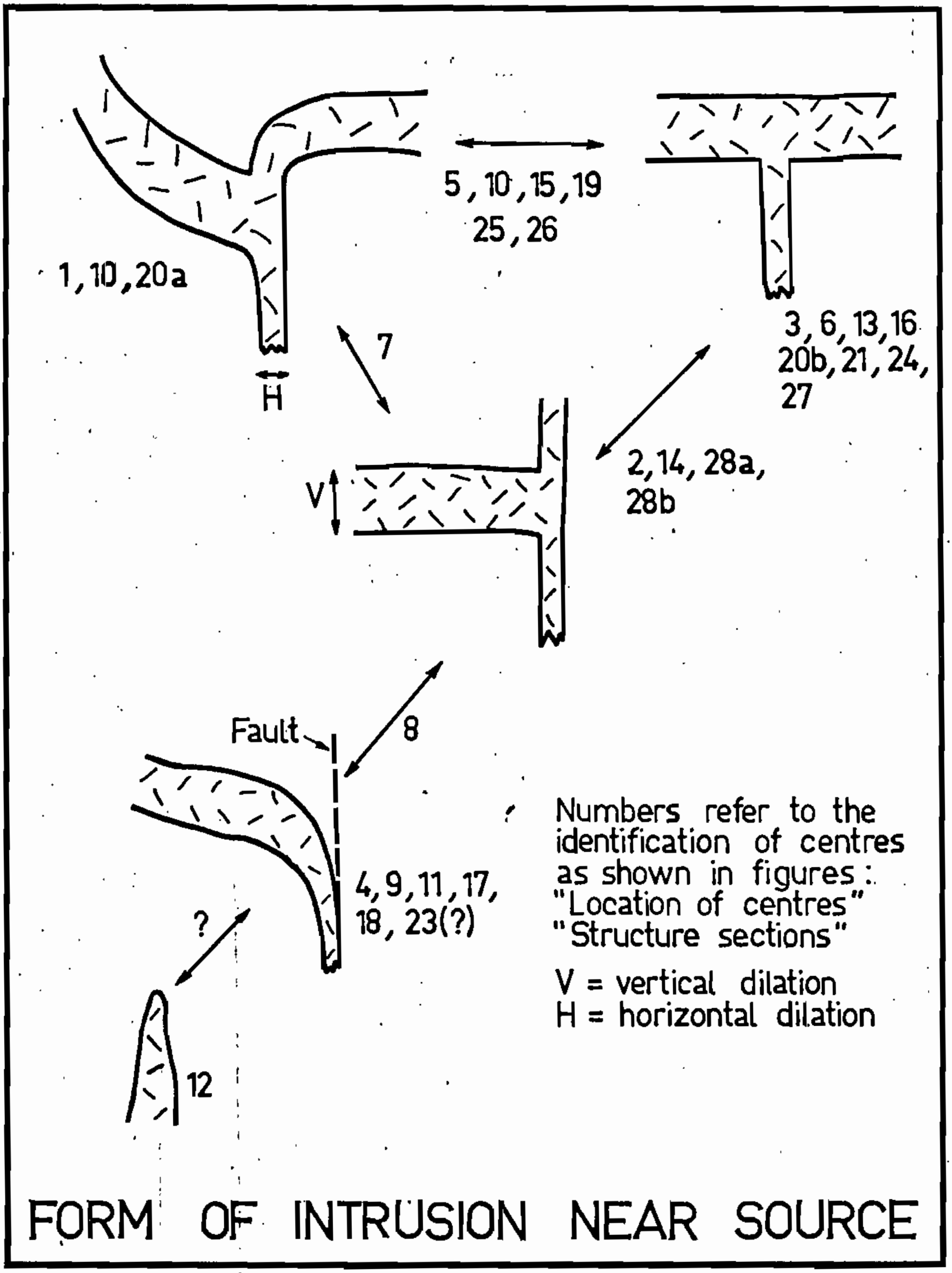

1,10,20a
5,10,15,19
25,26
3,6,13,16
20b,21,24,
27
H
7
2,14,28a,
28b
V
Fault
8
4,9,11,17,
18,23(?)
?
12
Numbers refer to the identification of centres as shown in figures: "Location of centres" "Structure sections"
V = vertical dilation
H = horizontal dilation
FORM OF INTRUSION NEAR SOURCE

Fig. 11

The level of any "T" may be related to the depth at which the excess buoyancy of sediment over magma equals the tensile strength of the potential parting surface.

It will be observed that this argument appears to preclude magma intrusion, by sill wedges, close to the surface. At distance, where the fracture may die out, this is not so although it should be remembered that the body behind the wedge may be thick and will tend to tear the fracture tip upward (see also p. 126). Thus a balance must be struck between horizontal stress, parting strength and amount of overburden. Jones and Pugh (1948, p. 93) have also noted that certain layers in a heterogeneous succession might be more suited to lateral intrusion depending on their particular properties. The fracture process is dominant near the source and the shape of the intrusion cannot be controlled by the magma itself close to the feeder as suggested by Bradley (1965).

An example of the control of loading on fracture is seen on Skye where sills(sheets) intrude a pitching syncline but are not concordant with it. Rather they show intrusion such that magma pressure matched the load pressure which was constant and substantial due to lava cover. That the intrusions cut the sedimentary rocks in such a fashion shows that a fracture was being followed (Anderson and Dunham, 1966).

A further control on the form of the high level fracture not mentioned previously is that of the stress condition of the area at the time of intrusion (see page 106). Dolerite intrusions occupy trends related to the main trends that have persisted over a long period and such occupations suggest a secular persistence of stresses. This means that the inherent tensile stresses, close to the free surface anyway, exerted significant control on the intrusion fractures. Examples may be seen northwest of Mt. Faulkner where the interrelation of the three main trends is clear. Elsewhere other steep dolerite boundaries show one or other of these trends. Elongation of the feeder sytstems, however, only partly reflects such trends. The South Hobart (S18), Nelson (S24), Boyer (S13), Lachlan (S14), Huonville (S20), Collins Cap (S15), Bridgewater-Faulkner (S9), Craigow-Rumney (S11), Mangalore (in part, S2), Brains Hill (S7) and Pittwater structures generally show a N-NNW orientation while Nierrina (S21), Craigow-Flagstaff and Grass Tree-Risdon (S10) show a NNE trend.

In summary, fracturing at high levels is induced by the feeder pressures but the feeder and fracturing need not be central or truly conical. Any asymmetries of form laterally or vertically can be related to boundary conditions prevailing in the rocks as a result of tensions or heterogeneities. Any fractures produced will be immediately filled by magma although there are limitations (p. 84). It may well be that at some distance from the source of fracturing, the magma will propagate a fracture and then fill it (p. 126). Such propagation is passive horizontal parting, and quite distinct from the active vertical-horizontal wedge-shearing that occurs about the feeder.

Such a mechanism provides for the slivers of material that "peel" away from major bodies. These minor intrusions represent filled fractures but which, with the development of other nearby fractures to full size, have been limited in growth (see comments p. 84). In addition, great care must be exercised in stating the source direction of the magma in a particular fracture if it shows an arch. Many such arches are illusions being, in the third dimension, just a kink on a rising surface. In reality, magma has not 'fallen' at all. Instances may be cited where a dome has formed (e.g. Mt. Wellington cap). This can only mean that the magma from several sources is synchronous although the fractures occupied need not be. It is possible that if the fracture system shows doming, a most unlikely occurrence, magma from one source could fill the system, providing the pressures were sufficient. Studies in this district show that domes merely represent either points of coalescence of synchronous bodies from individual centres or places of intersection giving dome illusions.

In the case of the nested sheets of Glen Grey, South Africa (Du Toit, 1905) all that is implied is a series of repeated synchronous intrusions each producing a fracture system which is sub-parallel and above (p. 123) the one before it. The comparative homogeneity of the rocks intruded accounts for the regular angle of the fractures.

The presence of pre-intrusion faults or major joint systems is the one remaining aspect of fracture control of some significance. Some faults have been definitely categorised as pre-injection and in every case major upsteps have taken place along them. The effect of any joint systems cannot be fully estimated but it is likely that many of the concomitant features originated in this way. It should be observed that the intrusion or fracture system need not totally follow pre-existing structures, or to the surface, as each intrusion is three-dimensional and only a partial component will utilise them.

6.6 Parameters of intrusion

Injection of magma is controlled gravitationally (p. 108). Due to the inability to specify the total load on the magma source the potential magma pressure is unknown. The actual pressure at the point of flaring is somewhat less due to the effects of friction losses, viscosity and compressibility variations.

There is no evidence of high level forcible intrusion and the intrusion was probably relatively rapid although estimates can not easily be given of speed (see discussion, p. 124). The intrusion has taken place by filling and expansion of fractures. As the magma density would be about 2.6-2.65 gm/cc, and the average intruded rock density less than 2.3-2.4 gm/cc, it would be expected that the block of material dislocated by each fracture and filling would float upon the magma. Thus while the density of the sedimentary column remains low, little or no magma could ever reach the surface even if free openings were available (Bradley, 1965, p. 40). The magma was under a limited pressure since only a limited sheet thickness is supported by any given intrusion.

As the magma nears the base of the lower density rocks it passes a point at which the overburden load is less than the magma pressure. The magma could thereafter intrude laterally and do less work than by proceeding to the surface. In those areas where folded basement rocks (density 2.6-2.7 gm/cc) were present any feeder dykes would pass through since there is no trigger for fracture (see also Carey, 1958b). At any time after the pressure exceeds the load, the roof rocks can be sheared and lifted, the actual site of fracture instigation depending on the features discussed on page 114.

In Tasmania, the lowest known intrusions occurred 5-7,000 feet(1.5-2.1 km) below the Jurassic surface. The pressure to lift this load is not less than 7,000 lbs/sq in.(5×10^5 gm/cm^2). The loss due to the shearing and delay in horizon occupation is inestimable. However, Mudge (1968) arrived at a similar figure for magma head in similar intrusions in the United States. The figure stated above would be increased if a lava plateau was in existence. If the roof is now lifted by 1,200-1,500 feet(350-450m), i.e. the thickness of emplaced sheets, then the magma pressure must have been 6.2×10^5 gm/cm^2(pressure to put dolerite on the surface: 6.8×10^5 gm/cm^2).

If the pressure of magma from a given source is less than 6×10^5 gm/cm^2, or the column has been loaded by previous intrusion then the subsequent intrusion must take place at a higher level and probably above any previous body. In the limit this means, that even with a very low pressure, magma can be extruded provided the roof rocks available for intrusion are either very thin, or very dense, i.e. contain many intrusions (also Bradley, 1965, p. 53 - on S. Africa).

If the magmatic pressure is variable, the location of fractures will be variable, and if the pressure is greater than 6×10^5 gm/cm^2 intrusion can be initiated below a previous intrusion (e.g. S10). The magmatic pressure on S10, compared with that calculated theoretically on maximum depth, probably reflects a larger, freer channel with fewer energy losses. This also shows that given appropriate conditions the energy was available to put magma on the surface.

If the effective magmatic pressure is varied, as a result of pipe or other constrictions, it is possible that a large sheet fed from several points may show thickness variations and steps, or tilt the roof blocks. It is possible that the Collins Cap-Grove sheet which appears to show such thickness changes was formed in this way. Lombaard (1952) has made similar observations.

Using the values estimated for the intrusion pressure it is possible to gain some idea of the rate of intrusion. An orifice 0.5 miles(0.8km) in radius is assumed in the calculations below. Consider the Boyer intrusion as an example (S13). The sedimentary roof load was about 10^{18} gms. Once the roof was fractured, the initial upward acceleration of the roof can be directly calculated from Newton's second law as 12 cm/sec^2. Thus in the first second the roof is lifted 6 cms. These figures are probably maxima, as no allowance has been made for the elastic recoil following fracturing which will be the critical impulsive term during the first second. Assuming a conical fracture, the volume of magma emplaced is about 10^{13} cm^3. This volume passed through a pipe with area 2×10^{10} cm^2 in one second. Hence the velocity of the material in the pipe was 5×10^2 cm/sec, and the flow laminar. At these rates, assuming no pulsations, it would have taken 10^4 to 10^5 seconds to emplace a full sheet. This time does not include the effects of supply restrictions, diminishing rate of uplift and fill with time and is clearly a minimum. It does show, however, that the total emplacement time could have been very short - perhaps of the order of a year.

The above approach is very simple, but serves to give an indication of intrusion rate. The process is not accelerative as it soon reaches a terminal velocity determined by viscosity, density, volume and supply requirements.

6.7 Sill intrusion

Of all the aspects of the hypabyssal intrusion of dolerites that of sill intrusion is perhaps the best known. Sills result from two processes, each of which may have common controls determined by the intruded rocks.

Sill intrusion may take place along a pre-existing fracture or bedding parting. The fracture may have been produced as a result of pressure transfer at the time of injection from the feeding column. Such a fracture may not persist concordantly from the propagating centre, the distance being controlled by horizontal heterogeneities. This process was realised by Anderson (1938).

Alternatively, intrusion may take place by the method proposed by Bradley (1965) or Mudge (1968). These authors envisage sill propagation as a self-reproducing process, in that a sill wedge intrudes a well-defined parting surface under a fluid barrier or seal. The role of water or steam pressure is unknown but it is thought that the confining pressure under the temperature conditions involved is sufficient to aid the splitting process (Jones and Pugh, 1948, p. 94; Bradley, 1965, p. 39). Neither author states how the wedge started away from the feeding column but a fracture is implied. If the initial fracture was of restricted extent then it might be expected that one horizon might be occupied for some distance due to self extension. This process ignores the tendency of the magma to approach the free surface and when, or if, the distance and pressure gradients are critical it must break upward to a parting at a lower potential. Bradley (1965, p. 36) was aware of this occurrence and good examples are seen at Boyer, Nierrina and also at Victoria Land (Hamilton, 1965). Well away from the intrusion source and particularly high in the intruded sequence, where the intrusion is reaching nil potential, this process will be the only one available. The magma could not easily force higher in fractures even if they were available. Thus consistent horizon propagation would be expected high in an intruded sequence.

The wedge hypothesis does involve some assumptions and limitations not noted by Bradley (1965). In the limit their application may preclude or halt intrusion by this means. The angle of the wedge must be small or else ragged edges will develop due to fracturing over the wedge. Further, as the material in any wedge chills quickly, the process must be very rapid in order to intrude cleanly. There is no reason to suppose that initiation of a sill could not take place at or near the fracture velocity in the medium. Obviously, further from the source there will be a lag between fracture and fluid fill. Bradley also noted (p.36) that if there is a low angle wedge there is much unsupported roof and a raised magma pressure is needed to support it, and that forcible and not flotational intrusion is the appropriate process. Once a tongue of material is emplaced the intrusion becomes flotational.

6.8 Roof uplift and plug intrusion

Many examples of direct roof uplift have been observed within this district. This structure is characterized by a continuous sheet with a dyke or plug "bubble" in the roof. The best example is that of the Red Hill dyke. Many other plugs throughout the upper parts of the Triassic rocks pose similar problems. These features have variable shapes and relief above the supporting sheet, are closed in form and often have a sub-rounded outline. The only means of emplacing such features, without disruption of the intruded rocks, is to push the roof upward. There is no direct evidence, in most cases, of associated faulting or fracturing due to any causes. These structures are rarer in the Permian rocks. Production of such a structure implies either roof weakness or vertically directed stresses. The latter are only possible in association with feeders, particularly in the case of deeper rocks, and in fact feeders or possible feeders are close to the Permian cases (Red Hill, Mt. Hull).

The lack of bowing and distortion about plugs in Triassic rocks indicates that these were not generally in a soggy, plastic condition but were capable of tensile fracture. The rapidity of the process may be significant here. If the sedimentary column has suffered two previous intrusions, intrusion below the level of Upper Triassic rocks is precluded. The excess pressure differential may be substantial since the load-pressure balance may have occurred below one of the previous bodies and, if lateral fracturing is prevented, all force may be applied to the weakest rocks in the column. Marked irregular disruption would occur and vertical intrusions of no particular form would predominate. This is not common in the area under study since there are few places where the lower horizons have been fully occupied, thereby forcing feeder pressures upward. There are few chunks of high Triassic-Jurassic rocks visible to examine.

Similar structures have been observed elsewhere. Lombaard (1952) has described cupolas on sheets leading to further fracturing and intrusion. Anderson and Dunham (1966) found similar plugs and irregularities on the sills of Skye.

6.9 Multiplicity of intrusion phases

It was deduced in Section 4.4, p. 83 that more than one sheet in a column requires multiple injection with a period greater than the crystallization time. The structural configuration of the intrusions (fig. 4, folder) verifies this conclusion in practice.

The first intrusions to occur should be the simplest in form due to relative paucity of faulting and lack of differential loading of other intrusions. Subsequent intrusions are affected by fracturing induced by earlier intrusions, the effect of loading and magma pressure (see p. 123).

Four, and possibly five, pulses of intrusion are indicated within this district (Sect. 5.1, p. 91, fig. 8, p. 94). However, there is no evidence to suggest that each major sill has itself been built up of many minor pulses of intrusion having close proximity in time. The implication is that a major sill represents one surge of material and that it fills fractures to the thickness that the pressures can support. Modern volcanism would suggest an oscillation of magma input during intrusion but no obvious evidence of this is present.

Extended intrusion should be anticipated in all provinces as a direct result of the mechanism of magma production not being a flash process. Within this area period "c" appears to represent the major pulse, but this is probably an illusion since much of the material intruded in the other periods has been eroded.

6.10 Termination of intrusion

Termination may be used in the particular sense of one body or in terms of the whole intrusive phase.

Some aspects of the former have already been mentioned. Vertical constrictions or pressure dissipation would prevent intrusion. It might be expected that intrusions would lens out and dissipate as local wedges and tongues (e.g. Skye:

Anderson and Dunham, 1966). No information on this subject is available in this district.

In the latter case the intrusive province would cease to be active if the supply of magma was cut off, either in transit or at source. Changes of conditions of temperature and pressure and perhaps crustal saturation with pipes are important. Subsequent intrusions approach more closely to the surface, whether or not they start deeper (see p. 123). As the sedimentary pile is loaded the magma is forced higher before intrusion can take place. It would ultimately reach the surface as volcanic activity, if the magma supply were maintained. There is no direct evidence of Jurassic volcanism in Tasmania, although the feldspathic, lithic rocks of the Upper Triassic imply concomitant and pre-intrusion volcanism (see p. 111). The evidence is admittedly poor.

7. CONCLUSIONS

Dolerite intrusions at all scales within the Hobart district are inclined, stepped sheets (chonoliths), which have resulted from four or five substantial pulses of injection. Each intrusion has a crude trough or basin shape and a dyke or pipe feeder is associated with the intrusion base. Although previously called cone sheets these intrusions are not directly comparable with the originally defined sheets of Scotland. Indeed, many probably have a "T" fracture system above the feeder rather than a "Y". As mentioned by Carey (1958a) such sheets occupy a fracture system, at least near the feeder, and generally become horizontal as the free surface is approached.

The feeders generally occupy wedged fractures and have local pinnacles which may be comparable to pipes. Above the vertical feeding wedge a series of fractures is instigated of which those at the level of critical overburden pressure will be adopted - and then only if partings, confining pressures and barriers are present to provide a preferential selection. In the Permian rocks the calcareous members of the Bundella Mudstone and Cascades Group have provided these properties at about the level of effective pressure - load. The fractures have been produced by direct shearing above the feeding wedge or by splitting due to water pressure confinement below impermeable strata. The latter factor is probably very significant at the higher levels of the intrusion. Regardless of process it is unlikely that a sill would propagate far from the source while the potential is high unless strong heterogenetic controls are present (unconformities, bedding). Only Carey (1958a) and Bradley (1965, p. 36) have noted this tendency to split upward and suggest mechanisms of intrusion with respect to this observation. As the nil potential for the magma is approached concordancy will then dominate and the sill will self propagate until the friction forces overtake the pressure available, which is diminishing rapidly with distance from the source. No clear terminations have been seen in Tasmania.

Sills are not observed to have a wide areal extent, probably as there is no unbroken expanse of Triassic rocks in which to find them. However, in the past there has been a tendency to say that because a sill occurs in Cascades Group at many points across the area that it is one and the same body. Thus on this logic it might be said that because two horizons are commonly occupied (right physical properties at the appropriate pressure levels and therefore relatively fortuitously) that there are two consistent sills. Dyke limbs are then passages to high level for such sills. It is generally a dangerous assumption but one which has often been made (e.g. S. Africa, Du Toit (1954); Guyana, Hawkes (1966a, b); Antarctica, Hamilton (1965), McKelvey and Webb (1959)). Close examination of maps shows that this solution is possible but not necessarily true. Drilling or continuous outcrop is required but is rarely present. In view of the experience gained in this district it is believed that many of the idealised(?) sections so common in the literature will be found to be inadequate under close examination.

Widespread sills probably reflect feeder separation. In a region of few centres the proportion of vertical or lateral forces would be less and more persistent sills might be anticipated. This is especially so away from the centres. The presence of synchronous or pre-existing intrusions is important as these affect the local environment.

Under static head conditions subsequent intrusions will approach the surface as a direct result of column loading. If the magma supply is sufficient, determined largely by the continuation of the processes producing melting, a lava plateau would result. No evidence of a Jurassic lava plateau is preserved today.

The pressure on the magma was at least 7×10^5 gm/cm^2. Assuming an 11 km, 2.67 gm/cc Sial and a 24 km, 3.00 gm/cc Sima, a pressure of about 8×10^5 gm/cm^2 is possible assuming the magma to have a density of 2.65 gm/cc. Such calculations show that the dolerite could not have been derived from depths much greater than the Moho, as the density potential shows very rapid expansion thereafter. A corollary to this observation is that the Antarctican dolerites which are very similar compositionally were also intruded under a similar pressure whereas the South African dolerites were under much greater pressures using the theories here developed, are not as tholeiitic and therefore were derived from a greater depth.

The petrological studies so far undertaken are not, in the writer's view, adequate to permit the conclusions that have been made on uniformity of material and one major intrusion. Further detailed examinations are necessary as only limited deductions are possible from chilled margin or grain size studies. Granophyres are directly related to feeders, e.g. Red Hill, Hickmans Hill (McDougall, 1962) to Nierrina centre (S21); Flagstaff Hill to S10/S11, and are generally rare. Other granophyres have been noted at Single Hill and Battery Point. The granophyre - feeder relationship implied and the residual anomaly values suggest a feeder just offshore in each case. Some of the previous petrological conclusions such as those of Edwards (1942) on bottomless dykes may need re-examination. His example of Gunnings Sugarloaf is predominantly a thick sill fragment with a narrow marginal feeding dyke. He believed the whole hill to be a very wide dyke.

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APPENDIX ONE

COMPARISON WITH OTHER PROVINCES

The term 'province' refers to a region which has undergone a major basic hypabyssal intrusion irrespective of age. Table 2, p. 148 shows the similarities and characteristics of the intrusions which any mechanism must explain. Excluded from the table are those provinces which are minor, and which have been compared by Mudge (1968).

At the time of intrusion most provinces were receiving fresh-water sediments in relatively stable continental environments. The intrusions terminated sedimentation. Two exceptions to this state are the North American Palisades province, which in places had suffered marked tilting prior to intrusion, and the English Whin Sill province about which few details are known as to thickness and attitude of the intruded rocks at the time of intrusion. In each case, except for parts of the Palisadan province (e.g. Hotz, 1952, 1953), the intruded rocks were sub-horizontal and still are. The basement rocks are everywhere a mixture of folded or crystalline rocks.

The thickness of the flat-lying sedimentary cover varies from province to province. In Tasmania and Antarctica the maximum thickness is of the order of 5,000-7,000 feet (1,500-2,100 m; Mudge, 1968) whereas the Karroo systems of South Africa average 10-20,000 feet (3-6,000 m; Du Toit, 1954). Reliable estimates are not possible for other provinces.

Little is known of the feeders anywhere. In the Hobart district large pipes and dykes about a mile (1,600m) in diameter have been suggested (p. 103). Plugs of dolerite up to one mile long and half a mile wide have been observed in pre-Permian rocks elsewhere in Tasmania (sheets 39, 44 geological atlas, Geological Survey Tasmania). In South Africa only narrow dykes have been observed in the basement complex. These are usually much less than 100 feet (30m) wide (Du Toit, 1920; Lombaard, 1952; Walker, 1958, 1959). In the Guyana province of South America dykes up to 1,800 feet (550 m) wide are present (Hawkes, 1966a, b). The Whin Sill of England and the sills of the Scottish provinces, e.g. Skye, are fed by small dykes less than 200 feet wide (Holmes and Harwood, 1928; Anderson and Dunham, 1966). Little information is available on other regions.

Every province contains stepped sheets and dykes on various scales, but only in Tasmania and South Africa have basin or "conical" sheet structures been suggested or described previously (Carey, 1958a; Sutherland, 1966; Du Toit, 1905, 1920; Walker and Poldevaart, 1949; Lombaard, 1952; Walker, 1959). Similar structures may be inferred from the sections of Hamilton (1965) for Victoria Land, Antarctica. The flat-bottomed "basins" of Hotz (1952, 1953) are not directly comparable due to the slight differences in intrusion environment.

Volcanism cannot always be shown to be related to the underground activity, and often there is argument as to whether it precedes or follows it (Du Toit, 1920; Lombaard, 1952; Bradley, 1965). However, the consensus of evidence would suggest both pre-, post-intrusion volcanism in South Africa (Lombaard, 1952); pre-intrusion volcanism in Skye (Anderson and Dunham, 1966); apparently contemporaneous volcanism in the Serra Geral rocks of South America (Oliveira and Leonardos, 1943; McDougall and Ruegg, 1966), and an uncertain relationship in Antarctica (Gunn and Warren, 1962). No volcanism can be proven conclusively in relation to the dolerites of Tasmania and England.

TABLE 2: Dolerite Provinces - basic facts

Province	Approx. age $x10^6$ yrs.	pulses intrusion est.	sheet scale (feet)	scale of prov.
Tasmania	mJ 160-168	≥ 4	1000-1500 1800	moderate
Antarctica	mJ *+ 147-175	≥ 4	600-1000	moderate
South Africa	J + 154-190	7	100-300 av.	v. large
North America	Tr-J	≥ 1	1000av	small
South America: Guyana	pE	≥ 2 (implied)	1000-1200	moderate
Brazil	J-K o 120-126	≥ 2 (implied)	-	v. large
Britain: Whin Sill	post-Carb.	≥ 1	80-100av 240	v. small
Skye	Tertiary	≥ 2	-	small

* Webb and Warren, 1965

\+ McDougall and Ruegg, 1966

o McDougall, 1963

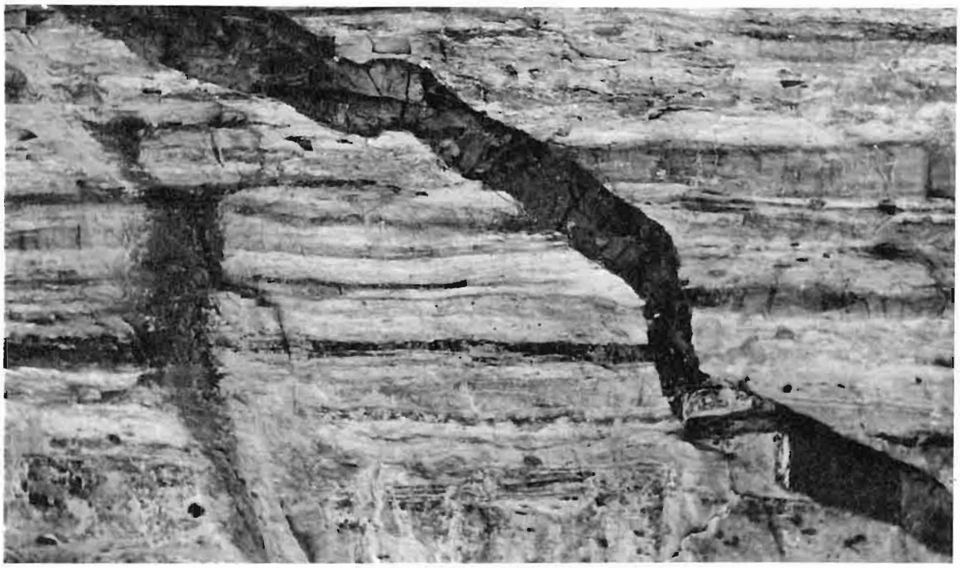
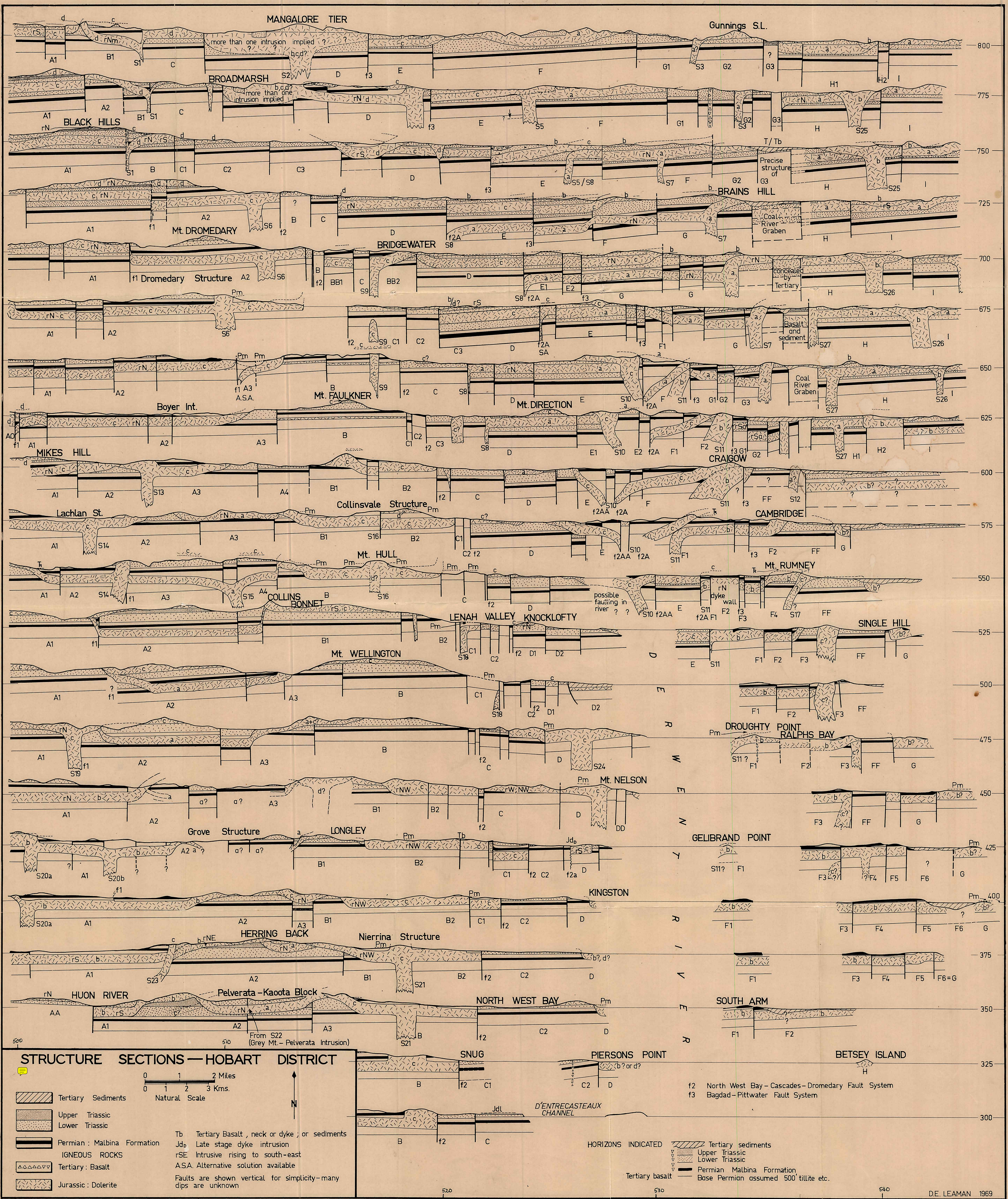


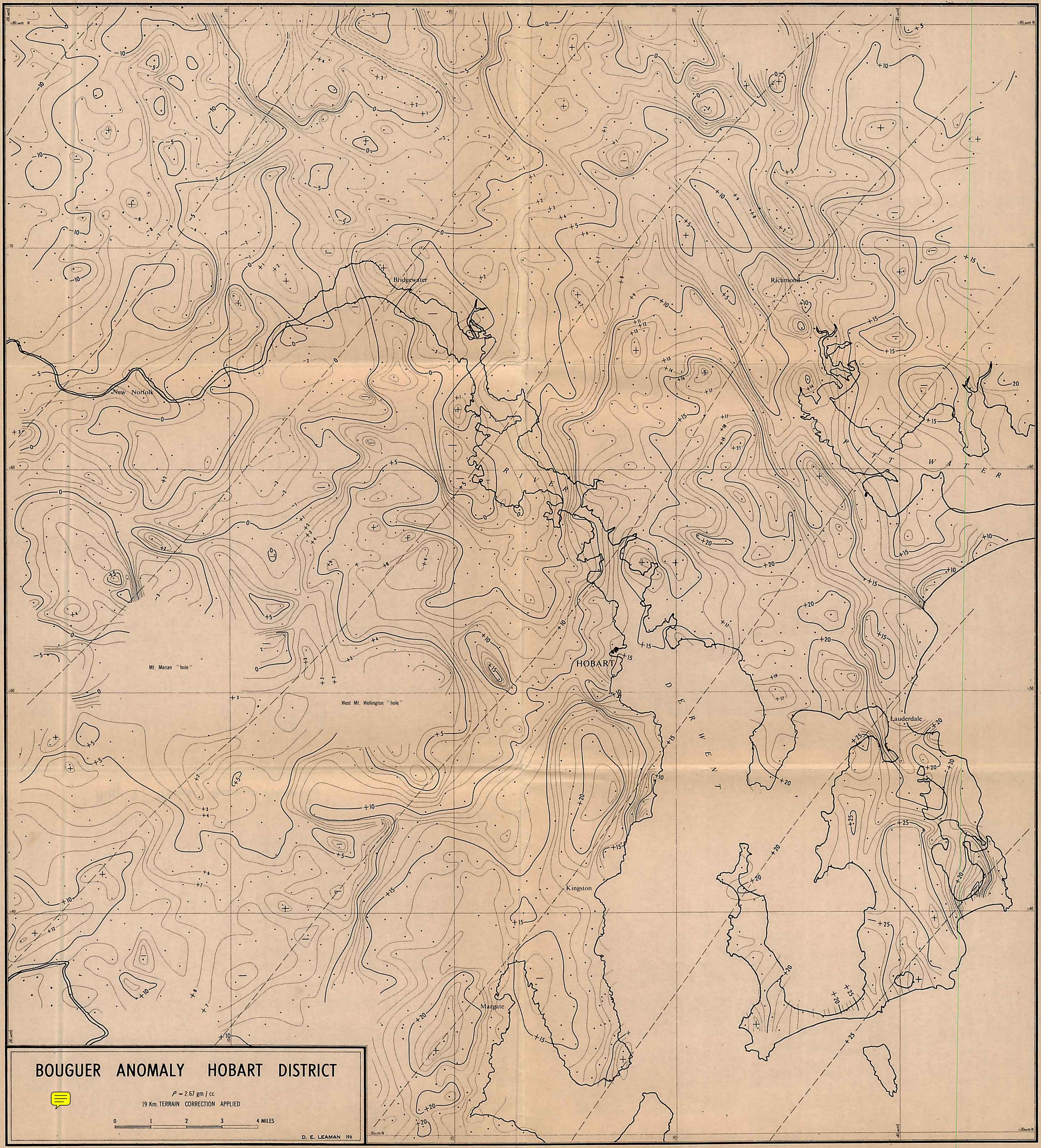
Plate 1: Dilation associated with small inclined sheet, Sihgle Hill.
Vertical component approx. 8 inches
Horizontal component approx. 4 inches

Plate 2: Form of granophyric bodies, Single Hill. Late stage dyke, intruded near intrusion boundary, shows chilled margins (see Everard, 1968). Various ages of fracturing are also apparent.

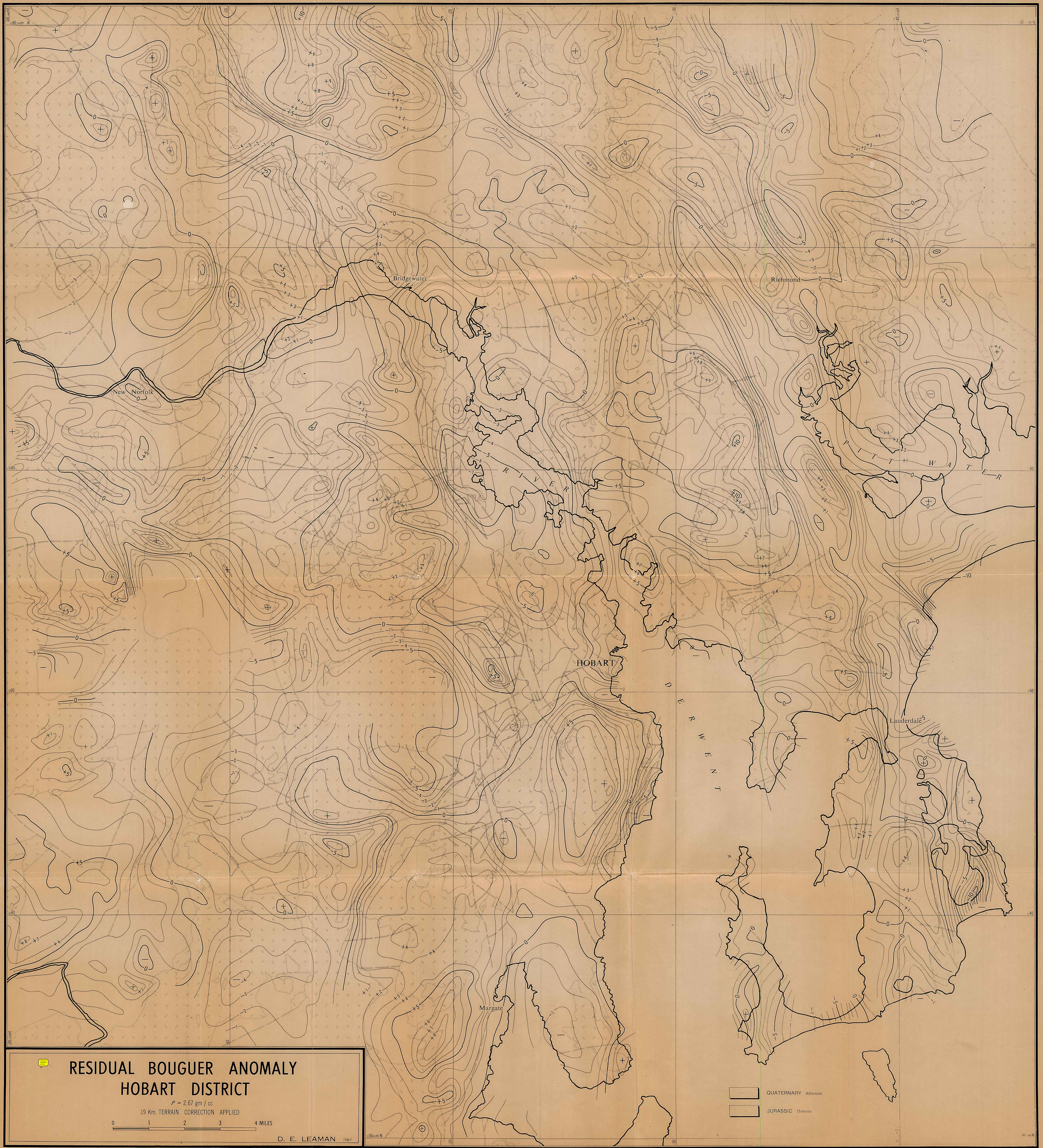
NAME INDEX

The list below includes all geographical place names, and all structure names with a geographical component, referred to within the text. Where the name occurs on a figure feference is given, otherwise coordinates are provided.


STRUCTURE SECTIONS — HOBART DISTRICT
MANGALORE TIER
Gunnings S.L.
BROADMARSH
BLACK HILLS
Mt. DROMEDARY
BRAINS HILL
BRIDGEWATER
f1 Dromedary Structure
Coal River Graben
Boyer Int.
Mt. FAULKNER
Mt. DIRECTION
MIKES HILL
CRAIGOW
Lachlan St.
Collinsvale Structure
CAMBRIDGE
Mt. HULL
Mt. RUMNEY
COLLINS BONNET
LENAH VALLEY
KNOCKLOFTY
SINGLE HILL
Mt. WELLINGTON
DROUGHTY POINT
RALPHS BAY
Mt. NELSON
Grove Structure
LONGLEY
GELIBRAND POINT
KINGSTON
HERRING BACK
Nierrina Structure
HUON RIVER
Pelverata-Kaoota Block
From S22 (Grey Mt.-Pelverata Intrusion)
NORTH WEST BAY
SOUTH ARM
SNUG
PIERSONS POINT
BETSEY ISLAND
D'ENTRECASTEAUX CHANNEL
DERWENT RIVER
0 1 2 Miles
0 1 2 3 Kms.
Natural Scale
N
Tertiary Sediments
Upper Triassic
Lower Triassic
Permian : Malbina Formation
IGNEOUS ROCKS
Tertiary : Basalt
Jurassic : Dolerite
Tb Tertiary Basalt, neck or dyke ; or sediments
Jdp Late stage dyke intrusion
rSE Intrusive rising to south-east
A.S.A. Alternative solution available
Faults are shown vertical for simplicity - many dips are unknown
f2 North West Bay - Cascades - Dromedary Fault System
f3 Bagdad - Pittwater Fault System
HORIZONS INDICATED
Tertiary sediments
Upper Triassic
Lower Triassic
Tertiary basalt
Permian Malbina Formation
Base Permian assumed 500' tillite etc.
D.E. LEAMAN 1969



Bridgewater
Richmond
New Norfolk
HOBART
Kingston
Margate
Lauderdale
Mt. Marian "hole"
West Mt. Wellington "hole"
R I V E R
D E R W E N T
BOUGUER ANOMALY HOBART DISTRICT
ρ = 2.67 gm / cc
19 Km. TERRAIN CORRECTION APPLIED
0 1 2 3 4 MILES
D. E. LEAMAN 196


Bridgewater
Richmond
New Norfolk
RIVER
PITT WATER
HOBART
DERWENT
Lauderdale
Margate
QUATERNARY Alluvium
JURASSIC Dolerite
RESIDUAL BOUGUER ANOMALY
HOBART DISTRICT
ρ = 2.67 gm / cc
19 Km. TERRAIN CORRECTION APPLIED
0 1 2 3 4 MILES
D. E. LEAMAN 1969