

THE GEOLOGY OF
THE MOUNT LYELL MINES AREA, TASMANIA -
A RE-INTERPRETATION BASED ON STUDIES AT
LYELL COMSTOCK, NORTH LYELL
AND THE IRON BLOW AREA

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'I can hardly imagine a more interesting subject for an enthusiastic student of the natural sciences to investigate than this very Mount Lyell mine, ...'

E.D. Peters, 1893



Frontispiece: View north-west over Mt Lyell mine workings and Gormanston township from Owen Spur. Face of North Lyell Fault is visible at right hand end of workings, with Mt Lyell range behind. Mt Dundas in background.

'... we may anticipate with every confidence that these gold deposits will descend to very great depths, and thus be practically inexhaustible.'

G. Thureau, 1886

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

A handwritten signature in black ink, appearing to read 'Corbett', with a stylized, cursive script.

K. D. Corbett

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ABSTRACT

This study is based mainly on detailed mapping of the Mt Lyell mine lease, particularly the Lyell Comstock, North Lyell and Iron Blow areas, with the aim of clarifying the relationship between the volcanic schists and the Owen Group conglomerate sequence, determining the general nature of the alteration zone and the setting of the various orebodies within the zone, and reconstructing the geological history of the area.

The upper part of the Mt Lyell system is preserved at Lyell Comstock, where the alteration zone cross-cuts the upper andesitic unit of the Central Volcanic Complex and culminates in the basal unit of the overlying Tyndall Group. An exhalative zone is present in the Lower Tyndall, consisting of small lenses of massive lead-zinc ore associated with breccias containing clasts of chert and sulphide, and showing strong sericite-pyrite alteration at the base. Also present are lenses of limestone, many containing abundant fossil fragments of late Middle Cambrian age. Alteration and mineralisation die out rapidly up section, and the volcanoclastic rocks of the Middle and Upper Tyndall Group clearly post-date the alteration, providing unequivocal evidence of a Cambrian age for the system.

Within the upper part of the alteration zone at Comstock are numerous bodies of pale cherty silica ('silica heads'), wrapped around by sericite-pyrite schist. The chert bodies culminate in the 300 m wide mass of the Comstock chert body which caps the system. This huge mass of chert, up to 200 m thick and extending at least 600 m down dip, has discordant lateral margins, and, like the other chert bodies, is largely of replacement origin. Numerous veins and masses of bright red hematite- jasper- barite material cut the chert body, indicating a major period of oxidation. The presence of clasts of this distinctive red vein material in the Middle Owen Conglomerate along the Great Lyell Fault scarp, together with abundant chert detritus, provides clear evidence that the chert-bearing part of the alteration zone had been uplifted, veined with hematite, and exposed to erosion by Middle Owen time in the Late Cambrian. The Comstock ore lenses of pyrite-chalcopyrite with minor bornite are located in the footwall position of the Comstock chert body.

At North Lyell, a large displaced mass of schists, with many chert bodies, extends some 500 m into the margin of the Owen basin, and appears to have collapsed eastwards from the scarp of the Great Lyell Fault. Other masses of less altered schist, partly connected to the main schist belt to the west, and to the North Lyell mass, lie within the 'Tharsis Trough' along the basin margin between North Lyell and the Iron Blow mine, obscuring the surface expression of the Great Lyell Fault. Several remnants of the sole of these collapsed masses are exposed resting directly on upturned beds of conglomerate and sandstone along the Tharsis Ridge- Razorback Ridge 'shoulder' structure. A large mass of pale chert, identical to the Comstock chert, lies at the schist-Owen contact at the eastern margin of the schist mass at North Lyell, and appears to represent part of the cap-like chert zone at the top of the alteration system. It has been misinterpreted, however, as silicified Owen beds, leading to a widely-held misconception of post-Owen (i.e. Devonian) silicification and associated bornite mineralisation, since the bornite-rich North Lyell orebody lies along the footwall of the chert. This study clarifies that critical relationship.

Bodies of semi-massive hematite, closely associated with hematite-chert-rich breccias, are developed along the schist-Owen contact from North Lyell to the Iron Blow. These bodies, and the associated breccias, interdigitate with the Owen sediments, indicating that they were formed during deposition of the Middle and Upper Owen beds. The hematite alteration

extends below the bodies into the underlying schist, indicating that the schist mass was exposed at the surface, and that it was oxidised and eroded as it collapsed or rolled into place. The abrupt change from the coarse fluvial Lower Owen to the red, hematite-rich, shallow marine-deltaic facies of the Middle Owen, with its abundant volcanic-derived chert and hematite clasts, appears to coincide with the exposure and erosion of the schist mass. This mass contained abundant pyrite and other sulphides, and its rapid exposure at surface (possibly while still hot) appears to have resulted in intense oxidation to produce large quantities of hematite and barite, much of which was deposited as clasts in the Owen sediments. Similarly, much of the cherty alteration material now appears as a widespread and abundant clastic component in the Middle and Upper Owen beds.

A 100 m-wide zone of upturning and folding of Upper Owen sandstone beds occurs along the schist-Upper Owen contact at the eastern margin of the schist masses. The Haulage Unconformity is developed where the younger Pioneer Sandstone, of probable Middle Ordovician age, truncates these folded beds as it transgresses across them to rest, in a few places, on the schist mass. The folds lack cleavage and were apparently formed when the beds were only semi-consolidated. The folded zone can be attributed to a further advance of the schist mass against the Owen contact some time in the early Ordovician.

Recognition of the North Lyell schist mass as a section from the chert-rich upper part of the alteration zone, closer to the geographic centre of the overall system than Comstock (which is at the northern margin), allows some reconstruction of the major elements of the Mt Lyell system. Within the overall alteration zone was a core zone, 200-500 m wide, of pyrite-rich sericite-chlorite schists, with an upper section of 500 m or so dominated by cherty silica bodies up to 50 m across. This culminated near the top in a cap-like zone of chert masses up to 200 m thick, with bornite-rich orebodies located just beneath the cap over the central part of the system. The presence of pyrophyllite and other indicator minerals in this upper zone indicates that 'high-sulphidation' conditions may have applied during bornite deposition.

Small lead-zinc massive sulphide bodies were formed in the exhalative zone towards the lateral margins of the system, as at Comstock, but in the central parts of the system it appears that massive pyrite-chalcopryrite bodies were more typical, as exemplified by the Iron Blow sulphide body. This body also lies against the Upper Owen contact in a schist collapse zone, and has a gossan-like Cambrian hematite mass developed on it, indicating its exposure at surface during Owen time. Slightly deeper in the system, within the zone of silica heads, are deposits dominated by disseminated pyrite-chalcopryrite (e.g. Crown Lyell 3) or with a small amount of bornite (e.g. Western Tharsis, Comstock), and deeper still, below the chert-rich zone, are the large, low-grade, disseminated orebodies such as Prince Lyell.

There is clear evidence at Mt Lyell that a large part of the alteration system was uplifted, exposed, and eroded during Owen Group deposition, including much of the chert-rich (and ore-rich) upper part. The cover of Tyndall Group rocks must have been stripped off during deposition of the thick Lower Owen sequence, and the alteration zone was exposed, oxidised, and eroded, and large sections of it collapsed into the Owen basin during Middle and Upper Owen time. A possible explanation for the 'upwelling' of the schist mass could be that there was significant volume increase associated with the large-scale hydrothermal alteration, particularly the hydration of feldspars to sericite and of ferromagnesian minerals to chlorite, as noted by Edwards (1939). Further chemical and mass balance studies are required to test this, however.

INTRODUCTION

The Mt Lyell copper mine at Queenstown, western Tasmania, is Australia's largest and longest-lived copper mine, having been in virtually continuous production since mining commenced in 1893, and having produced over 1.2 Mt of copper, 770 t of silver and 45 t of gold from approximately 120 Mt of ore mined. The original Mt Lyell Mining and Railway Company amalgamated with its major competitor, the North Mt Lyell Copper Company, in 1903, and purchased the surviving smaller companies over the next couple of decades, so that the field has been a one-company operation since these early times (Blainey, 1967). Some 20 different ore bodies have been mined, with all production since 1990 being from the underground Prince Lyell deposit. The mine has had a chequered history, with several 'boom' and 'bust' periods, and problems due to falling copper prices in recent decades. The mine was purchased by Consolidated Gold Fields Pty Ltd in 1964, sold to Gold Mines of Australia in 1994 (when it was re-named Copper Mines of Tasmania), and purchased by Sterlite Industries in 1999 to provide sulphide concentrate for a smelter in India.

Understanding the geology of Mt Lyell has been a challenge for geologists since the earliest times. The geology is dominated by a complicated contact relationship between the schistose host rocks (derived from Middle Cambrian volcanic rocks of the Mt Read Volcanics series) to the west and the slightly younger (Late Cambrian) Owen Group siliciclastic conglomerate-sandstone sequence to the east. The contact is formed by a major west-dipping growth fault, the Great Lyell Fault, but large masses of the schists lie within the Owen Group rocks and appear to have 'spilled over' or been displaced from the fault into the Owen basin. Other puzzling features of Mt Lyell geology include the bodies of cherty silica within the alteration zone in places, including some very large masses hundreds of m across; bodies of semi-massive hematite and hematitic breccia with included barite along the schist-Owen contact in places; and the predominance of 'footwall-hosted' copper-gold mineralisation over exhalative lead-zinc deposits.

Numerous previous descriptions of the mines and geology at Mt Lyell have been given, with some of the major works being those of Gregory (1905), Wade and Solomon (1958), Markham (1968), Reid (1976), Walshe and Solomon (1981), Cox (1981), Solomon and Carswell (1989), Arnold and Carswell (1990), Hills (1990), Raymond (1996), and Wills (1996). The author has been involved in mapping at Mt Lyell on two previous occasions (Corbett, 1979; Corbett et al., 1989).

The present study is based on detailed mapping, mainly at 1:1,000 scale, undertaken by the author over the period 1996 to 1999 of most of the mining district from Lyell Comstock in the north to the Copper Estates area in the south. Some of the mapping was done on a consulting basis for Copper Mines of Tasmania, and the remainder as thesis mapping and for personal interest. Some important earlier mapping by Arnold (1985), Herrmann (1986), and Arnold and Dufty (1991) was incorporated into the study after field checking. A new digital geological map of the Mt Lyell field has been produced from the mapping (Fig. 1). The mapping has been backed up with study of the core from numerous drill holes, study of some 120 or so thin sections of rocks from both Owen Group and volcanics (See Appendix 1), and study of numerous old reports and mine plans.

The mapping project has integrated, for the first time, the geology of the upper part of the Mt Lyell system at Lyell Comstock with that of the displaced masses of schists and volcanics in the North Lyell - Iron Blow area, and the deeper levels of the system in the Prince Lyell -

Western Tharsis area. This has enabled a coherent interpretation and reconstruction of Mt Lyell geology to be developed (Corbett, 2000; 2001).

The original study was somewhat wider in scope than is presented here, and included a moderately detailed study of the sedimentology of the Owen Group and an examination of the geological relationships in the Gormanston to Copper Estates area. Time and space constraints have not allowed inclusion of these aspects.

HISTORY OF IDEAS ON MOUNT LYELL ALTERATION AND MINERALISATION

The diversity and complexity of geological units and relationships at Mt Lyell, coupled with the considerable economic interest and potential of the ore deposits, has stimulated a very large amount of geological study and speculation over more than 100 years, with several scores of geologists participating. Much of the important work has been done by mine geologists and consultants, and is contained in unpublished company reports. Copies of many of these are held at Mineral Resources Tasmania library, but some are only available from the mine office or mine archives. Theories regarding the nature and origin of the ore deposits have waxed and waned and swung pendulum-like over time, with few periods of general consensus. Previous summaries of geological thought at Mt Lyell have been compiled by Wade (1958), Solomon (1964), Reid (1976), Arnold (1985), Raymond (1996) and Wills (1996).

The association of volcanism with massive sulphide ore deposits was first recognised in the 1960's, and a volcanic-related syngenetic origin was applied to the Mt Lyell ores (and other deposits of the Mt Read belt) in the late 1960's and has persisted as the favoured origin to the present day. Prior to this, an origin related to Devonian igneous activity (the age of most of the Tasmanian granites) was generally accepted, although the earliest interpretations in the late 1800's involved syngenetic-volcanic processes. A model involving a Devonian hydrothermal event, in addition to the Cambrian one, was resurrected in the early 1980's, when silicification at North Lyell was misinterpreted as a post-Owen phenomenon, and this misconception has persisted. Table 1 shows the main theories and the progression of ideas with time (based partly on Raymond, 1996).

The mining history commenced with a gold-mining phase from 1883 to 1893, when the upper tributaries of Linda Creek were sluiced and the 'iron blow' hematite outcrop was opened up. Thureau (1886, 1889) reported on this phase, and suggested a combination of fissure-filling and volcanic processes to explain the hematite and massive pyrite. Peters (1893) proposed an origin for the sulphide body as a syn-volcanic 'swamp deposit' subsequently tilted on edge. Gregory (1905) clarified many features of the geology, but saw the orebodies as replacement deposits younger than the schists and influenced by the intersections of NW-trending faults with the 'Great Lyell Fault' contact. Several later workers believed the volcanic host rocks to be Devonian intrusive porphyries, with the mineralisation related to this intrusive phase (Nye et al., 1934; Edwards, 1939; Connolly, 1947). Even after the Cambrian age of the bulk of the host rocks was established, the concept that the copper mineralisation was related to Devonian intrusive activity persisted through the 1950's (eg Carey, 1953; Bradley, 1956; Wade and Solomon, 1958; Solomon, 1959).

The possibility of two distinct mineralising events, one Cambrian and one Devonian, was first raised by Hills (1914), whose work on the Jukes-Darwin Range clearly showed that some

TABLE 1: Theories on origin of mineralisation at Mount Lyell

Devonian mineralisation in Devonian porphyries	Devonian mineralisation in Cambrian volcanics	Cambrian mineralisation & Devonian mineralisation	Cambrian mineralisation re-mobilised in Devonian	Cambrian syn-volcanic mineralisation only	Cambrian followed by syn-Owen min'n
				Thureau 1886	
				Peters 1893	
	Gregory 1905				
		Hills 1914			
	Hills 1927				
Nye 1934					
Edwards 1939					
Connolly 1947					
	Carey 1953				
	Bradley 1956, 1957				
	Wade & Solomon 1958	Campana et al 1958			
	Solomon 1959				
			Hall & Solomon 1962		
		Solomon 1964		Campana & King 1963	
			Solomon & Elms 1965		
				Solomon 1967, 1969, 1976	
				Markham 1968	
				Green 1971	
				Walshe 1971, 1977	
				Reid 1975	
				White 1975	
				Walshe & Solomon 1981	
				Hendry 1981	
				Cox 1981	
				Corbett 1981, 1986	
			Bird 1982		
		Sillitoe 1984, 1985			
		Solomon 1984	Arnold 1985		Bird 1985
			Solomon et al 1987, 1988	Gulson & Porrit 1987	
			Solomon & Carswell 1989		
			Hills 1990		Berry 1990
			Arnold & Carswell 1990		
			Hart 1992		Raymond 1992
			Berry 1992		
				Large et al 1996	Raymond 1996
					Wills 1996
					Huston & Kamprad 2000
				Corbett 2000, 2001	

local magnetite-hematite-chalcopyrite mineralisation was related to the Cambrian Darwin Granite. This concept of dual events was supported by Campana et al. (1958) in a regional review of West Tasmanian geology. The progression to a model of Devonian *remobilisation* of Cambrian syngenetic ores is seen in the early 1960's in the papers of Hall and Solomon (1962) and Solomon and Elms (1965), while Campana and King (1963) were perhaps the first to opt for a dominantly Cambrian age for the Mount Read belt ores generally.

A syngenetic origin for the Mount Lyell deposits was implied by Solomon's (1967) interpretation of the hematite bodies on the schist contact at North Lyell as fossil gossans, and was further confirmed by Markham's (1968) careful mineragraphic work showing that all the Mount Lyell ores pre-dated the Devonian cleavage and that some were of exhalative type. The concept of a Cambrian volcanic-related syngenetic origin for the Mount Lyell deposits was established at this stage, and was supported by most workers through the 1970's and 1980's- perhaps the longest period of consensus. The massive lead-zinc bodies at Tasman Crown and Comstock mullock quarry, and the massive pyrite-chalcopyrite body at the Iron Blow, were generally regarded as exhalative products of the system, and the disseminated chalcopyrite-pyrite bodies as submarine replacements within permeable volcanic horizons (eg Reid, 1976; Solomon, 1976; Walshe and Solomon, 1981; Cox, 1981; Hendry, 1981). However, the origin of the bornite-rich high-grade deposits at North Lyell remained a problem.

A swing back to support for post-Cambrian epigenetic processes was fostered by a group of mine geologists and consultants at Mount Lyell in the early to mid-1980's (Bird, 1982, 1985; Brook, 1984; Sillitoe, 1984, 1985), when theories of Devonian remobilisation were reactivated, and an Ordovician mineralising event was also suggested. An important element in this 'breakaway movement' was Sillitoe's (1984) interpretation of the North Lyell chert body as a Devonian silicification product of Owen Conglomerate, implying that the closely associated bornite mineralisation (which is partly hosted within the chert) was also probably of Devonian age. This concept of a Devonian age for the silicification and associated bornite mineralisation (remobilisation?) at North Lyell became widely accepted (eg Solomon, 1984; Arnold, 1985; Solomon et al., 1987; Solomon and Carswell, 1989; Arnold and Carswell, 1990; Hills, 1990), but has been strongly refuted by the present study, which shows the North Lyell chert to be analogous to the Comstock chert and part of the Cambrian alteration system. Important mapping work was carried out by Arnold in 1985 on the central part of the mine lease, in which the importance of the 'silica heads' as an alteration type was recognised.

The alteration associated with the hematite-barite bodies and cherts on the schist contact at North Lyell was studied by Hart (1992, 1993). He initially concluded that a post-Owen (i.e. Devonian) event was responsible, then, after confirming that hematite clasts were present in the Owen, suggested a syn-Owen age. Like many others, Hart assumed that the chert body was derived by silicification of Owen conglomerate at the same time as the hematite alteration, a false assumption which confused his interpretations. As shown by the present study, the chert is part of the Cambrian alteration zone, whereas the hematite is a later syn-Owen phenomenon.

In a study of pyrite generations at Prince Lyell, Raymond (1992, 1996) noted hematite inclusions in the second and third generations of pyrite (post-dating the main chalcopyrite mineralisation event), and concentration of hematite in the adjacent footwall volcanics and along the Great Lyell Fault zone. He suggested that the fault must have been active at the time of this pyrite formation to provide the source of oxidising fluids, implying that some of the

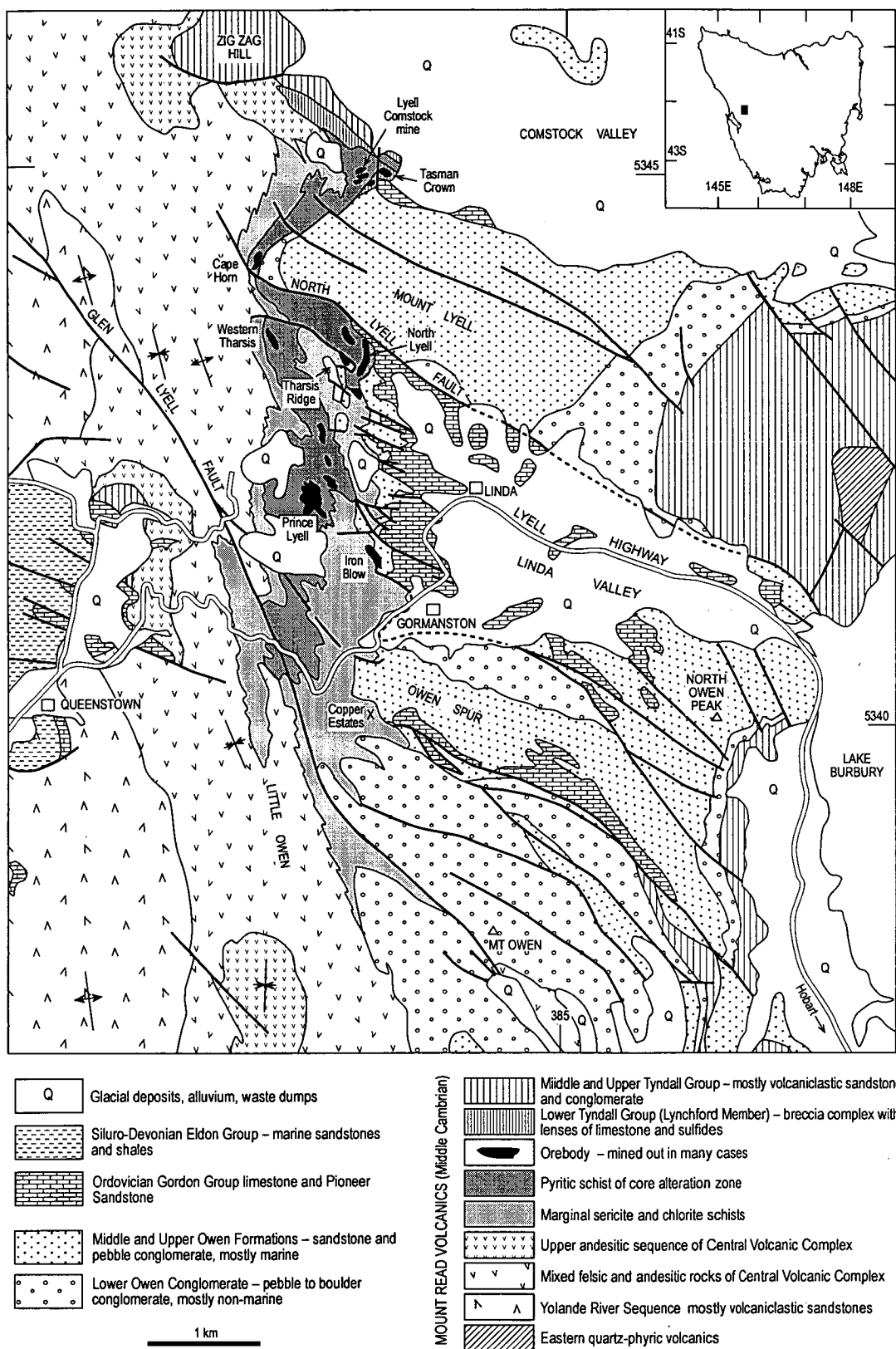


Figure 2. Simplified geological map of the Mt Lyell–Mt Owen area, West Coast Range, showing alteration zone at Mt Lyell mines. Modified after Corbett et al. (1989).

mineralisation was contemporaneous with Owen Conglomerate deposition against the growth fault. He thus postulated an 'Ordovician' age for the second generation pyrite, related to mixing of hydrothermal fluids with oxidised fluids from the Owen Group. The presence of hematite in the Prince Lyell mineralisation suggests early interaction with deep-circulating oxidised waters, as Raymond suggests, but if, as seems highly likely, the Great Lyell Fault was active during volcanism and probably served as a focusing mechanism for the large alteration zone, then oxidised fluids could have penetrated deeply along the structure well prior to Owen Group deposition.

A strong magmatic influence on the Mt Lyell hydrothermal system, related to Cambrian granites, has been advocated recently by Large et al, (1996), noting particularly that magnetite-apatite lenses within the Prince Lyell orebody closely match those within the alteration halo of the nearby Darwin Granite. Many other features also point to a strong Cambrian magmatic influence at Mount Lyell.

Most recently, the presence of 'high-sulphidation' mineralisation within the Mt Lyell system has been documented by Huston and Kamprad (2000; in press) from their work at Western Tharsis, and the possibility of an Ordovician age has again been raised. It was recognised that the disseminated pyrite-chalcopyrite mineralisation at Western Tharsis was overprinted by a minor phase of bornite mineralisation associated with alteration involving pyrophyllite, topaz, zunyite and woodhouseite, minerals generally regarded as indicators for 'high-sulphidation' conditions. Both phases were regarded as belonging to a single mineralising event, and correlation to the bornite mineralisation at North Lyell, and the interpretations of Hart (1993) and Raymond (1996) regarding the syn- Owen Group age of hematite -pyrophyllite alteration in that area, led to the suggestion that this event could be of 'Ordovician' age. Such an age is clearly refuted by the present study, but the recognition that the bornite mineralisation is of 'high-sulphidation' type is a significant advance.

GENERAL GEOLOGY OF THE MT LYELL AREA

Mt Lyell is located more or less centrally within the N-S trending West Coast Range, which is made up of the Middle Cambrian Mt Read Volcanics overlain by the Late Cambrian Owen Group siliciclastic conglomerate-sandstone sequence. Regional reviews of the geology have been given by Corbett (1981, 1992), Corbett and Solomon (1989), and Crawford et al (1992). The general geology of the area is shown in Figure 2, and the stratigraphic terminology and relationships in Figure 3.

The Mt Read Volcanics and Associated Alteration Zone

The Mt Read Volcanics form a 10-20 km wide belt of dominantly submarine, medium to high-K, calc-alkaline, post-collisional, felsic to andesitic volcanics extending through western Tasmania (Corbett, 1992; Crawford et al., 1992). The major unit involved in the alteration and mineralisation at Mt Lyell is the Central Volcanic Complex, comprising feldspar-quartz-phyric rhyolitic to dacitic lavas and breccias, and pumice breccias, intermixed with andesitic lavas, breccias, intrusives and volcanoclastics, in a pile at least 600 m thick. The upper 300 m of this complex consists largely of andesitic rocks, and is informally referred to as the upper andesitic unit. The only basement rocks to the Mt Read Volcanics seen in the Mt Lyell area are the altered tholeiitic basalts, of probable late Proterozoic age, seen in a small structural window at Miners Ridge, 3 km south of Queenstown (Corbett, 1979; Crawford et al., 1992). If such a

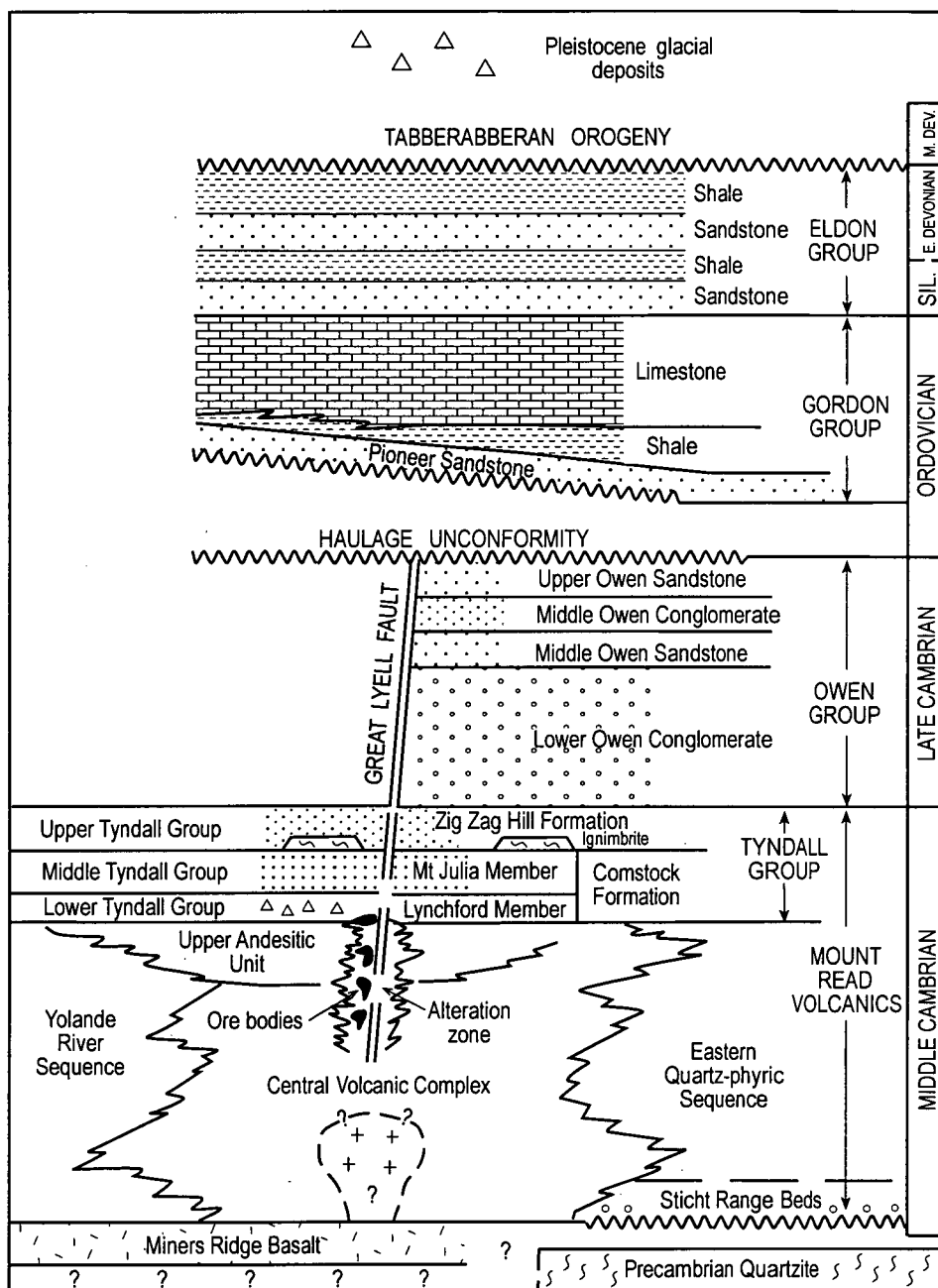


Figure 3. Stratigraphic column for Mt Lyell area showing terminology adopted in this report.

basaltic substrate is widespread, as seems likely, and was involved in the hydrothermal convection system at Mt Lyell, then it may in part account for the copper-rich nature of the Mt Lyell deposits.

The large hydrothermal alteration zone at Mt Lyell lies almost entirely within the Central Volcanic Complex, and can be seen to cross-cut the upper andesitic unit at Lyell Comstock, where it culminates in the basal part of the overlying Tyndall Group (Figs 1,2). The zone corresponds essentially with the 'mine sequence' of Cox (1981), and is sub-conformable with the steeply west-dipping but east-facing lithological units in the general mine area (Fig. 4). The zone consists mainly of sericite-quartz-rich and chlorite-rich schists, and extends for some 6 km along strike, from Lyell Comstock in the north to the foothills of Mt Owen in the south (Figs 1,2), where it appears to finger out into relatively unaltered rocks. It has an average width of about 1 km.

The alteration zone lies parallel and adjacent to the contact of the volcanic sequence with the younger Owen Group sediments to the east, this contact being formed by the steeply west-dipping Great Lyell Fault (first named by Gregory, 1905). The Owen Group sequence is 'ponded' against this fault to a depth of the order of 2 km (Fig. 4). The fault contact is well exposed in the Cape Horn open cut area, where it separates schists from Lower Owen Conglomerate (Plate 1a). However, through the main part of the mine area the fault surface is obscured by large masses of the schists which appear to have spilled over or collapsed from the fault scarp into the adjacent margin of the Owen basin (Figs 4,5). These schist masses rest against Middle Owen or Upper Owen rocks on an irregular contact which shows evidence of sedimentary interaction between the two rock units. This 'camouflaging' of the Great Lyell Fault through the mine area has led to considerable confusion in interpreting the geology and the nature of the contact, and is the subject of much of the present study. The most important of the displaced or collapsed schist masses is at North Lyell, where a 500m-deep mass originally contained a number of rich orebodies, most of which have now been mined out.

The Great Lyell Fault appears from the present study to have been a reverse-type growth fault throughout deposition of the Owen Group, and is presumed to have been active during much of the Mt Read volcanism, providing the 'plumbing system' for the large alteration zone. The westerly dip of the fault results in most of the mine area being underlain at depth by the younger conglomerate (eg Figs 4, 6). Several other similar alteration zones are located along the line of the Great Lyell Fault for some 20 km to the north, including the Basin Lake and Howards Anomaly prospects, culminating in the large alteration zone of the Henty gold deposit- a silica-hosted 'shallow-water VHMS' deposit in the base of the Tyndall Group with many similarities to Lyell Comstock (Halley and Roberts, 1997; Callaghan, in press).

The recent mapping has shown that the alteration zone at Mt Lyell has a mappable central core of pyrite-rich sericite-chlorite-silica schists, typically 200-400 m wide and with over 5% pyrite in many places, flanked by marginal zones of pyrite-poor sericite and chlorite schist. Virtually all of the copper orebodies are contained within the central pyrite-rich zone (Figs 1, 2). The marginal schists commonly have some primary volcanic textures preserved (eg flow-banding, brecciation, porphyritic textures), but these tend to be obscured or obliterated in the more intensely altered central zone. Carbonate is common to abundant in the marginal schists, but tends to be rare in the core zone schists. Siliceous alteration is essentially confined to the core zone. Contacts between the zones are typically irregular and interfingering, with various

outliers and inliers of one type or another, and contacts between marginal schist and relatively unaltered rocks range from poorly defined to well defined.

Numerous bodies of cherty silica are present in the upper part of the core zone where this is preserved at Lyell Comstock and North Lyell (Fig. 1), and these previously enigmatic bodies are herein shown to be an important part of the overall alteration system and a critical element in reconstructing the original form of the zone and its history. They are considered to represent zones where the original volcanic rocks have been more or less completely replaced by silica. This upper part of the alteration zone is absent over the main part of the mine area, and appears to have been eroded off during the period of Owen Group deposition (Fig. 5).

At the top of the alteration system at Lyell Comstock, above a very large chert mass referred to as the Comstock chert, is an exhalative zone hosted within the basal part of the Tyndall Group, the uppermost part of the Mt Read volcanic succession. This exhalative zone contains several small lenses of massive lead-zinc-rich sulphide. The Tyndall Group consists of a lower unit (corresponding to the Lynchford Member of the Comstock Formation of White and McPhie, 1996) rich in breccias, conglomerates and sandstones, with lenses of limestone and andesitic lava, followed by a middle unit of mainly volcanoclastic sandstones (Mt Julia Member) and an upper unit of mainly volcanoclastic conglomerates (Zig Zag Hill Formation). The middle and upper parts of the Tyndall Group are essentially unaltered, and clearly post-date the mineralisation and alteration, as recognised by Green (1971). Fossils in some of the limestone lenses in the middle Tyndall unit give a late Middle Cambrian age (Jago et al. 1972). A welded ignimbrite body in the top of the middle unit just north of Comstock is indicative of a shallowing of the marine depositional environment (White and McPhie, 1997).

The Tyndall Group units at Comstock face north but have sub-vertical to overturned south-westerly dips which are anomalously steep and are interpreted herein to be a result of the forceful upwelling of the alteration zone rocks in the post-Tyndall period, particularly during Owen Group deposition.

The distribution of the main ore deposits in the Mt Lyell system is shown on Figure 1, and Table 2 gives details of production, grade, mineralisation style and history. A geographic-stratigraphic grouping of the ore deposits may be made as follows:

- (1) At the top, an exhalative group includes the lead-zinc body mined at Tasman Crown (the smaller lead-zinc body at Comstock mullock quarry has not been mined as such), and the Iron Blow and South Lyell massive pyrite-chalcopyrite deposits over the central part of the system.
- (2) The Lyell Comstock group of pyrite-chalcopyrite-minor bornite lenses, lying just below the Comstock chert body in the upper part of the alteration zone at the northern margin of the system.
- (3) The North Lyell group of orebodies, also lying in the upper part of the alteration zone but over the central part of the system. These comprise an upper subgroup of high-grade bornite-rich deposits (North Lyell, 12 West, Crown Lyell 2 and Lyell Tharsis high-grade), lying along the footwall of the large North Lyell chert body, and a group of lower grade chalcopyrite-pyrite deposits (Crown Lyell 3, Crown Lyell 1, Lyell Tharsis low-grade) lying slightly lower in the zone.
- (4) The Western Tharsis pyrite-chalcopyrite-minor bornite deposit, lying just within the zone of cherty silica bodies but probably at a lower level in the system than the North Lyell deposits.

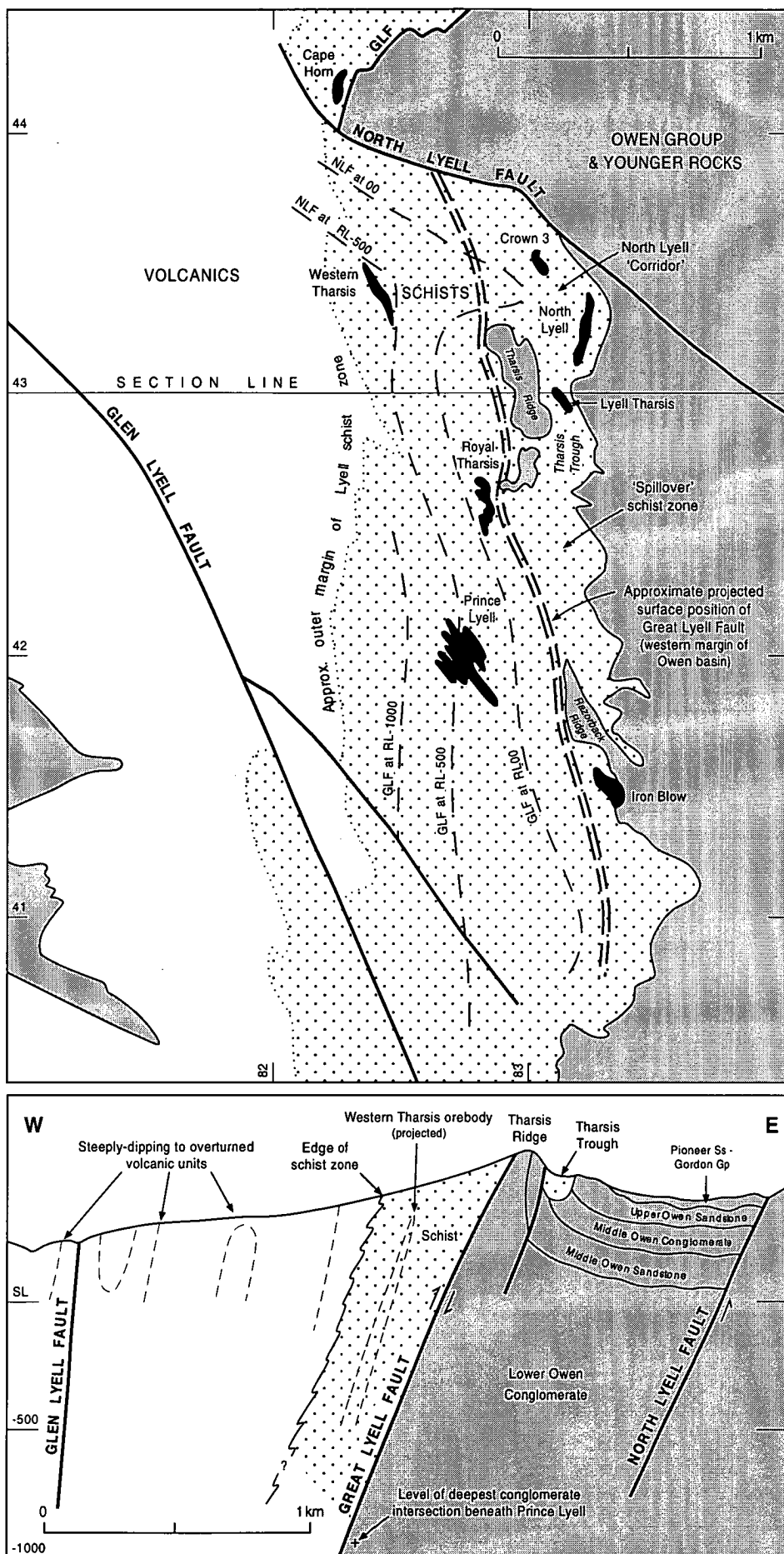


Figure 4. Simplified map and cross-section of the Mt Lyell field showing the form of the schist–Owen Group contact, the Great Lyell Fault (GLF), North Lyell Fault (NLF), the North Lyell Corridor, Tharsis Trough and Tharsis Ridge structures. Approximate structure contours on the faults are in metres above and below sea level, based on drill hole intersections.

- (5) A large group of low-grade pyrite-chalcopyrite deposits lying below the chert-rich zone in the deeper levels of the system, including the very large Prince Lyell deposit, A Lens, Razorback and Royal Tharsis. The upper levels of Prince Lyell, and the A Lens deposit, were mined together in the West Lyell open cut. The Cape Horn deposit, lying north of the North Lyell Fault, appears to be equivalent to these.
- (6) A group of younger secondary 'copper clay' deposits consisting mainly of native copper and cuprite hosted within shales and limestone-derived clays of the lower Gordon Group in the area along the eastern margin of the schists between North Lyell and Gormanston. The three main mines here were King Lyell, Lyell Blocks and Lyell Consols (Solomon, 1969).

The Great Lyell Fault, North Lyell Fault, and Schist-Owen Contact

The contact zone between the volcanic rocks and Owen Group sequence in the area between Gormanston and North Lyell, and between Cape Horn and Lyell Comstock mines, was designated the 'Great Lyell Fault' by Gregory (1905). This term has remained in use since then, although there has been considerable confusion and disagreement over the actual nature of the contact, and the nature of the fault. The general line of the Great Lyell Fault and the zone of altered and mineralised rocks is offset sinistrally by the NW-trending North Lyell Fault, on which the large conglomerate mass of the Mt Lyell Range has been uplifted (Figs 1,2). From Cape Horn mine northwards, the situation is relatively straightforward, since a clearly defined fault surface dipping steeply west separates the volcanic rocks (schists) to the west from the Lower Owen Conglomerate to the east (Plate 1a). This fault surface, offset here and there by NW-trending cross-faults, continues north-eastwards to Comstock, intersecting progressively younger units of the north-dipping Owen sequence (Fig. 1). Some complication is evident at the Tasman Crown mine, however, where a lobe of the volcanic rocks appears to overlap eastwards across the fault line and has a puzzling relationship with Owen Group and Pioneer Sandstone units, which it appears to overlie.

Between North Lyell and Gormanston, where the volcanic rocks are mostly in contact with Upper Owen Sandstone, the situation is again unclear, with large masses of volcanics/schists lying more or less surrounded by Owen Group rocks to the east of the position where the Great Lyell Fault would be expected to surface (Fig. 4). The fault position is well controlled underground, from numerous intersections in workings and drill holes, and strikes south-eastwards from the western side of Tharsis Ridge to the western side of Razorback Ridge. The belt of schists lying *east* of Tharsis Ridge, and linking up with the schists east of Razorback Ridge, represents a kind of 'spillover' zone or displaced mass now lying within the Owen Group basin. The term 'Tharsis Trough' has been applied to the northern part of this zone. The schist within this trough structure retains a partial connection to the main schist belt west of Tharsis Ridge, as is evident in the saddles on Tharsis Ridge, and in the area between Tharsis Ridge and Razorback Ridge, where the schists overlie a buried ridge of Owen Group rocks (Figs 1, 15). Drilling within the zone suggests the schist mass has a rounded form which is unlikely to be related to later faulting (eg Fig. 15).

The schists within the spillover zone or Tharsis Trough are only 50-150 m deep, as shown by drilling and small workings, except at North Lyell, where a larger mass, 500 m deep and referred to as the North Lyell 'corridor', wraps across the north face of Tharsis Ridge (Fig. 4). The origin and mode of emplacement of these displaced schist masses has been a difficult and unresolved issue in understanding Mt Lyell geology, and is a central part of this study.

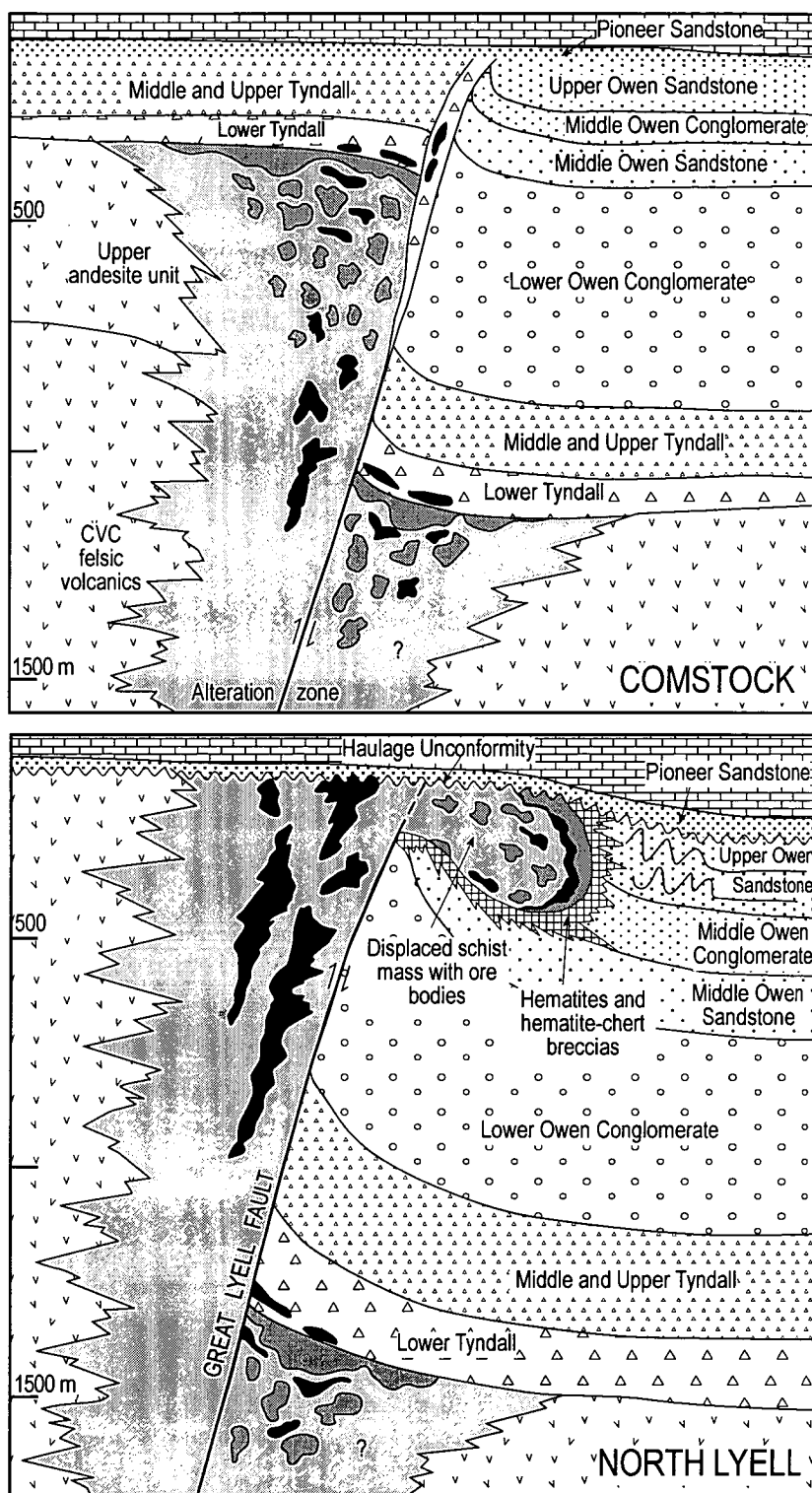


Figure 5. Comparative diagrammatic sections for the Comstock and North Lyell areas showing relationships between alteration zone, Great Lyell Fault, Tyndall Group, Owen Group, and displaced schist masses.

The nature of the contact between the schist masses and the Upper Owen sediments between North Lyell and Gormanston has been difficult to interpret. Many geologists (including the author in earlier times) have assumed it to be the 'Great Lyell Fault' without critical examination, but careful observation reveals that much of the contact has a sedimentary character, with the basal Upper Owen beds abutting the schists on an unsheared, erosional-type surface, with volcanic-derived clasts forming a basal breccia-conglomerate to the Upper Owen. In other places, a body of hematite or hematitic breccia lies on the contact, with a gradational contact via hematite-altered volcanic material below, and a gradational contact into the Upper Owen sequence above. In other places, there is evidence of some shearing at the contact, but not in the form of a major regional fault zone.

By contrast, the contact zone of the genuine Great Lyell Fault, as seen in underground workings west of the Tharsis Ridge-Razorback Ridge line (e.g. in the Prince Lyell mine), is a steeply west-dipping abrupt surface between Lower Owen Conglomerate and highly sheared schists, and is a convincing fault zone, similar to that seen at surface in the Cape Horn area (Plate 1a).

The steep westerly dip of the fault persists at least to the limit of deep drilling information, some 1.5 km below surface at the mine (Figs 4, 6), with no sign of the 'turn-under' to the east which has been suggested in many previous interpretations (e.g. Connolly, 1947; Wade and Solomon, 1958; Corbett et al, 1974; Hills, 1990), or that it represents a modified east-dipping normal fault as suggested by others (e.g. Campana and King, 1963; Williams, 1993). The fault appears to have been an active reverse-type growth fault throughout accumulation of the Owen Group, with east-side-down subsidence of the order of 2 km to accommodate the siliciclastic conglomerates and sandstones. At the same time, there appears to have been sufficient west-side-up movement of the volcanics to cause erosion of the cover of Tyndall Group rocks and expose the sulphide- and chert-rich alteration zone and remove much of its upper part (Fig. 5). The entire Owen Group sequence was apparently restricted to the eastern side of the fault in the mine area, there being no representative of the lower, middle or upper units in the Queenstown township area (Fig. 2). The fault zone was apparently not transgressed until the Pioneer Sandstone onlap in about the Middle Ordovician, this unit forming a blanket-like deposit across Owen Group and volcanic sequences alike (Corbett et al, 1974).

It seems highly likely that the Great Lyell Fault was also active during the period of Mt Read volcanism, and it is argued herein that the large tabular zone of hydrothermal alteration which extends along the fault through the Mt Lyell mining field was generated by fluids coming up along and beside the fault zone. The eastern half of the 1-2 km-wide alteration zone is probably present on the eastern side of the fault at depth, but this area remains tantalisingly unknown due to the depth of burial beneath Owen Group sediments (Fig. 5).

Some further movement on the fault occurred during the Devonian deformation, but the amount and direction of these movements appears to have varied, and there was significant east-side-up movement in places. The mass of Owen Group rocks forming the Mt Lyell range was uplifted along part of the Great Lyell Fault between Cape Horn and Comstock, and on the North Lyell Fault, exposing the Lower Owen rocks in the Cape Horn area (Figs 1, 7). Maximum uplift appears to have been of the order of 800 m on the North Lyell Fault, as indicated by displacement of the Lower Owen- Middle Owen boundary at North Lyell (Figs 18, 19). The amount of uplift decreases towards Comstock (and the edge of the alteration

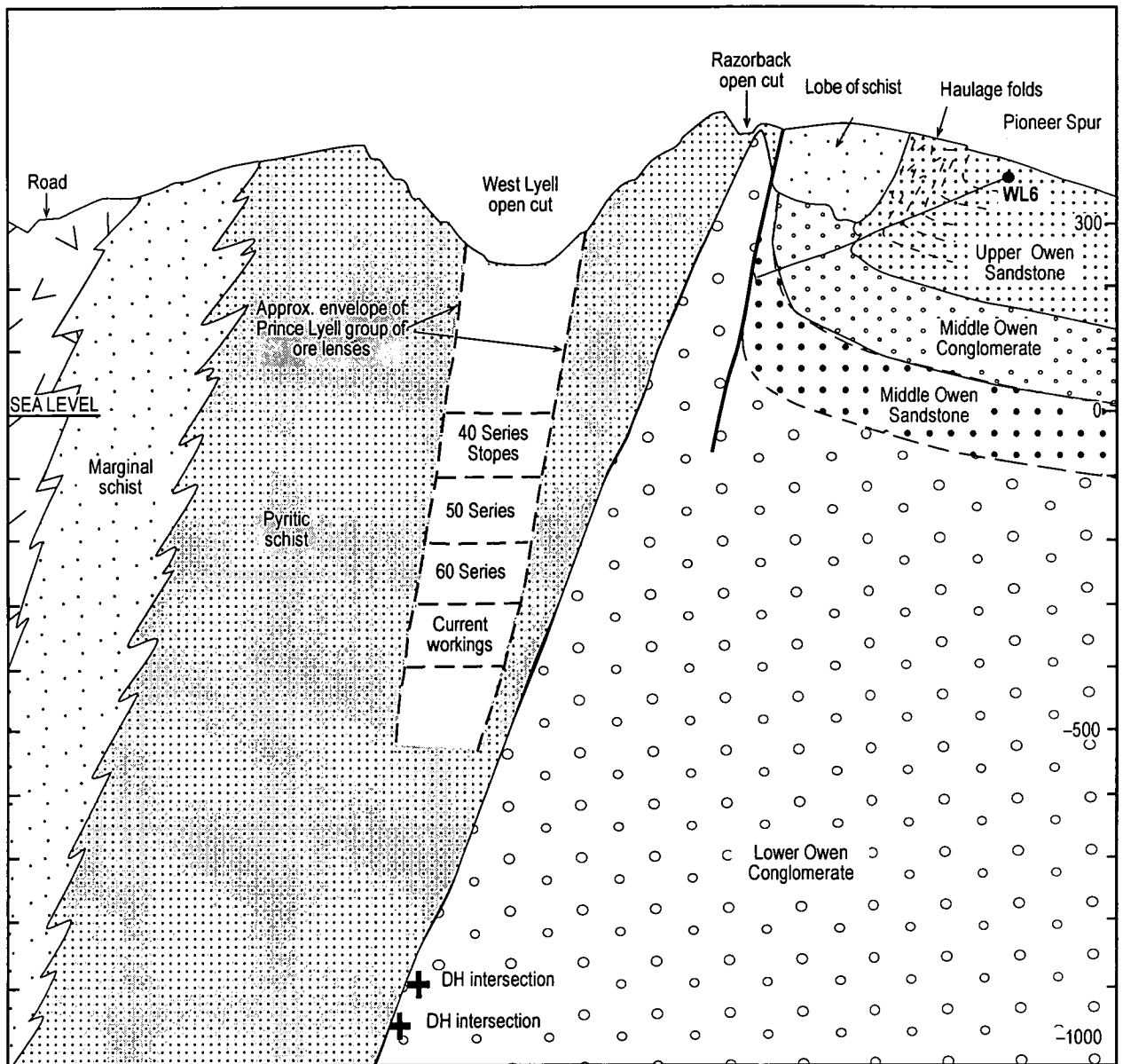


Figure 6. East-west cross-section through Prince Lyell mine and Razorback open cut at approx. 5342, 2050mN (AMG). Two deepest drill hole intersections of Great Lyell Fault are shown. Note that much of pyritic schist mass above 60 series is caving into mine area.

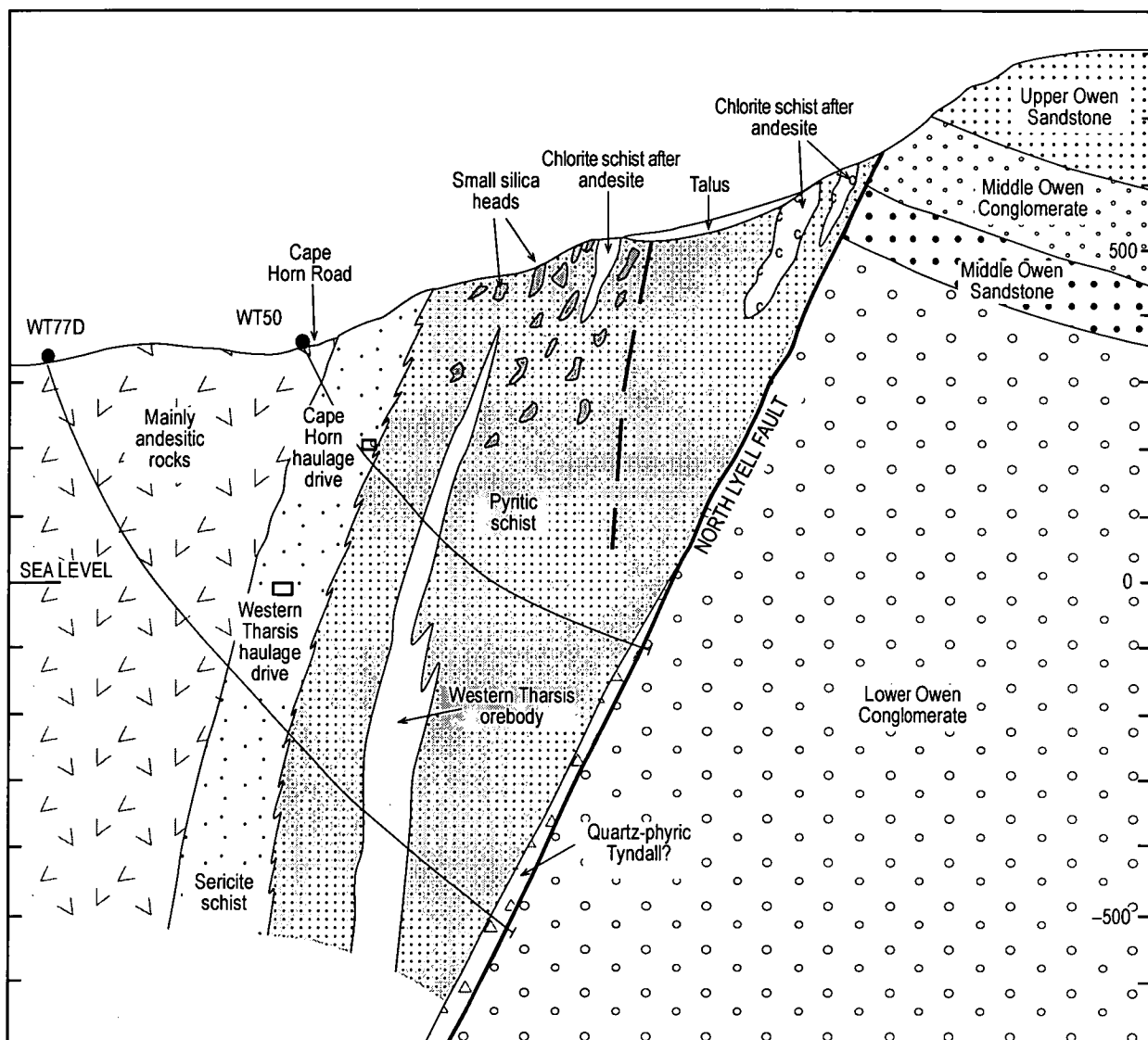


Figure 7. NE-SW cross-section through Western Tharsis deposit and North Lyell Fault on Mine Grid 8850N. Partly after Cordery and Greenwood (1995).

zone), in a hinge fashion, suggesting the possibility that the uplift was related to upward pressure from the buried alteration zone on the eastern side of the Great Lyell Fault.

Owen Group Siliciclastic Sequence

Terminology, correlation and age

The evolution of terminology for the Owen Group, and that adopted in this report, are shown in Figure 8. The siliciclastic sequence was initially referred to as the 'West Coast Range Conglomerate' (e.g. Nye et al, 1934; Connelly, 1947) and then as the 'Owen Conglomerate' (Wade and Solomon, 1958; Banks, 1962; Banks and Baillie, 1989). The term 'Owen Group' was first used by Corbett (1990), but unfortunately the formation names suggested at that time were from different parts of the West Coast Range, and subsequent work has shown some ambiguity in correlations which is better avoided. The terminology preferred here is based on the original four units of Wade and Solomon (1958) from a type section on Mt Owen: (i) Lower Owen Conglomerate; (ii) Middle Owen Sandstone; (iii) Middle Owen Conglomerate; (iv) Upper Owen Sandstone.

The 'Pioneer Beds', originally regarded as the upper part of the Upper Owen Formation (Fig. 8), are here regarded as a basal part of the overlying Gordon Group, since they are separated from the Upper Owen by an unconformity, but have a conformable and gradational relationship to the Gordon Group limestone sequence and are regionally associated with that Group. Since the unit is quite well mapped, consists dominantly of sandstone, and has definable upper and lower boundaries, the term 'Pioneer Beds' is herein replaced with 'Pioneer Sandstone'. Its type area may be regarded as Pioneer Spur and environs.

A correlation chart for the Owen Group between the Mt Lyell mine at North Lyell, the western end of Mt Lyell range at Cape Horn Spur, and the central/eastern parts of the Mt Lyell range, is given in Figure 9. The latter two columns are based on sections measured by the author (except for the sub-surface part of the Lower Owen), and the first on thicknesses indicated by detailed mapping and deep drilling. The sections demonstrate the pronounced changes in thickness and character away from the Great Lyell Fault contact with the volcanics.

The age of the Owen Group is rather poorly constrained at Mt Lyell. A widespread siltstone unit within the Lower Owen Conglomerate on Mt Lyell and Mt Owen appears to be a lateral wedge of Newton Creek Sandstone facies from the Tyndall Range area, where the Lower Owen conglomerates pass laterally into a marine sandstone-siltstone sequence with fossils of early to middle Late Cambrian (late Idamean to Iverian) age (Corbett, 1975; Corbett and Jackson, 1987; Terry, 1995; Laurie et al, 1995). The Upper Owen Sandstone has been tentatively correlated with an un-named sandstone-siltstone unit forming the top of the siliciclastic sequence on Misery Hill, 25 km to the NW of Queenstown, and containing fossils of latest Late Cambrian (Payntonian) age (Jago and Corbett, 1990; Corbett, 1990). The group is thus considered to span much of the Late Cambrian period, possibly extending slightly into the early Ordovician.

General features

The siliciclastic conglomerates and sandstones of the Owen Group are mostly hard, resistant rocks made up largely of quartzite sand grains and rounded clasts of quartzite and quartz-schist derived from the Precambrian basement to the east. A locally derived volcanic

CONNOLLY 1947			WADE & SOLOMON 1958			BANKS 1962			CORBETT ET AL 1989			CORBETT 1990			CORBETT 2001 THIS STUDY			GORDON GROUP
'Chocolate Beds'	UPPER SERIES	WEST COAST RANGE CONGLOMERATES	Pioneer Beds	UPPER OWEN CONGLOM.	OWEN CONGLOMERATE	Pioneer Beds	UPPER OWEN = CAROLINE CREEK SANDSTONE	OWEN CONGLOMERATE	Pioneer Beds	UPPER OWEN Oou	OWEN CONGLOMERATE = DENISON GROUP	Pioneer Beds	'ROLLESTON SUBGROUP' = UPPER OWEN	OWEN GROUP	Pioneer Sandstone		OWEN GROUP	
			Chocolate Sandstone			Chocolate Sandstone			Thin - bedded sandstone			'Linda Sandstone'			Upper Owen Sandstone			
'Razorback Beds'	MIDDLE SERIES		Yellow conglomerates	MIDDLE OWEN CONGLOM.		Chocolate beds	MIDDLE OWEN = Member B		Middle Owen Conglomerate	'Huntley Conglomerate' = Middle Owen Conglomerate		Middle Owen Conglomerate						
'Red Sandstone'			Red sandstone or alternating conglomerate & sandstone			Red sandstone			Newton Creek Sandstone correlate	Newton Creek Sandstone = Middle Owen Sandstone		Middle Owen Sandstone						
'Mountain Conglomerate'			Coarse pebble conglomerate with a red sandstone horizon			Conglomerate			LOWER OWEN = Member A	Lower Conglomerate		'Sedgwick Conglomerate' = Lower Owen Conglomerate	Upper conglomerate member		Lower Owen Conglomerate			
'Mountain Sandstone'						Sandstone							Planar-bedded conglom-sandstone member					
Lower Conglomerate	Conglomerate			Siltstone -sandstone member														
Breccia Conglomerate	LOWER SERIES		Lower OWEN CONGLOM.							Lower conglomerate member								

Figure 8. Evolution of terminology for Owen Group and terminology used for this report.

component is present at the base of the group in places, and forms a mappable unit (the 'Jukes Conglomerate') in some areas. A volcanic component consisting mainly of chert (from the siliceous alteration) and hematite detritus, and volcanic quartz grains, is prominent within the middle and upper units of the group in the Mt Lyell mines area

The thickness of the group increases westwards towards the Great Lyell Fault contact, reaching a maximum of the order of 2 km at the Mt Lyell mines. Most of this thickening is within the Lower Owen Conglomerate, which is at least 1200 m thick adjacent to the fault, as indicated by deep drilling beneath the Prince Lyell and Western Tharsis deposits, but thins to less than 400 m towards the eastern end of Mt Lyell (Fig. 9), about 4 km away, and thence to virtually zero some 2 km further east (Corbett et al, 1989). The base of the conglomerate sequence at the mine has not been reached even in the deepest drill intersections, some 1.5 km below surface at Prince Lyell (Fig. 6).

The bulk of the Owen Group sequence in the Mt Lyell- Mt Owen area is made up of the Lower Owen Conglomerate, which forms the lower 70 to 80 per cent of the section (Figs 4,6). The upper 20 to 30 per cent consists of the other three formations- the Middle Owen Sandstone, Middle Owen Conglomerate, and Upper Owen Sandstone- each of the order of 100 to 150 m thick. In the mine area, the three upper formations are rich in volcanic-derived detritus, particularly clasts of chert and hematite, and contain numerous lenses of chert-hematite-rich conglomerate and breccia. These volcanic-derived units appear to wedge out laterally away from the contact, and are sparse to absent beyond about 800 m from it, although hematite persists in the matrix of the sandstones for at least several km further east.

Lower Owen Conglomerate

This formation is well exposed towards the eastern end of Mt Lyell, where a complete and virtually unfaulted section is available. The upper part of the formation is exposed above Cape Horn mine at the western end of the range, and also on Tharsis Ridge in the mine area (Fig. 1). Many good cliff sections of Lower Owen are present on Mt Owen. The formation consists for the most part of grey-white to pale pink pebble to boulder grade conglomerate with interbedded pebbly sandstone (Plate 1b). Derivation is predominantly from the Precambrian metaquartzite basement to the east, with a minor volcanic input identified in the upper part adjacent to the Great Lyell Fault.

Four distinct members are recognisable within the Lower Owen at the eastern end of Mt Lyell (Fig. 9), and are also present on Mt Owen:

- (i) a basal unit of thick-bedded pebble to boulder grade conglomerate with lenses of pink sandstone, resembling coarse braided stream deposits;
- (ii) a unit of pink to grey sandstone passing up into grey micaceous siltstone with thin graded sandstone beds, possibly representing shallow marine to delta-front deposits (similar to the Newton Creek Sandstone facies north of the Tyndall Range (Corbett, 1975);
- (iii) a unit of planar-bedded pebble-cobble conglomerate and pebbly sandstone with strongly imbricated clasts, interpreted as terrestrial sheet-flood facies;
- (iv) an upper unit of cobble-boulder conglomerate with sandstone lenses, similar to the basal unit and also interpreted as braided stream facies (plate 1b).

Thus the Lower Owen in the Mt Lyell- Mt Owen area consists predominantly of terrestrial facies, whereas further north in the northern Tyndall Range- Newton Creek- Mt Julia area the equivalent position is occupied by a thick sequence of grey-green marine sandstone and

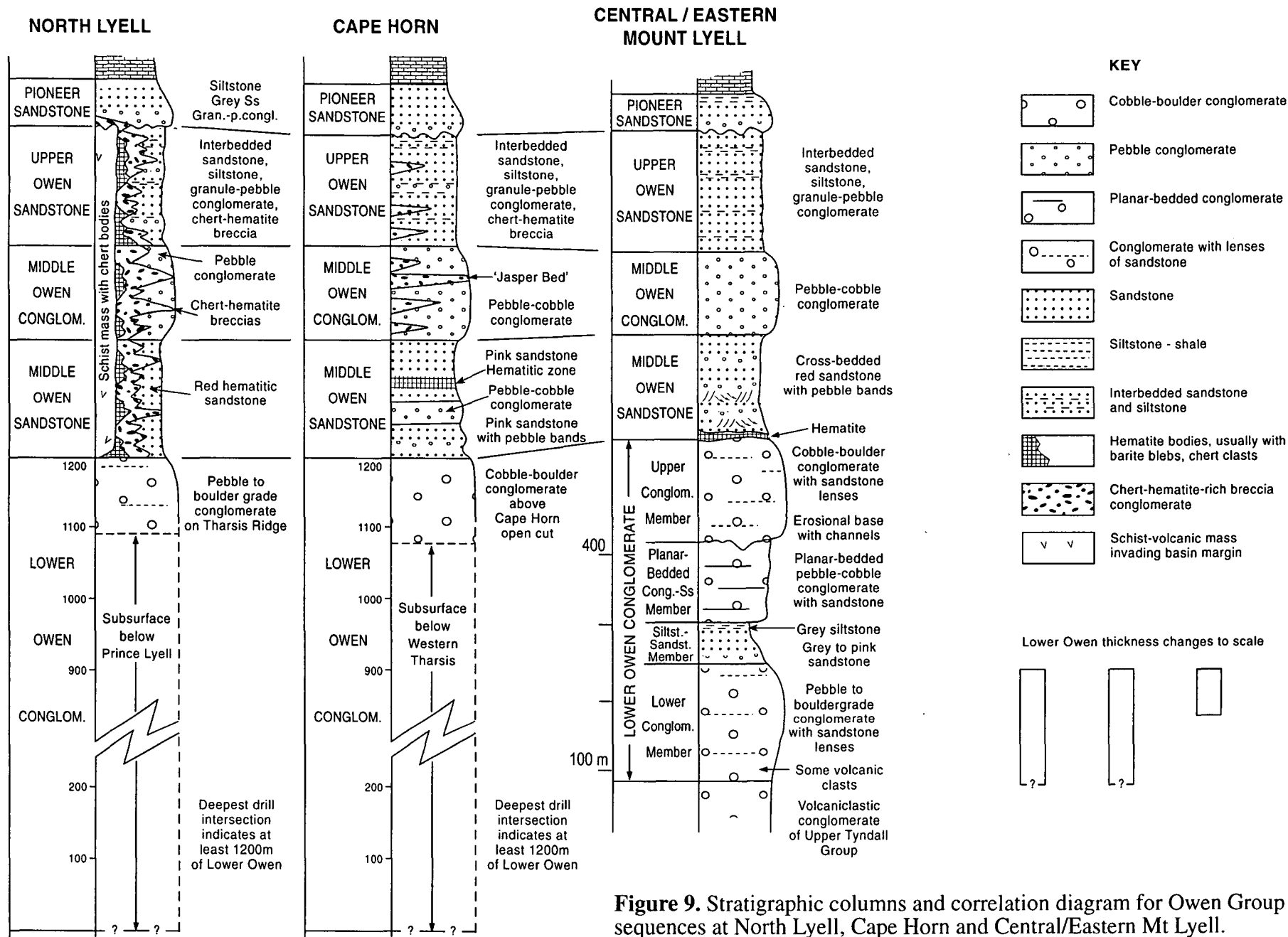


Figure 9. Stratigraphic columns and correlation diagram for Owen Group sequences at North Lyell, Cape Horn and Central/Eastern Mt Lyell.

siltstone assigned to the Newton Creek Sandstone, representing submarine fan-delta facies (Corbett, 1975; Terry, 1995).

In the Cape Horn area, limited exposures of the conglomerate sequence along the Great Lyell Fault surface, where much of the sequence is difficult of access, show considerable local slump-type disturbances of bedding and some internal unconformities suggesting active fault movements during sedimentation. A significant amount of volcanic detritus is apparent in the upper parts of the exposed sequence here, in the form of clasts in the conglomerates (typically of quartz-feldspar-phyric lava), and grains of volcanic quartz (typically with embayments) in the sandstones. One sandstone bed (OG 38) sampled had approximately 40% volcanic detritus apparent in thin section.

Middle Owen Sandstone

A dramatic change is evident from the coarse grey terrestrial facies of the Lower Owen to the red-brown, hematite-rich sandstone which dominates the Middle Owen Sandstone in the mine area. The contact in many places is marked by a wedge or lens of reddish-purple, locally-derived chert-hematite breccia-conglomerate, marking the first appearance of this facies type into the Owen sequence. The red sandstones are interbedded with units of granule-pebble to pebble-cobble grade conglomerate in places, and red/brown sandstone with lines or bands of white pebbles is a very typical expression (Plate 1c). Trough-type cross-bedding is abundant, but may be somewhat obscured by the intense hematite staining and associated liesegang banding.

In zones closest to the volcanics contact, such as on Tharsis Ridge, the sequence tends to consist of about equal parts of 'normal' red sandstone and beds or lenses of chert-hematite-rich pebble-cobble grade conglomerate-breccia up to several m thick (Plate 1d). In its most proximal form, as occurs adjacent to the schist contact at the NE end of Tharsis Ridge, the chert-hematite breccia has irregular clasts of chert and hematite up to 30 cm or more across, as well as clasts of sericite schist and other volcanic rock types, in a coarse matrix of chert, hematite, barite and altered volcanic material (Plate 2a). These coarse breccias finger out laterally into the 'normal' red sandstones.

The base of the Middle Owen Sandstone at the eastern end of Mt Lyell, some 3 km east of the mine, is marked by a zone of semi-massive hematite and intense hematization of the underlying Lower Owen Conglomerate beds. The hematite has been prospected by several shallow trenches, and serves to emphasise the abrupt change from the grey-white terrestrial Lower Owen conglomerates to the red, hematite-rich shallow marine-deltaic sandstones. This change may well be a basin-wide phenomenon, since a number of occurrences of semi-massive hematite and hematitic shale have been mapped on the Tyndall Range, a few km to the north, at the channelled contact between underlying coarse conglomerate and overlying sandstone (Corbett and Jackson, 1987).

Middle Owen Conglomerate

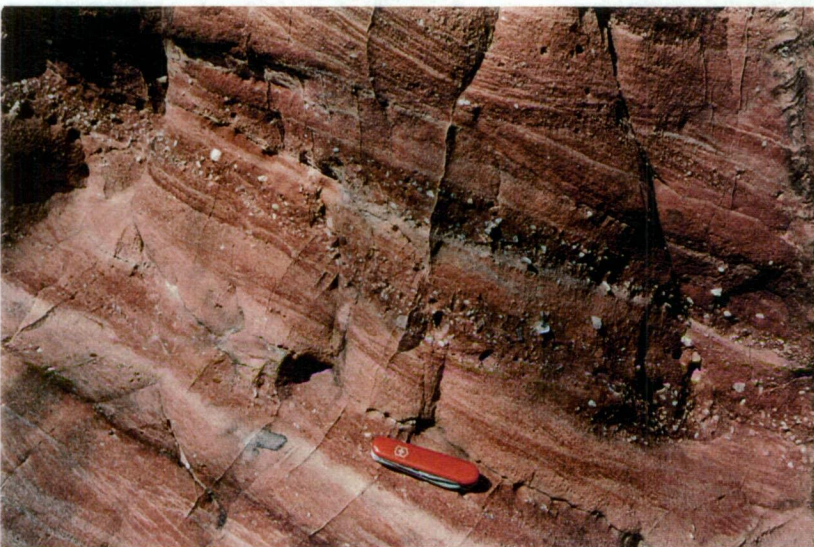
This formation is prominent along the southern slopes of Mt Lyell above the North Lyell mine, where it was originally referred to as the 'mountain conglomerate' (Connolly, 1947). It consists mostly of thick-bedded pebble conglomerate (Plate 2b) with sparse intercalated lenses and beds of coarse sandstone, and resembles a finer-grained version of the braided stream facies of the Lower Owen. Trace fossils and mudstone drapes in the upper part of the formation indicate shallow marine-tidal conditions, but most of the formation appears to be



(a) View looking north of Great Lyell Fault contact at Cape Horn open cut. Horizontally bedded Lower Owen Conglomerate to right, schists derived from Central Volcanic Complex to left.



(b) Typical Lower Owen Conglomerate texture from Upper Conglomerate Member, eastern end of Mt Lyell.



(c) Typical Middle Owen Sandstone exposed on lower part of Mt Owen Road. Red/brown hematitic cross-bedded sandstone with pebble bands.



(d) Middle Owen Sandstone on Tharsis Ridge: Interbedded hematitic sandstone and chert-hematite breccia-conglomerate.



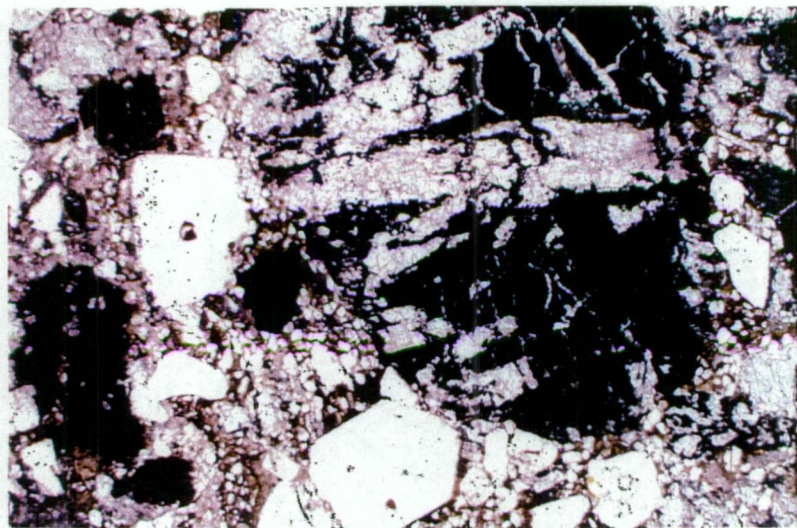
(a) Coarse proximal breccia of chert, hematite and altered volcanic clasts in hematite-barite-rich matrix at north-east end of Tharsis Ridge. Unit interfingers with Middle Owen Sandstone. Note large hematite clast left of centre, thin bands of pink sandstone to right.



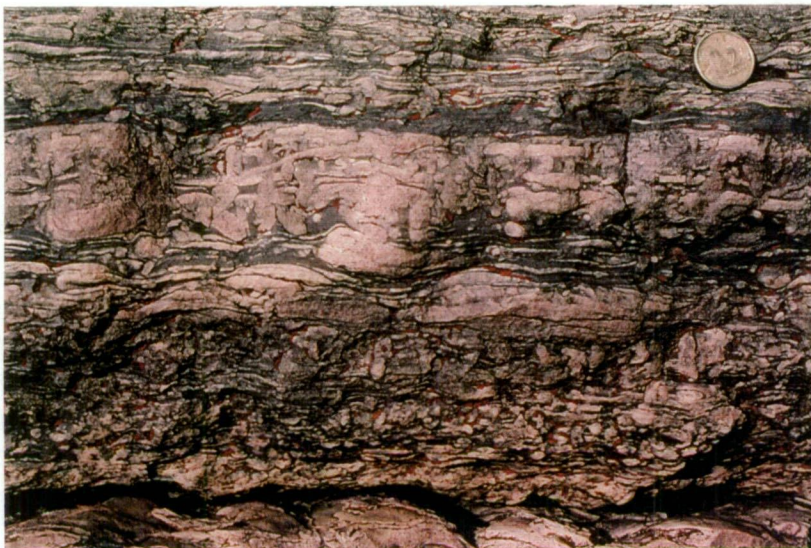
(b) Typical Middle Owen Conglomerate from cliffs above Cape Horn. Note rounded quartzite pebbles, imbrication, cross-bedding in sandstone layer.



(c) Part of 'jasper bed' within Middle Owen Conglomerate above Cape Horn, showing irregular clasts of pale chert (centre) and red jasper mixed with normal quartzite pebbles.



(d) Thin section photograph in normal light of sample from 'jasper bed' showing dark hematite clast with included barite crystals (white) in matrix rich in volcanic quartz grains.



(a) Typical interbedded sandstone-siltstone of Upper Owen Sandstone, showing flaser-type bedding, abundant burrows.



(b) Bed of chert-clast conglomerate-breccia within normal pink Upper Owen Sandstone, western end of Mt Lyell above Cape Horn.



(c) Basal part of Upper Owen Sandstone sequence on North Lyell Road, showing beds of chert-clast breccia-conglomerate interbedded with normal pink sandstone beds. Bed with siliceous 'boudins' is near left hand side.



(d) Close-up view of bed with siliceous 'boudins' showing large white chert clast and several smaller clasts.

terrestrial. In the mine area, the formation is well exposed on Razorback Ridge, where it consists of about equal parts of volcanic-derived chert-hematite-rich conglomerate-breccia and normal quartzite-clast conglomerate.

On Cape Horn Spur (west end of Mt Lyell range), the Middle Owen Conglomerate includes near its top a distinctive bed, 1.5 m thick, rich in volcanic-derived material and referred to as the '**jasper bed**' (Fig. 9). Clasts in this bed are up to 30 cm across, and in addition to the normal quartzite pebbles include (Plate 2c): angular to sub-rounded pieces of grey-white chert identical to the Comstock chert; fragments of bright red-pink jasper and of hematite-jasper-barite-chert rock identical to that forming the hematite veining in the Comstock chert (see Plate 6c,d); and abundant pieces of hematite and of hematite with included blebs of barite, some of them rounded. A thin section from this bed (OG 56; Plate 2d) shows a detrital hematite clast with included blades of barite, in a matrix rich in volcanic-derived quartz grains. A similar bed, or possibly the same one along strike closer to Comstock, was described by Solomon (1967) as resembling a 'fossil gossan' derived from weathering of the Comstock sulphide deposit, and the clast content indicates that the unit was largely derived by weathering of hematite-veined cherty alteration material such as outcrops at Comstock. Many other beds contain similar clasts of chert and hematite.

Upper Owen Sandstone

This formation abuts the schist zone along most of the eastern side of the mine area, and is also well exposed on the western summit of the Mt Lyell range. The sequence is a complexly interbedded mixture of sandstone, siltstone and granule-pebble conglomerate, with abundant trace fossils (Plate 3a) and sedimentary features (e.g. flaser bedding, mudcracks, intensely bioturbated layers, mud drapes) indicating deposition in shallow marine to tidal zone environments. Colour varies from red-brown (hence the early name of 'chocolate sandstone'), due to hematite enrichment and oxidation, to green and grey in a few unoxidised zones. Lenses and beds of chert-rich (Plate 3b) and chert-hematite-rich conglomerate-breccia are common throughout the formation in the mine area, and coarse chert-rich breccias are present in basal beds where the formation abuts the North Lyell chert body (Plate 3c,d). Some sandstone and siltstone beds appear to have been largely replaced by hematite where the latter forms semi-massive bodies on the schist contact in places.

The Haulage Fold Zone and Haulage Unconformity

The Upper Owen Sandstone beds are locally upturned and folded in a zone about 100 m wide along the schist contact between North Lyell and Gormanston, as described by Solomon (1964) and Arnold (1985). The author's mapping shows that a similar zone of upturned and folded Upper Owen beds, 50 to 100 m wide, is present in the Copper Estates area in the south, and another on the eastern side of the Comstock open cut in the north. The folded zone typically has an abrupt eastern margin, well exposed on Pioneer Spur and at Copper Estates, where the steeply dipping to overturned beds revert to a sub-horizontal attitude (after restoration of Devonian folding) at a prominent synclinal or monoclinal fold. This synclinal upturn was referred to as the 'Razorback Syncline' and featured prominently in early interpretations of the structure of the area (eg Connolly, 1947; Wade and Solomon, 1958).

Good outcrops of the zone on Whaleback, Linda and Pioneer Spurs show that the bulk of the beds are overturned parallel to the schist-Owen contact, dipping steeply west but facing east. Fold axes may be difficult to locate within the steeply dipping beds, but some well exposed

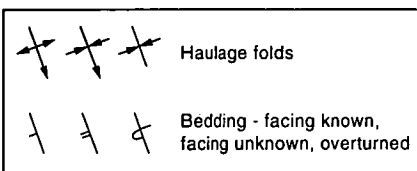
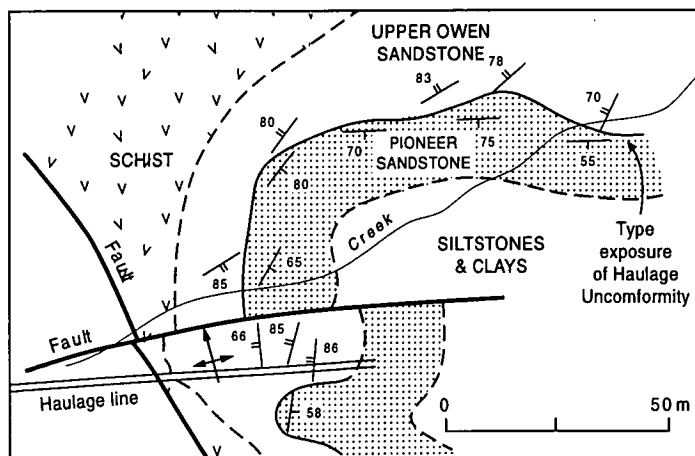
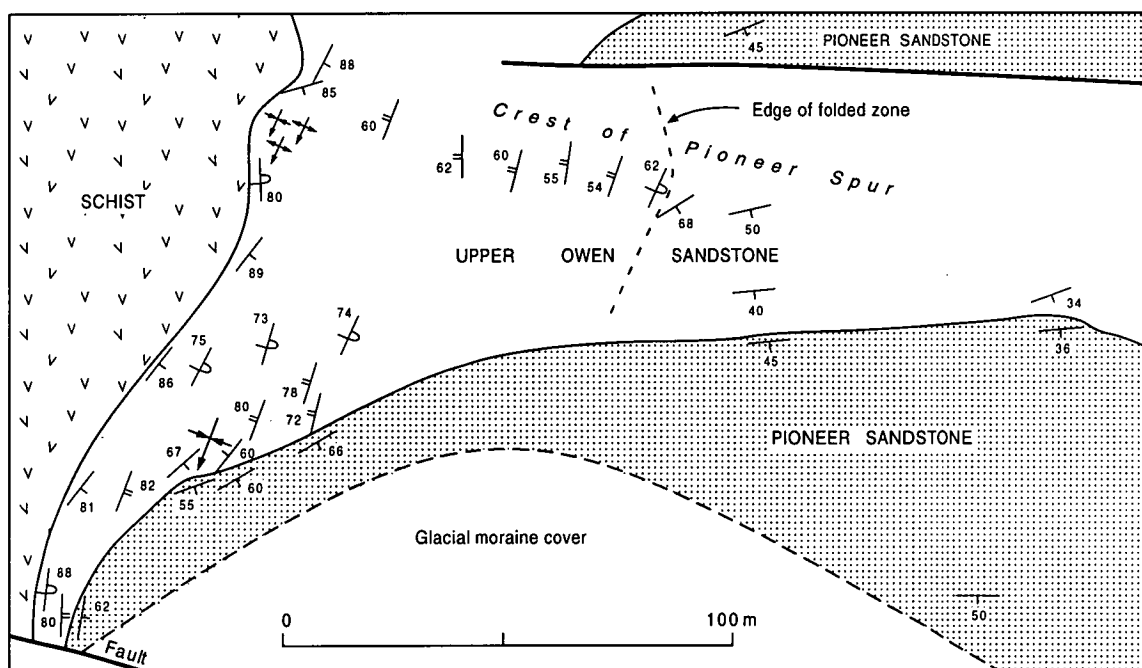
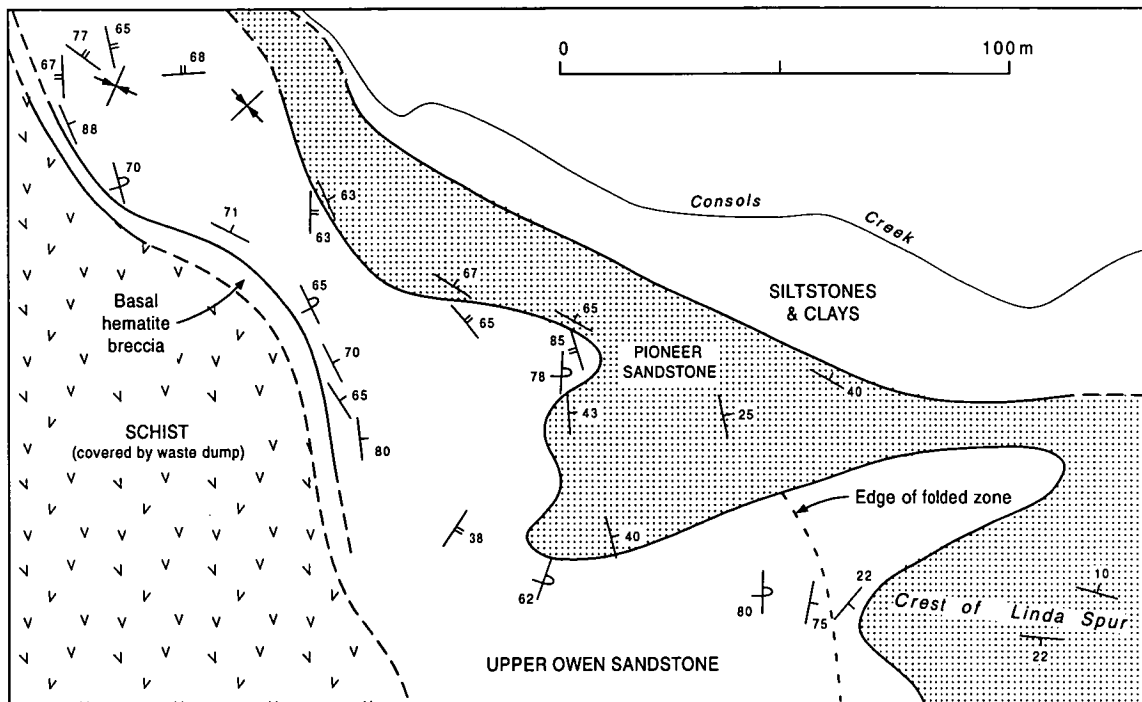


Figure 10. Detailed geological maps of three areas where Haulage Unconformity is well exposed. Top: Linda Spur–Consols Creek area. Middle: Western end of Pioneer Spur. Bottom: near base of Mt Lyell haulage line upstream from King Lyell.

examples are present west of the quarry on Whaleback Spur (Plate 4a) and on Pioneer Spur (Plate 4b). The folds vary from open to tight, and typically have axial planes dipping steeply west, with one overturned limb. The fold axes trend roughly N-S, but vary from NW to SW, probably due to overprinting by the later Devonian NW-trending D₂ folds. Some tightening and overprinting of the folds by the Devonian D₁ event has probably occurred in some places, producing folds which are tight to isoclinal, eg around the head of the Whaleback Spur quarry.

Most of the folds have no obvious associated cleavage, and appear to have occurred when the beds were semi-consolidated but sufficiently coherent to be mechanically competent. Williams (1993), in describing the Haulage folds, noted that the Upper Owen sandstones were soft enough to be penetrated by pebbles from the Pioneer Sandstone, but sufficiently coherent to flex with orthogonal thickness unchanged. Overprinted and compressed folds may show the Devonian (D₁?) cleavage.

Associated with the upturned and folded zone is the spectacular Haulage Unconformity (Wade and Solomon, 1958), developed where the overlying Pioneer Sandstone cuts across the upturned edges of the beds (Plate 4c,d). This unconformity is well exposed in a number of places between North Lyell and the Iron Blow, the type outcrop being at the base of the original Mt Lyell Haulage near the Iron Blow (Fig. 10, Plate 4d). One of the best exposures is that on the southern flank and crest of Pioneer Spur (Fig. 10), where the unconformity surface can be walked from near the schist contact, where there is marked angular discordance on the underlaying steeply-dipping to overturned and folded Upper Owen beds, eastwards to where the surface crosses the edge of the folded zone and becomes essentially conformable. One fold axis has been traced to the unconformity surface, but the best exposure of folds is on the ridge crest near the schist contact, where the Pioneer Sandstone has been stripped off.

A similar exposure of the unconformity is available on the north-west section of Linda Spur (Fig. 10), where the unconformity surface can be traced for several hundred metres across folded Upper Owen beds to the edge of the folded zone, where the two units become conformable. At various points along the unconformity surface on the folded zone here, the angular discordance ranges from zero (ie beds above and below are parallel) to 80°, indicating that the Pioneer Sandstone has transgressed an already folded sequence.

The folding and upturning clearly occurred after deposition of the Upper Owen beds and before deposition of the Pioneer Sandstone, while the Owen beds were semi-consolidated. The overturning indicates eastwards-directed movement, and strongly suggests that the deformation was caused by further advance of the schist mass from the Great Lyell Fault, as discussed further later.

Pioneer Sandstone and Gordon Group Limestone

The Pioneer Sandstone is of the order of 10-30 m thick in most areas, and can be subdivided into four sub-units in the type area around Pioneer Spur (Fig. 11). These are a basal unit comprising lenses of chert-hematite- rich conglomerate, similar to those described from the Middle and Upper Owen formations; a lower unit up to 15 m thick of pink to grey pebble-granule conglomerate with intercalations of sandstone and minor siltstone; followed by a 5-10 m thick unit of grey cross-bedded sandstone with chromite-rich bands and minor green siltstone (the 'typical' Pioneer Sandstone); followed by an upper unit of grey-green siltstone and shale with minor sandstone. The upper unit grades into calcareous shales and impure

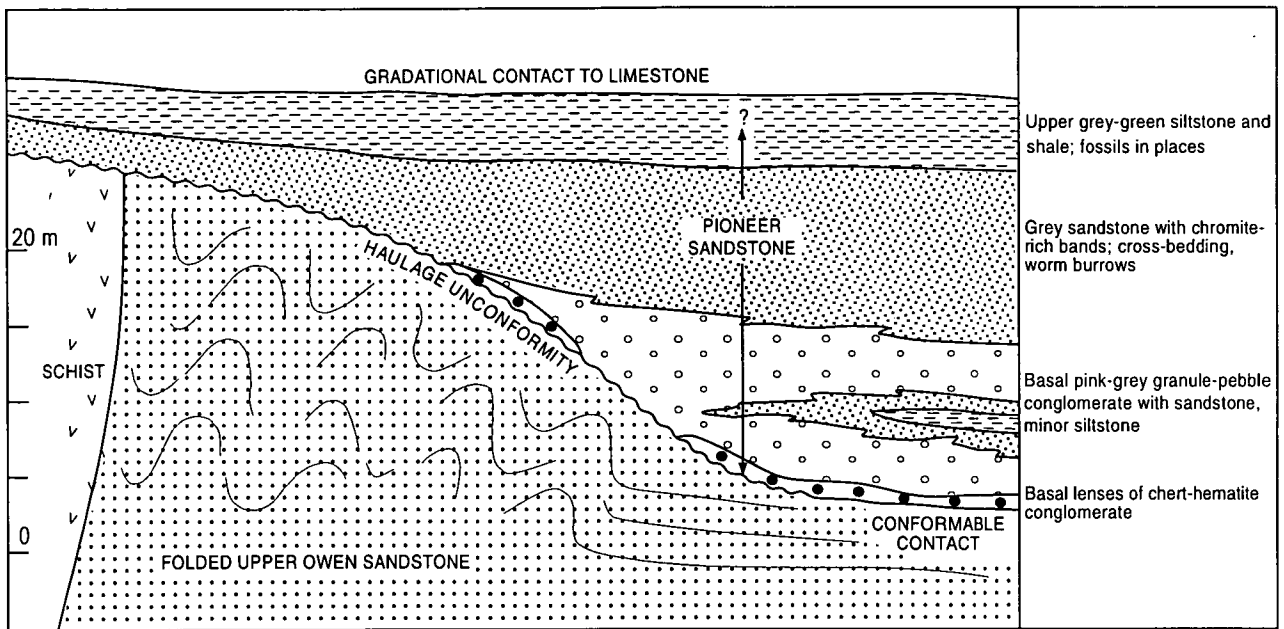


Figure 11. Stratigraphic diagram for Pioneer Sandstone in the North Lyell–Gormanston area.

limestones of the Gordon Group, and might be included with the limestones in some classifications.

The basal chert- hematite conglomerate is well developed near the old Balance Shaft site of the Lyell Blocks workings (Fig. 1), where it is up to several m thick. It contains clasts of chert (identical to the North Lyell chert) up to 20 cm across, and numerous hematite clasts, some in the form of small rounded pebbles. It is also well exposed on the upper crest of Linda Spur, where several separate beds of breccia are present intercalated with normal siliciclastic conglomerate and sandstone. A thin unit is present on the lower slopes of Pioneer Spur, and in one place contains several blocks of red sandstone identical to the Middle Owen Sandstone (Plate 5a; OG 80) .

The lower conglomeratic unit is best developed around the lower eastern parts of the spurs between Gormanston and North Lyell, and appears to thin markedly and wedge out over the zone of Haulage folding in the Upper Owen beds. This implies that the folded zone formed a bulge or rise on the floor of the depositional basin, and suggests that the basal unit may largely represent material eroded from the upturned Upper Owen (and Middle Owen) beds. The granule-pebble conglomerate beds are up to a metre thick, and are typically interbedded with sandstone. A unit of pink to grey sandstone and minor siltstone which occurs within the conglomeratic sequence is virtually identical to some of the Upper Owen facies, and is difficult to differentiate from that unit in some places.

The grey cross-bedded sandstone facies (Plate 5b) is relatively widespread, and has trace fossils in places indicating shallow marine depositional environments. This facies forms the bulk of the Pioneer Sandstone correlate around Queenstown, where it rests directly and unconformably on volcanic rocks. The ultimate source of the chromite in these beds must have been the Cambrian ultramafic complexes such as occur throughout western Tasmania, but



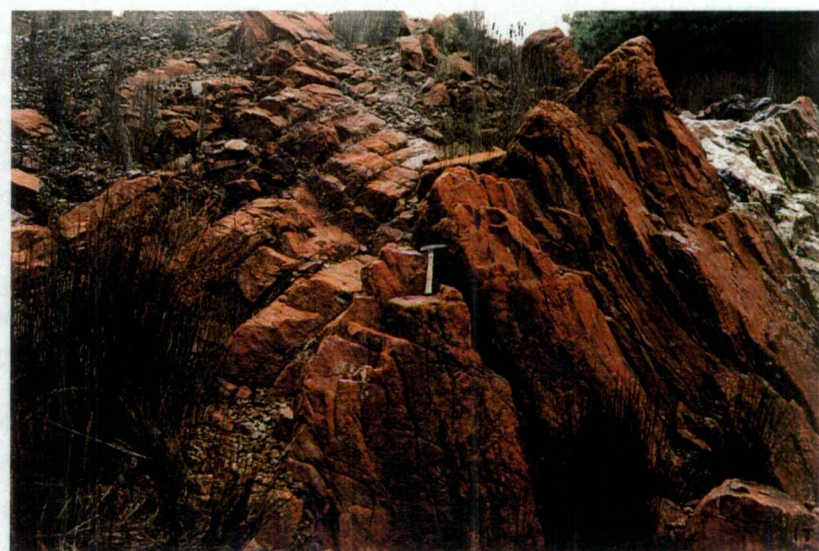
(a) Synclinal Haulage fold within Upper Owen Sandstones, 100 m west of Whaleback Spur quarry.



(b) Haulage fold within lower beds of Upper Owen Sandstone, crest of Pioneer Spur.



(c) View looking north of Haulage Unconformity at Whaleback Spur quarry. Pioneer Sandstone to right overlies steeply dipping Upper Owen Sandstone to left.



(d) Haulage Unconformity at original type area near foot of Mt Lyell haulage line. Pioneer Sandstone to left, dipping south, overlies Upper Owen Sandstone to right, dipping steeply west.



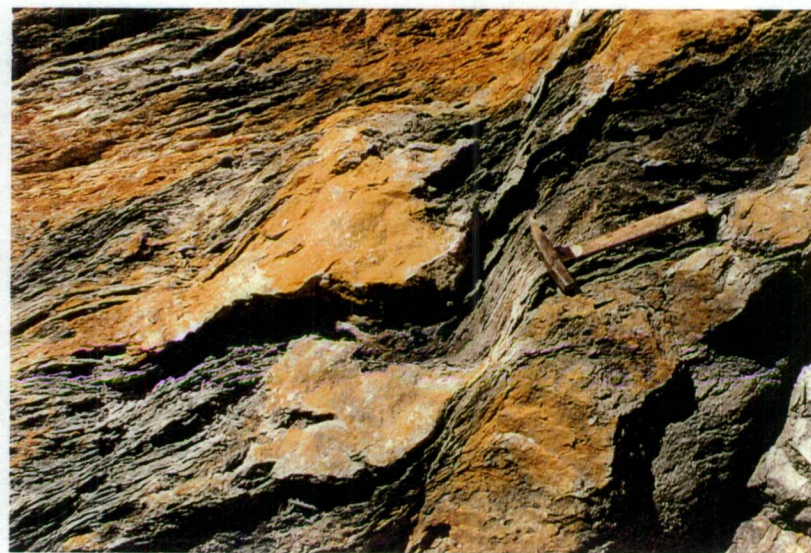
(a) Basal pebbly beds of Pioneer Sandstone overlying Upper Owen Sandstone beds on conformable contact, crest of Pioneer Spur towards eastern end. Note blocks of red Middle Owen Sandstone in base of Pioneer.



(b) Grey cross-bedded facies of Pioneer Sandstone with dark bands marked by concentrations of chromite, Lyell Blocks area.



(c) View looking south into Comstock open cut, showing sericite-pyrite schists of core of alteration zone, with chert bodies evident as grey patches. Telegraph pole gives scale.



(d) Small chert bodies within sericite-pyrite schist, Comstock open cut.

much or all of it in the Queenstown area may have been derived from re-working of the Owen Group sediments, which have been shown to contain chromite in at least some places (Bottrill, 1986).

The upper siltstone-rich unit is generally somewhat weathered and poorly exposed. It forms part of the 'copper clay' host unit in the synclinal valleys between Gormanston and North Lyell, and contains trace fossils and rare shelly fossils- mainly brachiopods- in a few places. The author has noted such fossils in drill hole NL 1101 at North Lyell.

Fossils from the Pioneer Sandstone have been examined by Laurie (1996), who described brachiopods from a correlate of the formation beside the Mt Jukes Road near the King River, and also from Whites Creek, on the northern side of Pioneer Spur. The brachiopods belong to the Family Rhyncotremitidae, which first appear in the fossil record in the Middle Ordovician (late Llanvirn to earliest Caradoc, or late Darriwilian to Gisbornian), and are known elsewhere in Tasmania in the upper part of the Cashions Creek Limestone in the Florentine Valley (Laurie, 1991). The fossils are from the middle to upper parts of the formation, and no age data are available for the basal conglomerates. However, it seems likely that most of the Pioneer Sandstone is considerably younger than the Upper Owen sediments, and that there is a significant time break associated with the erosion interval represented by the Haulage Unconformity. Some uncertainty exists, however, because of the lack of data on the age of the Upper Owen formation.

The Pioneer Sandstone marks a marine transgression which covered the Owen Group sediments, the zone of Haulage folds and the adjacent schist mass, and spread across the volcanic areas west of the Great Lyell Fault. The upper siltstones are overlain gradationally by yellow calcareous shales and black shales, passing up into limestones of the Ordovician Gordon Group. The siltstones, shales and associated limestone-derived clays contain blebby native copper and various secondary copper minerals in several synclinal valleys adjacent to the schists between North Lyell and Gormanston, forming the 'copper clay' deposits (Solomon, 1969). A large unstable wedge of the siltstones and clays, with scattered outcrops of Pioneer Sandstone, is present against the North Lyell Fault at the North Lyell open cut. The distinctive black puggy clays of the Gordon Group have been incorporated into bouldery glacial deposits in places, where ice has over-ridden them, as in the zone just east of Lyell Blocks.

The limestone sequence is overlain by sandstones and shales of the Silurian- Early Devonian Eldon Group in large synclinal valleys to the east and west of the West Coast Range.

Middle Devonian Deformation - the Tabberabberan Orogeny

Devonian structural aspects of Mt Lyell geology have been treated in some detail by Cox (1981), Arnold (1985), Berry (1990, 1992) and Williams (1993). The West Coast Range area was strongly deformed during the Middle Devonian Tabberabberan Orogeny, which initially produced broad, N-S oriented folds with poorly developed cleavage (S₁), followed by NW to WNW-oriented folds with associated strong cleavage (S₂). It is this S₂ cleavage which forms the SW-dipping schistosity in the 'Lyell Schists' (Cox, 1981; Williams, 1993). A strong down-dip stretching lineation is associated with this cleavage, and most of the orebodies are elongated parallel to this lineation (Cox, 1981). The D₂ folds are very prominent in the Owen

Group rocks, particularly in the North Lyell- Gormanston area, where a series of anticlinal ridges and synclinal valleys plunge eastwards into the Linda Valley (Fig. 1, and frontispiece).

Numerous NW-oriented faults are associated with the D₂ folds in the Owen Group rocks, but are often difficult to trace through the volcanic schists. Several of these faults appear to amalgamate to form a single fault cross-cutting the main part of Tharsis Ridge (Fig. 1). Fault-bounded wedges of volcanic rocks penetrate the Owen Group contact in several places near Whaleback Spur, one of them extending into the north-west corner of the aggregate quarry. These wedges are suggestive of tensional openings induced by folding of a sequence previously folded on perpendicular trends in the Haulage event, against an interface of relatively ductile schists.

The North Lyell Fault appears to be a late D₂ structure associated with major uplift of the large block of Owen Group rocks forming the massif of the Mt Lyell range. Associated uplift on the Great Lyell Fault in the Cape Horn- Comstock area has caused rotation of D₂ cleavages in this area into a north-easterly trend (Cox, 1981).

Late Devonian and Post-Devonian Rocks

Post-Tabberabberan rocks in the general Mt Lyell area include several lamprophyre dykes, Permo-Carboniferous sediments at Mt Sedgwick, and widespread Pleistocene glacial deposits. The lamprophyre dykes (Fig. 1) intrude the volcanic sequence in the mine area and the Owen Group sequence on Mt Owen (Corbett et al, 1989). They are uncleaved and probably late Devonian in age.

A thin sequence of marine sedimentary rocks- mainly pebbly siltstone, sandstone and minor limestone- of late Carboniferous to Permian age sits on a landscape unconformity of folded Owen Group rocks at Mt Sedgwick, some 6 km north of Mt Lyell. This sequence is intruded by a sill remnant of Jurassic dolerite which forms the summit of Mt Sedgwick. A smaller dolerite remnant is present near the western edge of Sedgwick Bluff (Calver et al, 1987).

Bouldery glacial debris, with large erratics of weathered Jurassic dolerite and Siluro-Devonian fossiliferous sandstone, blankets much of the Linda Valley and the eastern slopes of the mine area between North Lyell and Gormanston. It was deposited by an arm of the main King Valley glacier which flowed up the Linda Valley during the extensive (?)Early Pleistocene Henty glacial phase (Fitzsimons et al., 1993; Corbett et al., 1989). A local sequence of gravels, sands and clays, with in-situ tree stumps, underlies these glacial deposits in the valley between Pioneer Spur and Linda Spur, and appears to represent a late Tertiary (?Pliocene) fluvio-lacustrine deposit (Fitzsimons et al, 1993).

Similar coarse morainal deposits with weathered clasts of dolerite occur in the vicinity of the Tasman Crown, Lyell Comstock and Cape Horn mines, and along the Queen River valley to the Lynchford area (Corbett et al., 1989). They were apparently deposited by a glacier which overflowed from the Comstock Valley and the Mt Sedgwick area.

Glacial erosion may partially account for the absence of deep weathering and oxidation in the Mount Lyell area, where fresh sulphides are common at surface. A remnant of Tertiary gossan was preserved on the eroded top of the Iron Blow sulphide body where, coincidentally, the gossan abutted a large hematite formation on the eastern margin of the sulphides representing

the Cambrian gossan on this same body (see Fig. 22). Another remnant of Tertiary gossan is preserved on the small lead-zinc massive sulphide body at the Comstock mullock quarry (Plate 7a).

GEOLOGY OF THE LYELL COMSTOCK AREA - THE UPPER PART OF THE MT LYELL SYSTEM

Introduction

The Lyell Comstock- Tasman Crown area lies at the northern end of the Mt Lyell field (Fig. 1), and is separated from the main part of the field by a belt of rough bushland and the conglomerate bulk of the Mt Lyell range. This physical separation from the main active part of the field, and the fact that copper mining at Comstock ceased in 1944, before active geological monitoring and study became normal practice on the mine lease, possibly accounts for the poor integration of Comstock geology into the general knowledge of the field.

The area was pegged for gold around 1890, and copper was discovered in about 1898 after tunnelling into the pyritic schists. The Lyell Comstock Consolidated Copper Company Ltd developed the mine via 6 tunnels and a shaft but made little profit. The mine was bought by the Mount Lyell Mining and Railway Company in 1912, and worked until forced to close in 1921 due to a fall in copper price. It was re-opened in 1929 and developed by stoping to progressively deeper levels until final closure in 1944 (Blainey, 1967). The copper ore was railed down the narrow valley to the Mount Lyell smelter.

The Tasman and Crown Lyell Extended Mines NL company (now generally referred to as 'Tasman Crown') was formed in 1899 to work some low-grade copper discovered by tunnelling in schists east of the Comstock chert body. The lead-zinc sulphide lode was discovered near the end of No 2 tunnel in 1903, and a shaft was sunk through the overlying glacial gravels in 1910. A silver-lead concentrate was produced for the Zeehan smelter, but the mine was not profitable and was sold to the Horseshoe Syndicate in 1922. This group sent away several thousand tons of ore, but not profitably, and the mine was sold to the Mount Lyell Mining and Railway Company in 1933, mainly to provide access to the adjacent Comstock workings (Blainey, 1967). A description of the mine is given by Nye (1925).

Considerable exploration, mainly involving deep drilling and geophysical surveys, has been carried out at Comstock since the mine was closed, the most recent being reported by Halley (1994). Mapping has previously been undertaken by Komyshan (1985), Arnold and Dufty (1991) and Corbett (1989, 1997a). Honours research projects have been undertaken by Green (1971) and MacDonald (1991).

General Geology

The volcanic host sequence (Fig. 12) consists of felsic rocks of the Central Volcanic Complex overlain by the upper andesitic unit. The andesitic rocks trend NW-SE and face NE, with steep to overturned dips. The alteration zone cuts discordantly through the andesitic sequence, along a highly irregular boundary.

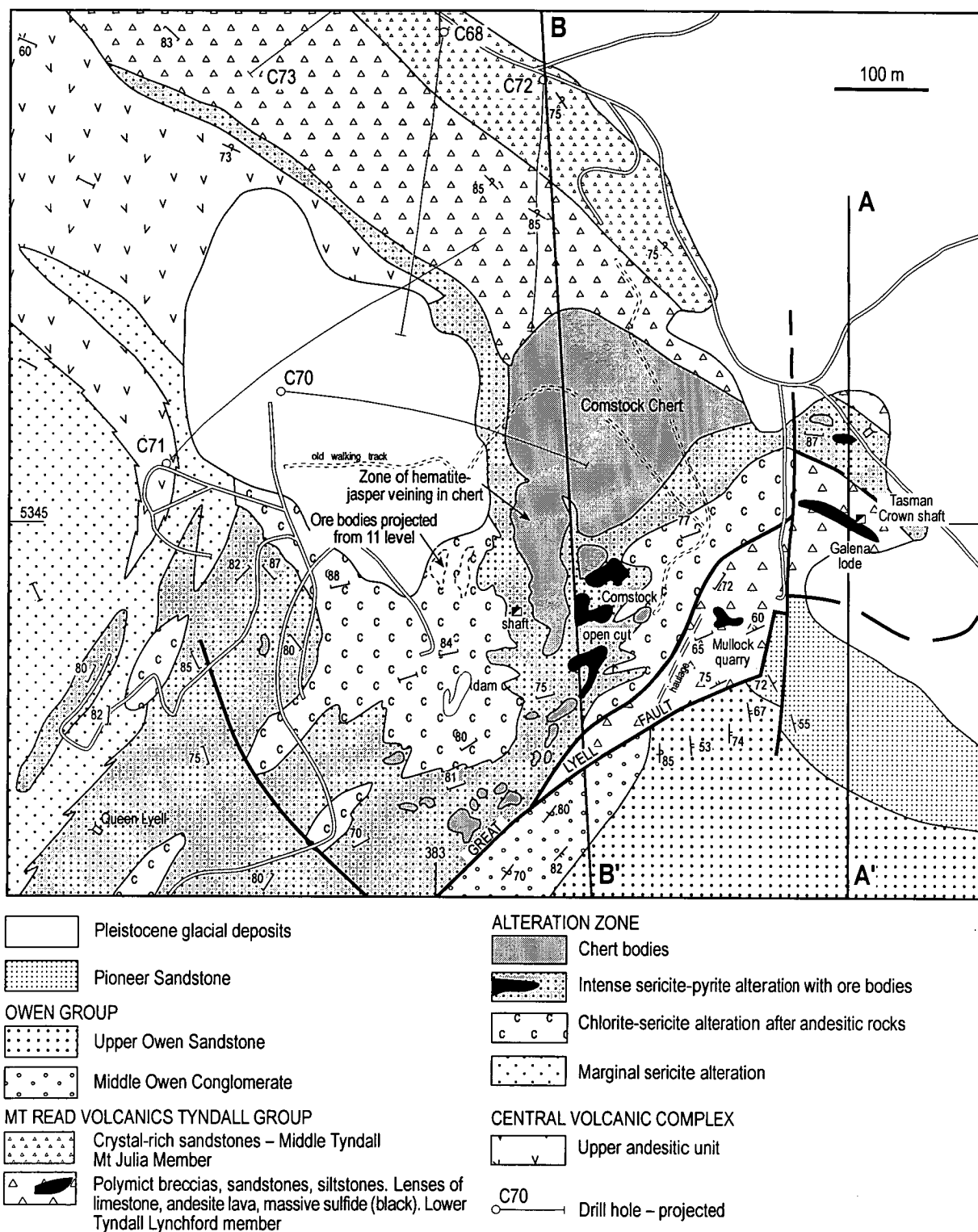


Figure 12. Geological map of the Lyell Comstock–Tasman Crown area (partly after Arnold and Dufty, 1991).

The Lower Tyndall Group unit is of the order of 150 m thick, and also faces NE, with steep to overturned dips. The Middle and Upper Tyndall Group, consisting of well-bedded volcanoclastic sandstones, conglomerates and minor siltstones, have a combined thickness of about 250 m, and are overlain disconformably by Pioneer Sandstone and Gordon Group limestone beneath the glacial cover. The sub-vertical dips of the host rock sequence and Tyndall Group strata mean that the present plan view of the volcanic rocks (Fig. 12) actually represents a cross-section perpendicular to bedding.

A wedge of Lower Tyndall Group rocks bounded by the Great Lyell Fault and a second parallel fault, lies immediately east of the Comstock open cut, and contains within it a well-preserved small lens of lead-zinc massive sulphide at the mullock quarry. The continuation of this wedge to the northeast, across a possible N-S cross-fault, contains the larger Tasman Crown galena-sphalerite lode. The mass of volcanics containing the Tasman Crown mine workings appears from early drill records to be floored at quite shallow depths by Pioneer Sandstone and/or Upper Owen Sandstone (Fig. 13a), suggesting an unusual overflow or collapse structure reminiscent of that at North Lyell, as described later. Unfortunately, there is very little surface outcrop in this area due to the deep glacial cover, and most of the core from the early drilling in the area has been discarded, leaving only sketchy drill logs on which to reconstruct the geology.

The Owen Group sequence east of the Great Lyell Fault dips moderately northwards except where the beds have been dragged into overturned westerly dips against the fault. The Pioneer Sandstone, on the lower northern slopes, has an angular discordance on the underlying Upper Owen beds adjacent to the Comstock open cut, representing the Haulage Unconformity. The Gordon Group limestone overlies the Pioneer Sandstone on the valley floor, beneath the glacial cover. The Owen Group sequence does not extend west of the Great Lyell Fault, which formed the basin margin during Owen deposition. In this western position, the Tyndall Group rocks are overlain disconformably by the Pioneer Sandstone (Fig. 13a,b; Corbett et al., 1974).

The Middle Owen Conglomerate, where exposed along the Great Lyell Fault to the south of the Comstock mine, contains a number of beds with abundant angular to sub-rounded clasts of chert up to 30 cm across, identical to that of the siliceous alteration bodies. As previously described, the 'jasper bed' also contains clasts of hematite-jasper vein material identical to that in the southern part of the Comstock chert body, as well as massive hematite, hematite with barite blebs, and pink jasper. The clast content clearly indicates that the siliceous alteration and the hematite-jasper-barite veining had already taken place, and that the alteration zone had been unroofed and exposed to erosion, by the time of deposition of the Middle Owen Conglomerate beds in the Late Cambrian. This evidence becomes particularly important when considering the origin and timing of the North Lyell mineralisation and alteration.

The Alteration Zone at Comstock

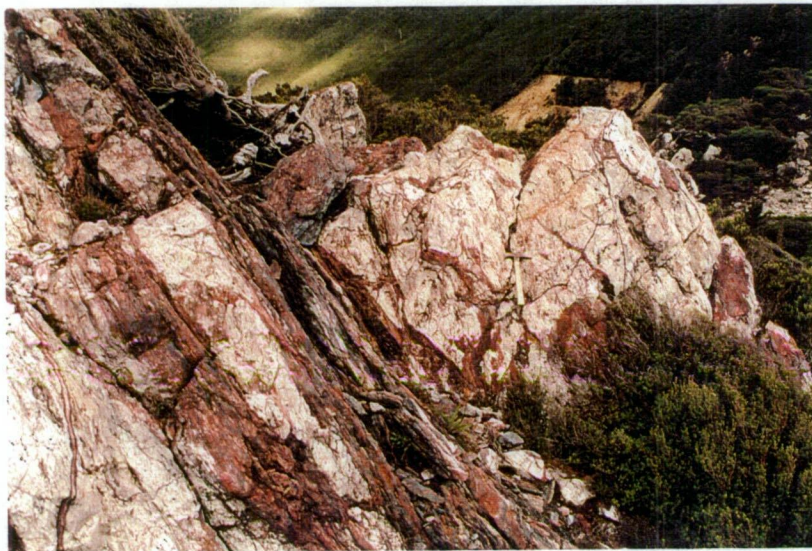
The alteration zone between Cape Horn and Comstock trends NE-SW, parallel and adjacent to the Great Lyell Fault contact with the Owen Group (Figs 1, 2). The zone terminates discordantly against the NW-trending Tyndall Group rocks, although some of the alteration extends into the basal part of that group. The main central part of the zone, dominated by pyrite-sericite schists, is about 350 m wide, with a further zone of marginal sericite-chlorite alteration extending a further 200-300 m west. The large Comstock chert body sits at the top of the central part of the alteration zone (Figs 1,12), discordantly overlain by Lower Tyndall



(a) Medium size chert body or 'silica head', Comstock open cut. Note wrapping effect of schists, small embayment of schist on left hand side, patches of vein quartz.



(b) Breccia texture within Comstock chert body. Angular white chert clasts showing jigsaw fit patterns in reddish hematitic 'matrix'.



(c) Outcrop of Comstock chert body with abundant veins of pink-red hematite-jasper.



(d) Detail of hematite-jasper veining in part of Comstock chert, showing banded textures.

Group rocks. A zone of smaller chert bodies tails off southwards in the alteration zone for about 600 m. Patches and zones of chlorite schist, after andesitic bodies, are present within the central zone.

Foliation within the schists trends northeast and dips steeply northwest, sub-parallel to the Great Lyell Fault. This foliation appears to be a local modification of the normally NW-trending S2 structure, warped by late D2 uplift of the large block of Owen Group on the Great Lyell and North Lyell Faults (Cox, 1981).

The sericite-pyrite-rich central part of the alteration zone is only 100-200 m wide at the Comstock open cut (Fig. 12, Plate 5c), where it can be seen to cut through chlorite-altered andesitic host rocks. Sharp contacts are evident in places between dyke-like arms of the sericite-pyrite schist and the more massive chlorite-altered andesite, the latter preserving some primary banding and breccia texture in places. A strong impression is gained that the intense sericite-pyrite-silica alteration overprints (and essentially replaces) the earlier chlorite alteration. South from the open cut, the sericite-pyrite alteration extends irregularly outwards through the chlorite-altered andesitic material to form a much wider zone (Fig. 12), and there is also some 'belling out' of the zone to the north along the top of the andesite sequence. Typical sericite-pyrite-silica schist with lenses of chert continues into the Tasman Crown workings.

The siliceous alteration bodies show a range of sizes from small blebs and flecks of chert a few mm to a few cm across within the sericite-pyrite schists (where they commonly resemble pebbles), to larger bodies a meter or so across usually somewhat wrapped and smoothed by the cleavage (Plate 5d), to larger bodies several meters to tens of meters across (Plate 6a), forming bold outcrops, to the 'end member' represented by the very large Comstock chert body, over 300 m across, at the top of the system. Only the larger chert bodies are shown on the map (Fig. 12), but a rough estimate suggests that cherty silica constitutes 20-30% of the core part of the alteration zone in the Comstock open cut area.

Many of the chert bodies exposed in the open cut are pyrite-rich, with inter-banded and disseminated pyrite, and these typically have a blue-grey colour (Plate 5c). Minor blebby chalcopyrite is also present within this type in a few places. Many have infolds and indentations of schist, suggesting an originally irregular shape which has been smoothed and wrapped by the schistosity (Plate 6a). Gradations exist from chert bodies with minor pyrite through zones of inter-mixed pyrite and chert to pyrite-sericite schist with minor chert, suggesting that all three components have been deposited more or less simultaneously.

The mineralogy of the alteration has not been studied in detail. The predominant yellowish micaceous mineral in the schists is referred to as 'sericite', although observations at Western Tharsis (Huston and Kamprad, 2000, in press) and at North Lyell (Bryant, 1975) suggest that some of it could be pyrophyllite. An apple green variety of the 'sericite' is present as blebs and patches within the schist, as are blebs and veinlets of fluorite. The pyrite content varies from a few percent to more than 60%.

Drill intersections along the upper stratigraphic margin of the Comstock chert body indicate that the sericite-pyrite-silica alteration extends a few meters into the basal Tyndall Group rocks in many places, commonly obscuring the boundary between the clastic chert-rich breccias above and the brecciated chert below.

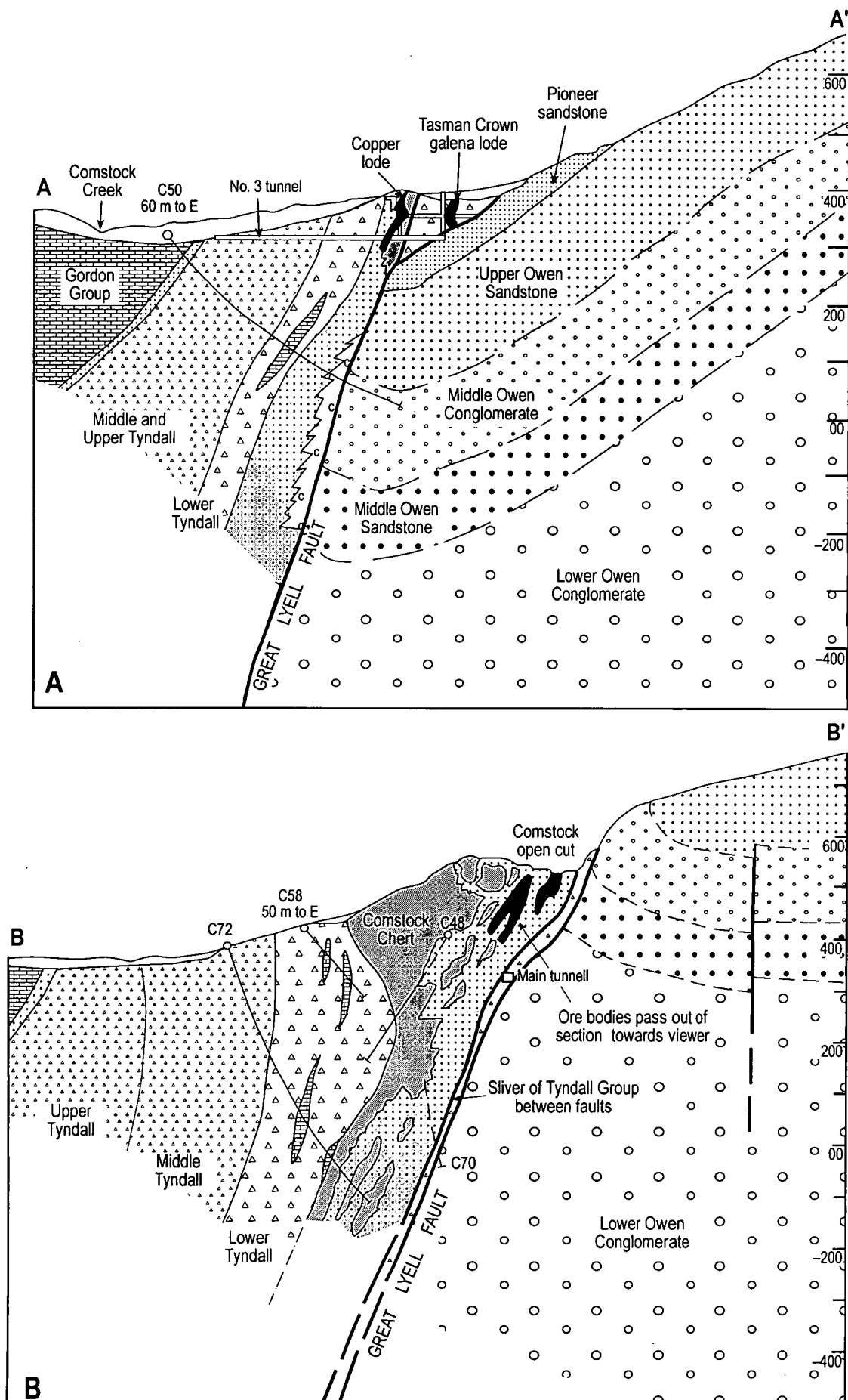


Figure 13. (A) Cross section AA' through Tasman Crown workings. (B) Cross-section BB' through Comstock chert and Comstock open cut. See Fig. 12 for location of sections and legend.

Nature of the Comstock Chert Body

The large body of white chert at Comstock, nearly 300 m across and with precipitous sides, has puzzled geologists for many decades. Although largely massive in appearance, the chert contains zones of brecciation (eg Plate 6b) and patches of apparent conglomeratic texture. Wade and Solomon (1958, their fig. 16) showed the body as an outlier of Owen Conglomerate, but referred to the cherts generally as being of hydrothermal origin. Markham (1968) considered that the irregular, pipe-like form of the body negated the possibility of a sedimentary origin, and suggested that the Comstock and North Lyell cherts were either completely silicified zones of volcanics or, alternatively, siliceous sinter deposits of volcanic hot springs. Solomon (1964), Green (1971), Reid (1976) and Corbett (1989) favoured a sinter origin for the chert. Arnold (1985) and Komyshan (1985) revived the concept of a fault-bounded outlier of silicified Owen Conglomerate for the body. Corbett (1997a,b) confirmed earlier observations by Arnold (1985) and others that the Comstock and North Lyell chert bodies were essentially similar, from mapping and drill core studies, and concluded that both were essentially replacement bodies within the alteration system.

The Comstock chert body is roughly triangular in shape, with its northern side more or less parallel to stratigraphy in the basal Tyndall Group and its other two sides cross-cutting stratigraphy in the andesitic unit. Drill intersections suggest the lower boundaries are irregular and interfingering with the schists (eg Fig. 13b). The pointed southern apex forms the north-western wall of the open cut, and has deep vertical cracks due to subsidence. This section of the body displays abundant veins up to 30 cm wide of red hematite and jasper (Plate 6c,d), some of them containing barite. Fragments of this distinctive hematite-jasper-barite vein material, as well as abundant fragments of the typical chert, occur in the Middle Owen Conglomerate, as previously noted.

Many zones and patches within the chert have a characteristic breccia texture consisting of small, highly angular fragments separated by pink, partly hematitic matrix material (Plate 6b). The presence of numerous jig-saw fit examples within the breccias indicates an in-situ brecciation process, and the occurrence of similar breccias in association with the hematite-jasper-barite veins suggests a relationship of at least some of the brecciation with the hematite veining event. The chert in thin section consists of a micro-crystalline quartz mosaic, variably recrystallised and veined. Blebs and veinlets of barite are present in places, as is rare fluorite in small veins.

On the scree-covered northern flank of the main chert body, near its stratigraphic top, are sparse outcrops showing conglomeratic or pseudo-conglomeratic textures. These consist of angular to sub-rounded 'clasts' of chert in a pink-brown oxidised matrix. The uniform composition of the clasts, and the preservation of some jig-saw fit examples, suggest that some of the 'conglomerates' are modified versions of the in-situ breccias, with rounding probably induced by cataclasis during tectonic or other movements. However, drill core samples from the top of the chert body also show what appear to be sedimentary conglomerates made up of chert clasts (and rare volcanic clasts) in a matrix of fine sericite-pyrite material. These conglomerates pass up into sediments of the Lower Tyndall Group complex, which typically include abundant chert-rich clastic units and limestone lenses, suggesting that the top of the chert body was exposed on the seafloor in early Tyndall Group

time, as also suggested by Green (1971). Some of the fine-grained chert-sericite-pyrite sediment could represent sinter-type exhalative deposits, but this remains to be confirmed.

Drilling to the north and west of the Comstock chert shows that the body continues down-dip for at least 700 m (eg Fig. 13b), but becomes thinner in this direction. A notable subsurface feature seen in this section is the large 'overhang' of chert on the north flank, forming a depression or basin some 250 m below surface, infilled with Lower Tyndall Group breccias. Drill intersections indicate that boundaries between chert and schist are generally highly irregular and unpredictable, as might be expected in an alteration zone.

The Lower Tyndall Complex

A number of good drill intersections show the Lower Tyndall Group to be a complex package of polymict and chert-rich conglomerates and breccias, with units of sandstone and siltstone, lenses of limestone, lens-shaped flows of andesitic lava and breccia, and lenses of exhalative massive sulphide. Considerable thickness variations are due mainly to irregularities or basins in the underlying rocks, with a thicker zone off the NW margin of the Comstock chert and a thinner zone over the chert body.

The lower part of the sequence is dominated by clastic breccias, conglomerates and sandstones, with lenses of limestone. The clastic rocks typically contain abundant clasts of grey chert up to 30 cm across, identical to that of the alteration zone. Many units are polymict, with clast types including chert, andesite, altered volcanics, quartz porphyry, sulphides (pyrite and galena, rarely sphalerite and chalcopyrite), and limestone (including fossiliferous types). These units demonstrate that there was considerable contemporaneous erosion of the alteration zone rocks, and of sulphides and limestone lenses, during accumulation of the Lower Tyndall complex.

Lenses of pink limestone occur at various levels through the sequence, and range from 5 to 30 m thick. Many show brecciation and strong hematite alteration. Several of the limestone lenses sit almost directly on the underlying chert of the alteration zone. Many of the lenses contain abundant fossil fragments (mainly of trilobites, but also including, in C50, echinoderm plates, hyolithids, small gastropods, and inarticulate brachiopods- Jago et al., 1972), suggesting that the lenses are, in part at least, normal bioclastic sediments. However, the abundance of vein-type and secondary carbonate throughout the Lower Tyndall sequence, particularly as an infill material in many breccias, and the close association of some of the limestone lenses with sulphides, strongly suggests that much of the carbonate is of hydrothermal origin. There is a suggestion from the presence of tube-type borings in fossiliferous limestone in DDH C72 that some of the biota may have lived around the hydrothermal vents or hot springs.

The fault-bounded sequence hosting the small massive sulphide body in the mullock quarry is also dominated by polymict breccias, conglomerates, and sandstones, including units with clasts of chert, andesite and sulphide. Also present is a quartz-feldspar porphyry body which appears to be partly intrusive and partly extrusive (from the presence of clastic breccia textures). In the western part of this zone, sericite-pyrite alteration has overprinted these lithologies to produce sericite-pyrite schists identical to those of the main alteration zone. The small massive sulphide body lies near the contact of these schists with less altered Lower Tyndall rocks. This fault-bounded strip of Lower Tyndall rocks, including porphyry, extends to considerable depth in the Comstock mine workings (Figs 13a,b). Descriptions from the underground workings at Tasman Crown suggest that this same Lower Tyndall sequence also

hosts the lead-zinc body in that mine, where there are no surface outcrops of the host rocks nor any preserved drill core. Dump samples are mostly of sericite-pyrite schist.

Mineralisation at Comstock and Tasman Crown

Lead-zinc massive sulphides in Lower Tyndall Group

The main galena lode at Tasman Crown consisted of banded to massive galena-sphalerite-pyrite in an E-W oriented sub-vertical body averaging 5 m wide and up to 90m long. The orebody was located 20 m horizontally from the Pioneer Sandstone contact, and was directly overlain by Pleistocene bouldery moraine (Fig. 13A). The body persisted in depth for about 50m before terminating against the north-dipping contact with Pioneer Sandstone.

Dump samples of the ore were described by Markham (1968), who noted alternating layers rich in pyrite, galena and sphalerite, and small-scale fold structures. Other minerals observed were tennantite, and bournanite (?) with traces of secondary chalcocite and covellite. He noted the strong similarity to the banded Rosebery ores, as had Solomon (1964), and suggested that an exhalative sedimentary origin was most likely.

Average assays for the ore were of the order of 28% Pb, 20% Zn, 0.5% Cu, 500ppm Ag, and 0.3ppm Au (Nye, 1925). Production figures are vague, but probably amounted to several thousand tons (Blainey, 1967; Wade, 1957; Nye, 1925) of mainly lead-silver ore. Nye (1925) gave a reserves estimate of 20,000 tons.

What appears to have been a secondary oxidised cap to the lode was present at its western end, in contact with the glacial drift. This deposit contained native copper and black oxide of copper as well as galena (Nye, 1925).

According to old mine plans, a second smaller galena lode was intersected in No 3 tunnel some 50m north of the copper lode, in a host rock with fragments of chert and sulphide in a schist matrix. This is probably the Lower Tyndall sequence in its normal position overlying the altered Central Volcanic Complex rocks (Fig. 13A).

The massive sulphide body in the mullock quarry was uncovered during excavations for stope fill for the Comstock stopes. It is roughly triangular in shape, about 20 m long, and is folded into a tight E-W oriented synclinal structure with a narrow keel (Plate 7A). At the keel, the sulphide is conformably bedded with, and apparently overlies, a sedimentary sequence of pyritic siltstone, sandstone and mass-flow breccia, supporting the interpretation of a sea floor exhalative origin. At its western end, the body is in contact with sericite-pyrite-altered host rocks derived from the Lower Tyndall, while to the east the host rocks are relatively unaltered, suggesting that the body lies at the top of the large footwall alteration zone. The body is strongly banded in pyrite, galena, sphalerite and chert, and grades near the margins into inter-banded pyrite and chert. No assay values have been published for the sulphides, but they appear to be of similar grade to the Tasman Crown body. The mullock quarry body is unusual in that it preserves a large remnant of well-developed limonitic gossan, 2-3m thick, on its upslope end (Plate 7A). Siliceous bands within the original ore have remained unoxidised. The gossan remnant must have survived being over-ridden by ice during the Pleistocene glaciation, since glacial moraine occurs at a higher elevation on the western side of the Comstock chert body.

Clasts of massive sulphide have been intersected in a number of drill holes through Lower Tyndall rocks to the north and west of the Comstock chert body, those in C71 and C72 being good examples. A few examples of probable exhalative mineralisation have also been intersected, the best being that in DDH C70, drilled from west of the chert body (Fig. 12). This hole passed through a 65m-wide channel-like structure infilled with Lower Tyndall breccias on the north-west margin of the chert, within which was an altered limestone breccia body containing two 30 cm-thick lenses of banded pyrite-galena-sphalerite. The brecciated limestone had interstices filled with crustiform banded minerals including galena, sphalerite, chalcopryrite, hematite, siderite and barite, and the limestone clasts showed alteration to bright red hematite and jasper. The massive sulphide bands gave best assays of 6% Pb, 11.2% Zn, 1700ppm Cu, and 1200ppm Ag (Dufty, 1991). Beneath the sulphide zone was another 22m of hematite-altered limestone breccia and 4m of pyritic chert-rich clastic breccia overlying sericite-pyrite schist with fluorite blebs, and brecciated pyritic chert mineralised with galena, sphalerite and chalcopryrite. The hole appears to have passed close to an exhalative mineralising vent closely associated with limestone development.

Drill holes through the Lower Tyndall further away from the chert body and the main alteration zone (eg C73, Fig. 12) have shown only minor mineralisation and much fewer sulphide clasts (Halley, 1993), suggesting that the alteration zone has been the feeder system for the mineralisation. Some limestone lenses have been intersected, however, including a 30m lens in C74, 800m north-west of the Comstock chert.

Chalcopryrite-pyrite ore in schists

Descriptions of the Comstock chalcopryrite orebodies have been given by Batchelor (1905), Nye (1934), Wade (1957), Solomon (1964), Komyshan (1985) and Corbett (1997a). The lodes or 'echelons' were located within the core of the alteration zone beneath the main part of the Comstock chert body, and comprised three irregular lenses hosted by sericite-pyrite schist and chert (Figs 12, 13B). The lenses plunged steeply west, more or less parallel to the Great Lyell Fault and to the base of the Tyndall Group (note projections from 11 level on Fig. 12). The southern lens (No 1) outcropped, but died out by 6 level. Lenses 2 and 3 were joined at several levels, and merged at depth to form a single persistent lode which was still well developed at the deepest (11) mine level, some 400 m below surface. A fourth ore lens (No 4) had its summit just above 7 level and was also still strong at 11 level. Approximate dimensions of the lenses in plan were 60 x 20 m.

The lenses were elongated in a north-east direction near surface, parallel to schistosity, but became more north-south oriented and 'chunkier' with depth. This change in shape appears to be related to the flattening of the Great Lyell Fault surface above 6 level (Fig. 13B), a phenomenon also seen at North Lyell and the Iron Blow, and considered to be related to partial collapse of the schist mass into the Owen basin, as discussed later. Mining was by cut and fill stopping from adits down to 7 level, and by internal shaft to 11 level.

The ore was mainly disseminated chalcopryrite with pyrite in sericite-pyrite-silica schists, with some bornite in No's 1 and 4 lenses. Other minerals recorded by Edwards (1939) and Green (1971) were chalcocite, covellite, molybdenite, galena, magnetite, hematite, digenite, tennantite, mawsonite, betekhtinite, stromeyerite and gold. Green (1971) noted that the specimens he described appeared to be identical in mineralogy and texture to some of the North Lyell ores described by Markham (1968). Edwards (1939) gave a bulk sample assay of Comstock ore as follows: 2.07% Cu; 0.37 g/t Au; 3.82 g/t Ag; 0.043% Pb; 0.025% Zn; 50.9%

SiO₂; 16.25% Al₂O₃; 10.7% Fe; 8.2% S; 0.9% CaO; 0.14% MgO; 0.006% Ni. Wade (1957) reported a steady decline in grade with depth, from 3.28% Cu in 1913 to 1.94% in 1944.

A low-grade pyrite-chalcopyrite-minor bornite lode similar to those at Comstock was located in the Tasman Crown workings 100m north of the galena lode (Fig. 13A). The body was hosted within sericite-pyrite schists adjacent to a chert body, in what appears to be a continuation of the main alteration zone (Fig. 12). Some galena was also associated with the irregular lode. The grade of the lode decreased with depth, and only a small amount of ore was produced (Nye, 1925; Wade, 1957).

Mineralisation associated with Comstock chert and similar bodies

Minor but significant gold and base metal mineralisation has been reported within the Comstock chert and adjacent schists, particularly in the upper part of the chert (Corbett, 1997a). Gold values of 0.3 to 2 ppm over 10 to 30m are present in a number of drill intersections, in some cases extending from the chert into the basal part of the Lower Tyndall sequence. Similar intersections are recorded from the lower part of the chert and associated schists in places. The nature of the gold occurrences has not been investigated.

Galena-sphalerite-chalcopyrite-pyrite mineralisation is also recorded in zones of brecciated chert, the best intersections being from two early holes (C43, C48) drilled underground from 5 level into the upper part of the chert. C43 recorded an 83m zone with 2.27% Zn and a 7m zone with >5% Zn and >1% Pb. C48 gave 61m of 1.87% Zn from the top of the chert into the basal Tyndall Group.

Markham's (1968) description of this 'chert breccia mineralisation' noted the additional presence of tennantite, hexastannite and rutile, and the presence of original colloform textures in some of the pyrite. Green (1971) also described samples of the mineralised chert breccia, including one showing framboidal texture in the pyrite, and suggested that the ores were transitional between the copper mineralisation below and the exhalative lead-zinc mineralisation above.

Model for Alteration and Mineralisation at Comstock

A diagrammatic cross-section model for the Comstock mineralisation and alteration is given in Figure 14. The large footwall alteration zone has an inner core of sericite-pyrite-silica schists and an outer zone of marginal pyrite-poor sericite-chlorite schist. The zone cross-cuts the andesites and felsic rocks of the Central Volcanic Complex, and lies along, or adjacent to, the Great Lyell Fault.

The margins of both the core zone and the outer zone are highly irregular and interfingering. Isolated outliers of altered rocks, and inliers of less altered rocks, are common. Large bodies of relatively impermeable rock, such as coherent andesite lavas or intrusives, appear to have formed partial barriers to the hydrothermal fluids in places, and tend to limit the extent or shape of the alteration zone or to form less altered 'kernels' within it.

Silica in the form of microcrystalline chert is a prominent component of the alteration assemblage. The chert occurs in a spectrum of forms, from small blebs, lenses and bands a few mm thick through to very large bodies tens or hundreds of meter across. Most of the bodies have been much modified in shape by the smoothing and rounding action associated with

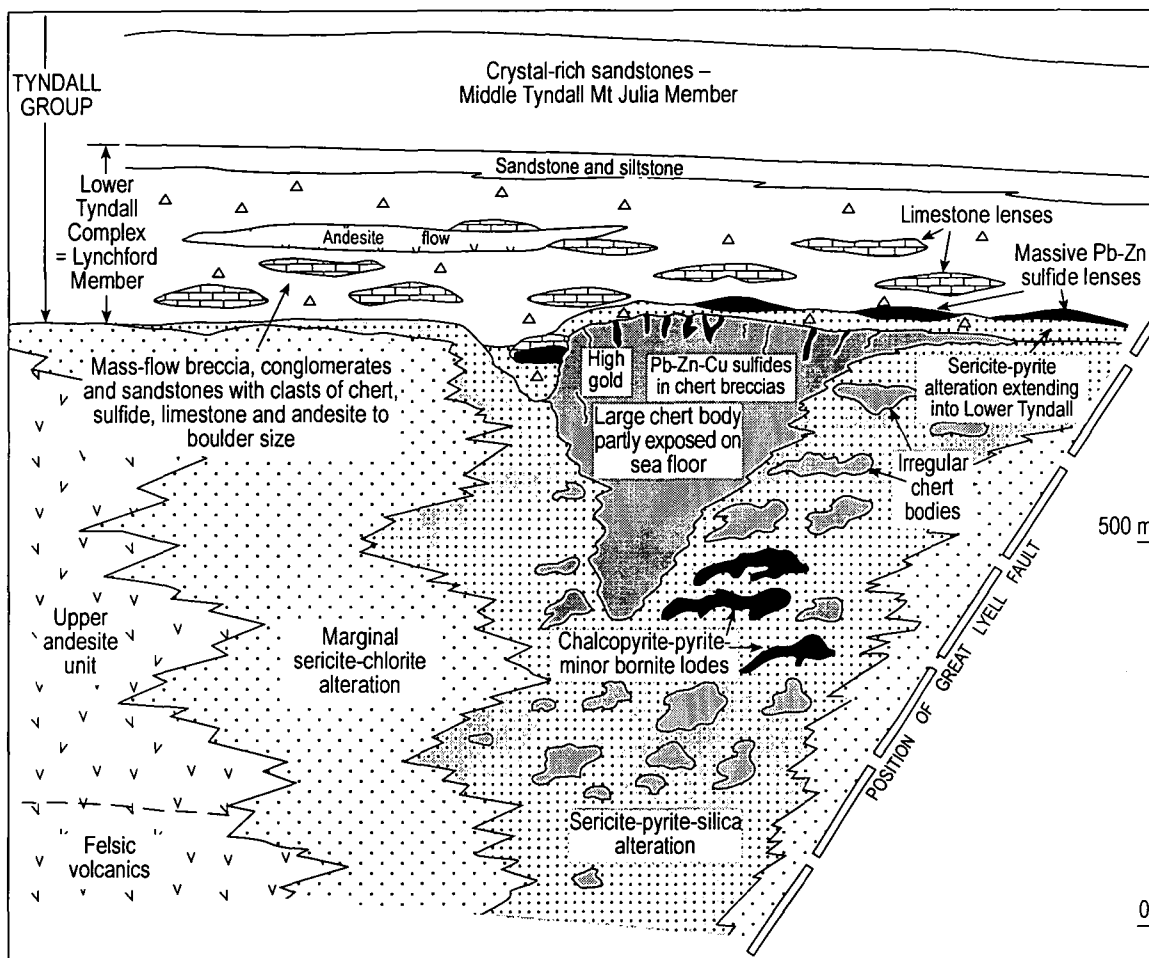


Figure 14. Cross-sectional model of the alteration-mineralisation system at Comstock.

schistosity development, there being a dramatic ductility contrast between the brittle chert and the highly mobile sericitic schist (eg Plate 5D). Weathering has also accentuated the hardness differences between the rock types.

The chert appears to be more abundant and to form larger bodies closer to the exhalative surface. Obvious mappable bodies disappear about 600m below the base of the Tyndall Group, although some siliceous alteration persists beyond this. The largest chert body, some 200 m thick, lies immediately beneath the exhalative interface. This body, or its extension along strike (now eroded), must have been exposed at the sea floor for some of the time to provide the abundant erosional detritus seen in the Lower Tyndall Group breccias. Enigmatic conglomerate-textured cherty rocks are preserved at the top of the body in places, and further study is required to determine whether sinter-type depositional products are represented. Most of the Comstock chert body, however, and the other chert masses, are considered to be of replacement origin.

The chalcopyrite-pyrite-minor bornite lodes are located immediately beneath the largest chert body, approximately 200-300m below the exhalative interface. It is possible that the chert body acted as an impermeable or poorly permeable cap to the system at some stages, and that fluid outflow was inhibited by it. Fluid overpressure may have been responsible for some of the brecciation of the chert. Some base metal sulphides were deposited within the chert breccias near the exhalative interface, as well as in lenses on the sea floor. The chalcopyrite lodes appear to correspond, in a general sense, to the zone of maximum pyrite deposition.

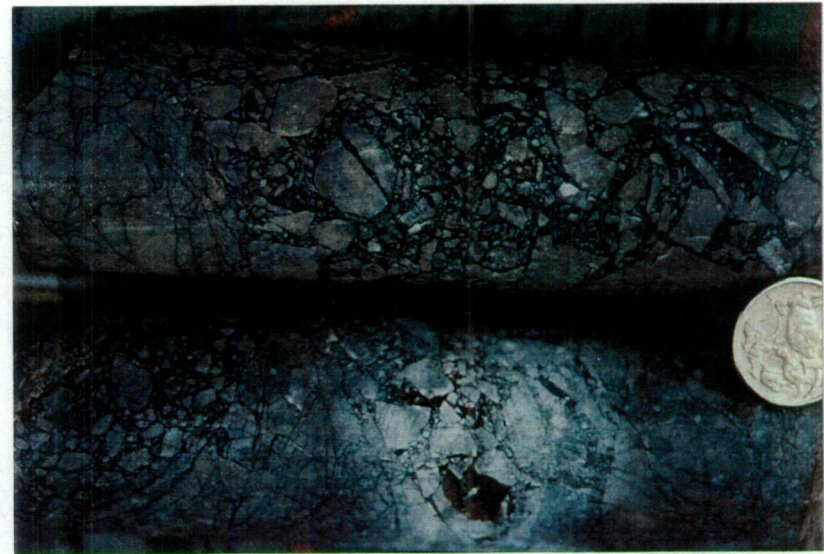
The major exhalative position lies in the lower part of the Lower Tyndall complex, in a sequence of chert-rich mass-flow breccias, conglomerates and sandstones, with intercalated limestone lenses. Sericite-pyrite alteration extends into this sequence in places, but does not appear to extend above the lower limestone lenses. Major exhalative sulphide lenses are so far known only from the eastern fault-bounded strip of Lower Tyndall, but small sulphide bands and abundant sulphide clasts have been intersected in the zone immediately above, and just down-dip of, the Comstock chert, suggesting that significant lenses could also be present in this area.

The limestone lenses are, for the most part, closely associated spatially with the alteration zone, in some cases sitting almost directly on the large chert body (eg in C72, Fig. 13B). The limestones typically lack bedding, are pink to red in colour due to hematite alteration, and are commonly brecciated. The example in C70 is completely brecciated in the upper part and has the interstices infilled with hydrothermal minerals including hematite, siderite, barite, galena and sphalerite. The presence of banded sulphides in this breccia suggests that it may be part of a complex exhalative mound.

The abundant fossil fragments in the carbonate lenses indicate that they were either areas of rich biological activity or significant graveyards, or both. The general composition of the fauna is suggestive of relatively shallow water, although the fragmental nature of most of the fossils suggests they could have been reworked into deeper water. The presence of burrows suggests that some of the fauna were residents. Jago et al. (1972) suggested that the C50 limestone represented 'a near-shore shallow bank deposit', although the general environment appears to be one of mass-flow deposits and density current deposition below storm wave base. The close association of the lenses with hydrothermal alteration and mineralisation, and the general



(a) Massive sulphide body at Comstock mullock quarry. Note synclinal 'keel' at bottom, with bedding in associated siltstone-sandstone units. Also note remnant of well-formed limonitic gossan at top.



(b) Breccia texture in North Lyell chert, in drill core from hole NL 1100 at 50 m. Note jigsaw fit textures, gradation to unbrecciated chert.



(c) Chert breccia rock with matrix of pyrite, from underside of North Lyell chert body. Pseudo-conglomerate texture produced by slight rounding of some chert clasts, probably by cataclasis, and slight differential weathering. Knife is marked in cm.



(d) Small silica heads boudinaged in sericite-pyrite schists, head of Crown Lyell 3 open cut.

abundance of secondary carbonate throughout the Lower Tyndall sequence, strongly suggests that much of the carbonate is related to hydrothermal activity.

The stratigraphy at Comstock indicates that the hydrothermal system was eventually buried under several hundred meters of mass-flow breccias, conglomerates, sandstones and siltstones of the Lower Tyndall Group, followed by several hundred meters of crystal-rich sandstones of the Middle Tyndall and volcanoclastic conglomerates of the Upper Tyndall. However, most of the system to the south of Comstock must have been unroofed and re-exposed soon afterwards in the Late Cambrian, as evidenced by the occurrence of abundant chert, jasper and hematite detritus in the Middle Owen Conglomerate, which was being deposited a short distance away on the other side of the Great Lyell Fault. It is suggested that the hematite-jasper-barite veining and alteration which affects part of the Comstock chert body and many of the limestone lenses occurred as the alteration zone was progressively unroofed during Lower Owen time, and finally exposed to erosion and oxidation at the beginning of Middle Owen Sandstone time. This process is discussed further after consideration of the North Lyell situation.

GEOLOGY OF THE NORTH LYELL AREA - A DISPLACED MASS FROM THE UPPER ALTERATION SYSTEM

Introduction

The geology of North Lyell is dominated by a large mass of schists wrapped around by Owen Group sediments (Figs 1, 15, 16). The mass is similar to the upper part of the alteration system at Comstock, particularly in the presence of numerous bodies of cherty silica in a 'matrix' of sericite-pyrite schist. The mass extends east from the main belt of schists and volcanics, and appears to have been displaced from its expected position some 800 m to the west at the level of Western Tharsis (Fig 1). The present study suggests that this displacement occurred during Owen Group deposition in the Late Cambrian.

Mining began at North Lyell in about 1896, when the North Mount Lyell Copper Company discovered patchy chalcopyrite mineralisation of the 'Eastern orebody' at the eastern margin of the North Lyell chert (Fig. 16). Rich bornite mineralisation on the under-side of the chert body was discovered accidentally by road builders in 1897, and was opened up to become the North Lyell orebody. The North Lyell Company built its own railway and smelters to process this rich deposit, but the company failed because of a combination of mismanagement and difficulty in smelting the refractory siliceous ores. Amalgamation with the Mount Lyell Mining and Railway Company in 1903 resulted in an ideal combination of pyritic ore (from the Iron Blow body) and siliceous ore to achieve the 'miracle' of pyritic smelting (Blainey, 1967). The North Lyell orebody expanded dramatically with depth (see projection on Fig. 16), and was progressively mined by open cut and underground methods until 1949. Five other major mines were also developed in this displaced schist mass- Lyell Tharsis, 12 West, and Crown Lyell 1, 2, and 3 (Table 2).

Form of the Schist Mass at North Lyell

The nature and origin of the schist mass at North Lyell, and the relationship to the Owen Group sediments, have puzzled geologists and miners since mining began. The general shape of the schist mass is indicated in plan and sections on Figure 15. The deepest section, beneath the main North Lyell-Crown Lyell area, is about 500 m deep, and is referred to as the

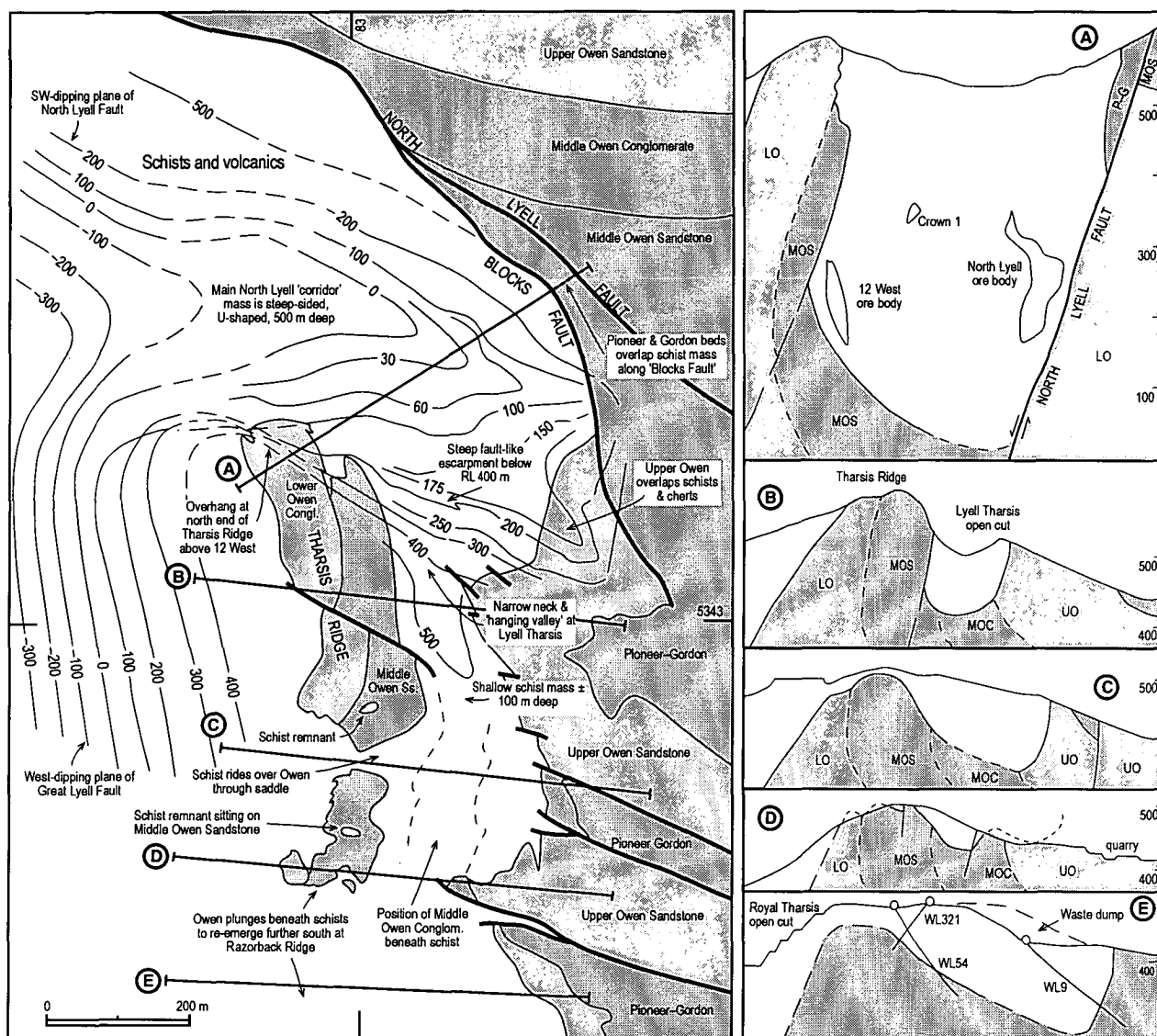


Figure 15. Simplified map and cross-sections of the North Lyell Corridor-Tharsis Trough-Tharsis Ridge area to show distribution of schist and Owen Group. Structure contours on schist-Owen contact are in metres above and below sea level. Compiled from drill hole intersections and underground mine plans.

‘corridor’ area. This is bounded to the north by the North Lyell Fault and a wedge of Gordon Group clays and Pioneer Sandstone. The contact of the clays on the schist mass is somewhat sheared and irregular, and has been referred to as the ‘Blocks Fault’, although the author’s mapping suggests that it is probably a sheared sedimentary contact where Pioneer Sandstone and Gordon Group clays have lapped on to the schist mass (eg some sections look unsheared, bedding is generally parallel to the contact). The contacts between the schist mass and the surrounding Owen Group sediments on Tharsis Ridge and along the eastern margin of the schist belt provide important evidence on the mode of emplacement of the mass, and are discussed separately.

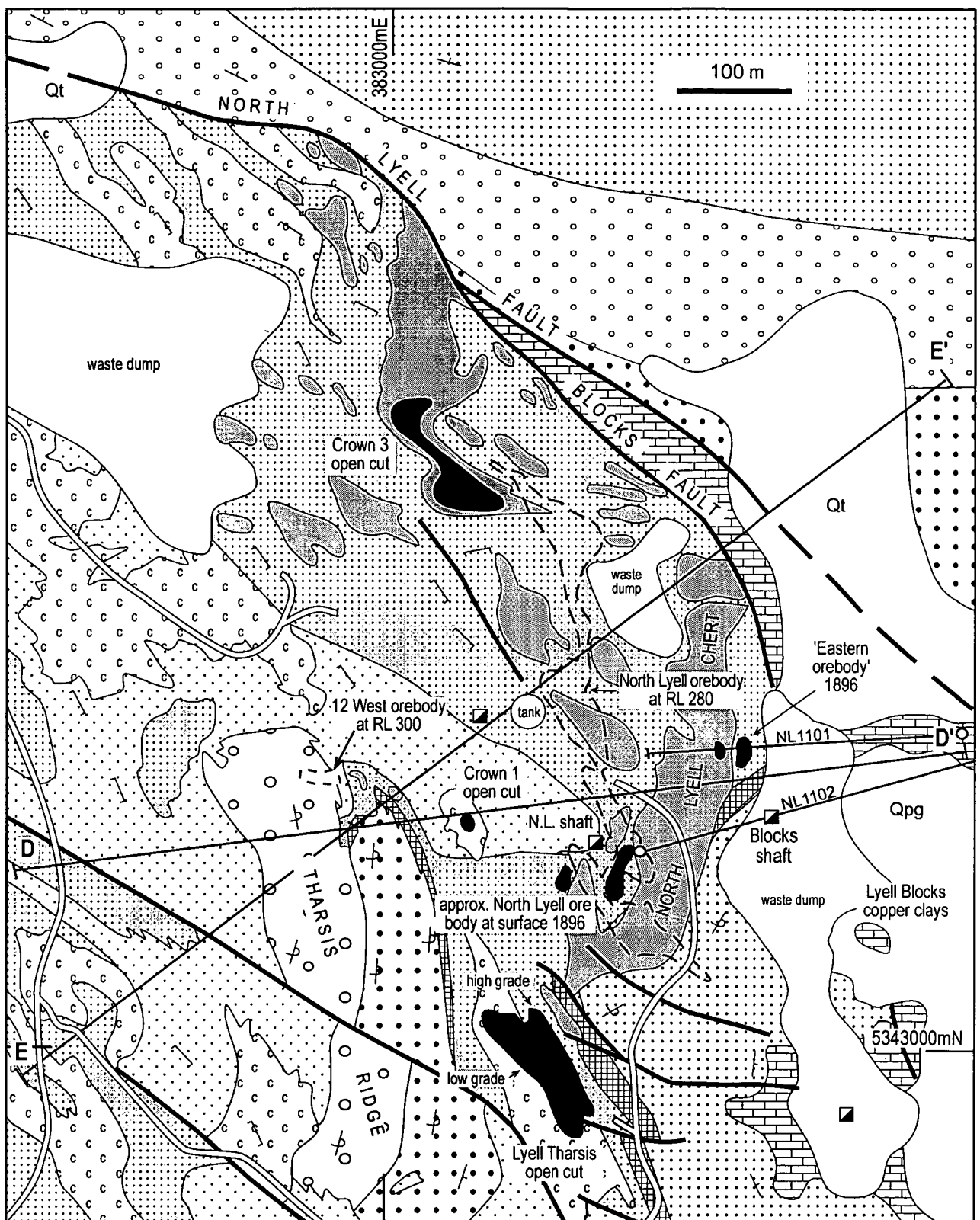
The corridor structure is completely floored by Owen Group conglomerates and sandstones, as indicated by numerous drill holes, and the floor slopes gently west to where the structure opens out and joins the main body of schists near the intersection of the Great Lyell and North Lyell Faults (Fig. 15). At its eastern end, the schist mass has a steep, east-dipping contact against mainly Upper Owen sediments, which onlap the mass and have an erosional-sedimentary contact with it.

The south side of the corridor mass, against the north-eastern flank of Tharsis Ridge, is steep, fault-like and partly overhanging, leading up to a shallower and narrower trough of schists which extends from the Lyell Tharsis area southwards towards Razorback Ridge. This shallow trough of schist is referred to as the Tharsis Trough, and is bounded to the west by the partially emergent Tharsis Ridge of Owen Group rocks (Middle Owen Sandstone and Lower Owen Conglomerate). The trough is underlain mainly by the Middle Owen Conglomerate (Fig. 15), which is exposed beneath the schists only in one place at the westernmost end of Whaleback Spur (Figs 1, 15). Along its eastern side, the trough is bounded by Upper Owen Sandstone.

There is continuity between schists of the Tharsis Trough and those of the main belt to the west across ‘saddles’ in the Tharsis Ridge area (section C of Fig. 15), and in the 600 m long zone between Tharsis Ridge and Razorback Ridge to the south (eg section E of Fig. 15). Several small outliers or ‘sole’ remnants of schist rest on the Owen Group beds on the southern part of Tharsis Ridge, and provide further evidence that the schist mass has overridden the Owen beds during its emplacement. As noted later, the Tharsis Ridge ‘shoulder’ appears to have been uplifted or upfaulted into its present position *after* the schist mass was emplaced, and most of the originally overlying schist (except for the small ‘sole’ remnants) has been stripped off.

Internal Geology of the Schist Mass at North Lyell

The main schist mass is dominated by cream-yellow sericite-pyrite-silica schists, typical of the central core zone at Comstock, and includes numerous cherty silica bodies or silica ‘heads’ and a large chert body at the eastern end (Fig. 16). Primary rock types appear to have been felsic lavas, breccias and possibly pumice breccias intermixed with some andesitic lavas and breccias. The pyritic schists wrap back along the south side of the corridor in a narrow sheared zone against the north-east flank of Tharsis Ridge, with several small chert bodies preserved in embayments against the Owen contact. A central zone of marginal sericite and chlorite schists (with volcanic textures such as flow-banding preserved in places) lies within the core of this asymmetrical fold-like structure. The schist mass also has a folded structure in cross-section (Figs 17, 18), with the main chert body and the zone of pyritic schists following the rounded



Qt	Qpg	Talus, glacial deposits
		Gordon Group clays & Pioneer Sandstone
		Upper Owen Sandstone
		Middle Owen Conglomerate
		Middle Owen Sandstone
		Hematite bodies
		Lower Owen Conglomerate

ALTERATION ZONE – MOUNT READ VOLCANICS

	Orebody – mostly mined out
	Chert bodies ('silica heads')
	Sericite–pyrite–silica schist
	Chlorite schist after andesite
	Marginal sericite–chlorite schist

Figure 16. Geological map of the North Lyell area. Note projected outline of North Lyell orebody.

shape of the structure and wrapping up the southern wall in attenuated form. This structure suggests that folding has been involved in emplacement of the mass, which appears to have behaved in a semi-coherent fashion (as also noted by Bryant, 1975).

Contacts between the schist types are typically somewhat diffuse and sheared, and are not well delineated at depth, so that the zone of marginal schist as shown in the cross-sections is somewhat idealised. A number of faults and shear zones are evident within the schist mass, one of the most prominent being a steeply SW-dipping structure lying just south-east of the Crown 3 open cut. Schistosity at North Lyell also dips steeply south-west for the most part. The pyritic schists generally do not persist south of the Lyell Tharsis area, the bulk of the Tharsis Trough being occupied by marginal schists (Fig. 1).

An unusual marginal schist type, consisting largely of grey-green volcanoclastic sandstone and fine-grained breccia, with intercalated zones of well-bedded grey siltstone and fine sandstone, is present around the northern end and north-eastern flanks of Tharsis Ridge (Figs 1, 16). This unit has abundant quartz phenocrysts in places, as well as clasts of quartz porphyry and fine-grained volcanic material, and resembles the lower Tyndall Group facies. It grades into sericitic schist in places, indicating that at least parts of it have been subject to intense alteration. Another patch of quartz-phyric Tyndall-like rocks is present against the Owen contact near Whaleback Spur quarry (Fig. 1), but in the absence of definite younger members of the Tyndall Group, and considering the rather confused nature of relationships in this general zone, it is not possible to make a definite identification. Thin veins of red jaspery material, reminiscent of the jasper veins in the Comstock chert, intrude the quartz-phyric unit in places on Tharsis Ridge. Contacts between the unit and the Lower Owen Conglomerate are well exposed around the northern end of Tharsis Ridge, and are described below.

The large body of dense white to grey chert at the eastern end of the schist mass is referred to as the **North Lyell chert** (Fig. 16). The body forms a bold outcrop at the mouth of the North Lyell open cut, but much of its extensions to the north are buried under spoil dumps. The body is in direct contact with Upper Owen sediments for about half its length, an association which has led to previous interpretations of it being part of the conglomerate sequence and references to it as 'silicified conglomerate' or 'quartzite'. The chert body is much more extensive at depth, and mine level plans (eg Bryant, 1975) indicate that it connects with the large mass at Crown 3 open cut (Fig. 16). The overall dimensions of the body are thus of the order of 700 m length, 100 m width (thickness), and 500 m down-dip depth, which is very comparable to the Comstock chert. The North Lyell chert body, however, is much more fragmented and brecciated than that at Comstock. As shown in the cross-sections (Figs 17, 18), the chert extends to the base of the corridor structure as a more or less continuous mass, with what appear to be broken or attenuated remnants of it extending up the southern wall to the surface.

The North Lyell chert shows the typical fine-scale brecciation textures of the Comstock body, with jigsaw-fit patterns indicating in-situ brecciation (Plate 7B). Other features of the chert include fine banding in places, small inclusions or blebs of barite, and a strongly hematitic matrix to the breccias in places (the term 'hematite-chert breccia' or 'HCB' was applied to this rock in some old reports). Another feature shown in several exposures in the open cut area, and in loose blocks on a nearby waste dump, is a monomict chert breccia texture with an abundant matrix of pyrite and possibly other sulphides (Plate 7C). These breccias contain some rounded chert clasts as well as angular ones, but appear to have resulted largely from

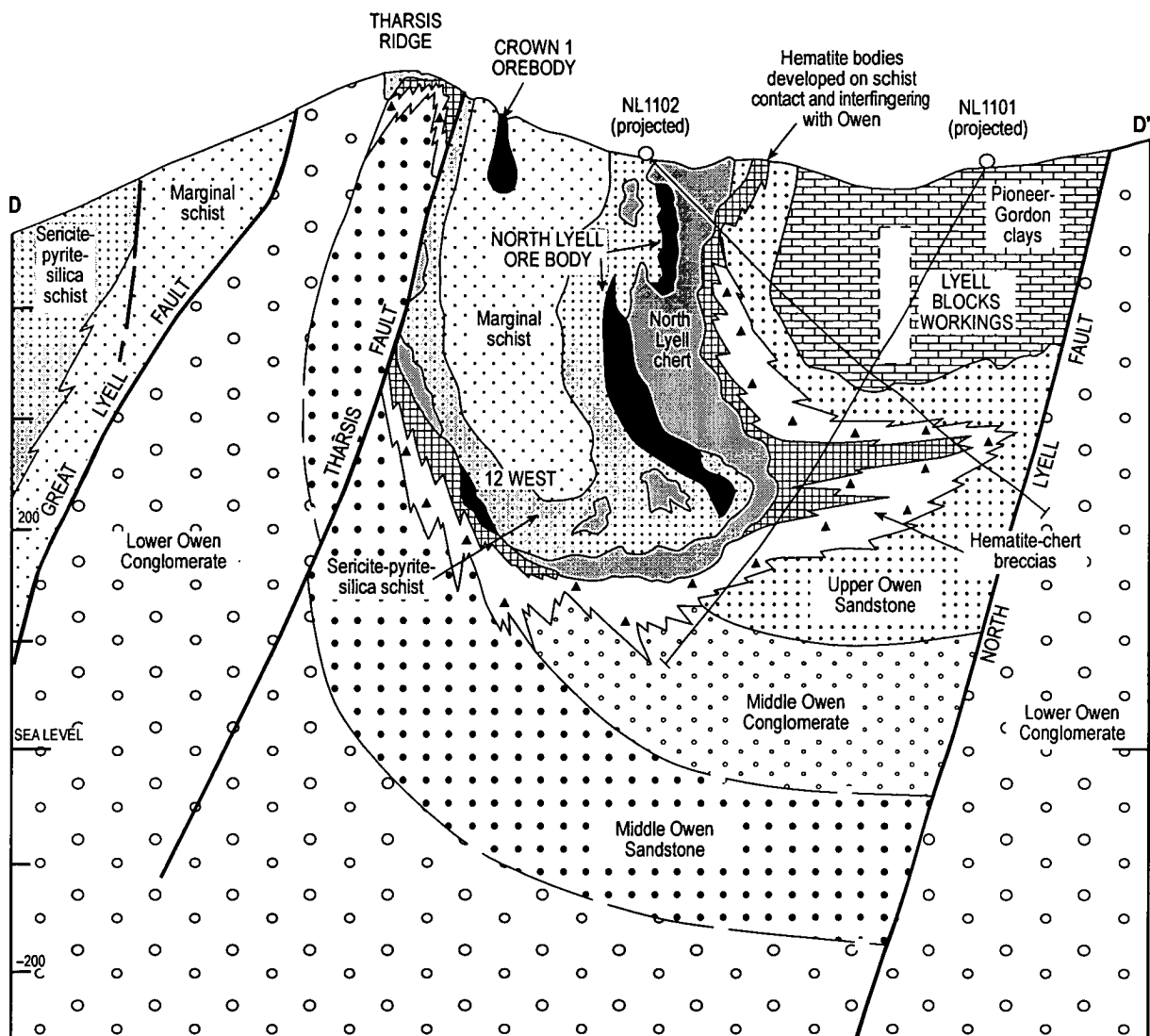


Figure 17. Cross-section DD' through North Lyell-Lyell Blocks area. See Fig. 16 for legend and locations of section and drill holes.

cataclasis of original sulphide-rich breccias similar to those noted from the top of the Comstock chert. These 'pseudo-conglomerate' textures have prompted many observers to interpret the chert as a clastic Owen Group rock. The sulphide-rich breccia may be from the same zone in which Wade and Solomon (1958, p.405) reported seeing bornite 'in all stages of replacing Owen Conglomerate'.

Several other workers have misinterpreted the North Lyell chert body as consisting wholly or partly of silicified Owen conglomerate (eg Sillitoe, 1984; Solomon et al., 1987; Arnold and Carswell, 1990), but careful study of surface outcrops and drill core intersections indicates that it is a Comstock-type replacement chert body within the Cambrian volcanics, with an erosional contact against the Upper Owen Sandstone. Numerous clasts and blocks of the chert, up to a metre or more long, occur in the lower beds of the Upper Owen sequence along the contact (Plate 3C,D), indicating deposition against an eroding 'wall' or face of chert.

The smaller chert bodies are generally either pyrite-rich or pyrite-poor. The pyrite-rich ones are typically bluish-grey in colour (Plate 7D), and may contain fine disseminated chalcopryrite as well as the abundant disseminations and thin bands of pyrite. Most of the bodies within a few hundred m of the North Lyell chert are of this type, and several of these are of ore grade, including the Crown 3 orebody. These bodies commonly show a finely brecciated texture, with sulphides concentrated in the interstices. As is the case at Comstock, the bodies tend to be strongly rounded, flattened, and in some cases boudinaged in the schistosity (Plate 7D). The pyrite-poor bodies tend to have a more porous to vuggy texture, and preserve faint remnants of primary volcanic textures in some cases, such as feldspar phenocrysts and original pumice clast shapes.

Mineralisation at North Lyell

Two main styles of ore deposits are present:

- (i) high-grade bornite-rich bodies typically located at or near the basal contact of the uppermost large chert body, and
- (ii) lower-grade chalcopryrite-pyrite bodies hosted in either siliceous bodies or chlorite-altered zones.

The poorly-known 'Eastern orebody' is now completely covered by spoil, but early records (eg Batchelor, 1903) suggest it was mainly patchy chalcopryrite in chert breccias and schists in a bouldery zone of deep weathering adjacent to the 'Blocks Fault'. It may have been equivalent to the chert breccia mineralisation in the upper part of the Comstock chert.

The bornite-rich deposits included the large North Lyell orebody, an extension of this at the north-west end referred to as Crown Lyell 2, a small body just off the south-east end referred to as the Lyell Tharsis high-grade deposit, and the 12 West orebody, located deep underground against the south wall of the corridor (Figs 16, 17, 18). Several other isolated small lenses on the south wall were not individually named (Bryant, 1975). This mineralisation was largely mined out before detailed geological studies were carried out, and available descriptions are rather scanty (Batchelor, 1903,1904; Wade and Solomon, 1958; Bryant, 1975; Sheppard, 1976).

The North Lyell orebody had a maximum strike extension of 600 m, a vertical extent of about 400 m, and was up to 50 m thick (Fig. 16). It was highly irregular in shape, with numerous projections and indentations which, in part, reflected the irregular shape of the base of the

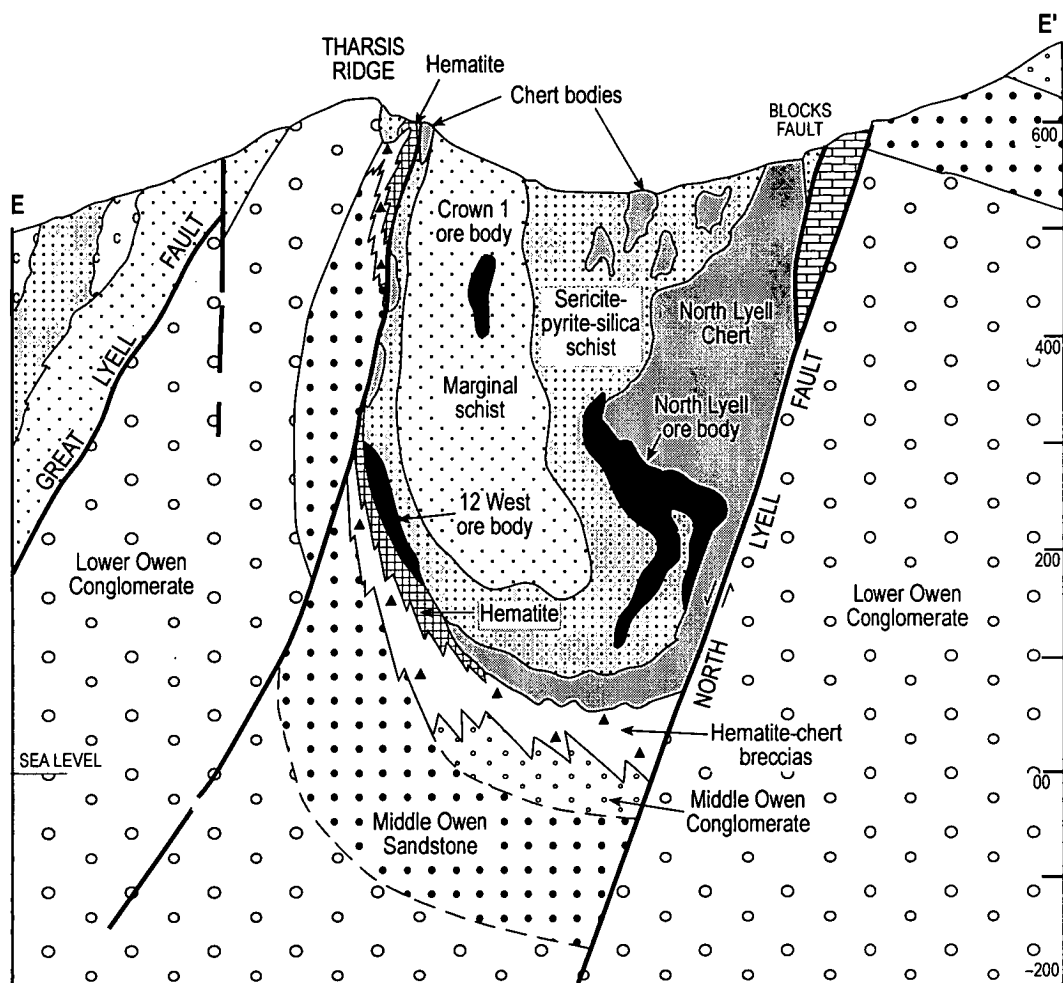


Figure 18. Cross-section EE' through North Lyell Corridor structure. See Fig. 16 for legend and location of section.

North Lyell chert body, against which most of the ore was located. Some 'prongs' of ore within the chert consisted of solid bornite, but most of the ore was in the immediately adjacent schists and cherty schists, and consisted of mixtures of bornite, chalcopyrite and chalcocite, with locally abundant pyrite. The typical mining method, according to Batchelor (1904), was to drive a tunnel in the soft schists parallel to the chert contact, then cross-cut back to the chert to intersect the ore. Minor minerals identified at North Lyell include tennantite, digenite, galena, sphalerite, covellite, mawsonite, enargite, betechtinite, molybdenite, linnaite and stromeyerite (Edwards, 1939; Markham, 1968).

The 12 West orebody was discovered during underground drilling in 1966, and is also poorly documented. Sheppard (1976) describes the ore as being about 80% bornite, with chalcopyrite, pyrite, chalcocite and tetrahedrite also present. The bornite occurs as massive patches, fracture fillings, grain boundary rims and minor disseminations in a grey cherty rock. A drill intersection examined by the author (NL 1003) through the margin of the orebody shows mainly chalcopyrite and pyrite in a cherty schist host rock, passing abruptly into a breccia of chert and sericite clasts in a dense hematitic matrix, passing into massive hematite and hematitic breccia, followed by red, hematitic Middle Owen Sandstone. Thus, the orebody sits near the eroded and oxidised contact of the schists against the Owen Group, with a hematite body on the adjacent contact. Bryant (1975) noted abundant pyrophyllite associated with the 12 West body, occurring in massive schists, in shear planes in the chert, and as flame-like aggregates in bornite. He also noted that pyrophyllite was abundant in samples from the North Lyell and Crown Lyell 2 orebodies.

Of the lower grade deposits, the Crown Lyell 3 orebody, which averaged 1.34% Cu, still has some upper remnants exposed at surface. It is hosted mainly within a pyritic chert mass attached to the footwall of the main North Lyell chert body (Fig. 16), with some ore extending into adjacent sericitic schist. Markham (1968) described the main ore type as disseminated chalcopyrite and pyrite, with small amounts of bornite, digenite, chalcocite, covellite, tennantite, galena, sphalerite, mawsonite, molybdenite, hexastannite, hematite, and goethite. Much of the chalcopyrite is located within fine carbonate veinlets and breccia fillings in the chert, and some of the pyrite displays relict colloform textures. The Crown Extended orebody appears to have been a faulted extension of this body at depth (Bryant, 1975).

The Crown Lyell 1 and Lyell Tharsis low-grade bodies are both hosted within chloritic schists derived from andesitic precursors (as indicated by remnant ferromagnesian phenocrysts), and consist of disseminated chalcopyrite and pyrite.

Owen Group Rocks at North Lyell

All four formations of the Owen Group are present in the North Lyell- Tharsis Ridge area. Only the uppermost part of the Lower Owen is exposed, and most of the Middle Owen Conglomerate and much of the Middle Owen Sandstone are concealed beneath the schist mass. The Upper Owen is well exposed along the eastern side of the schist belt.

The upper part of the **Lower Owen Conglomerate** is exposed along the western half of Tharsis Ridge and in a small block which is a continuation of this line above the Royal Tharsis open cut (Fig. 1). Bedding generally strikes N-S and is subvertical to overturned, facing east. The exposures consist mostly of grey-white to pink pebble to boulder grade conglomerate with interbedded lenses and zones of pink to grey sandstone, corresponding in general facies

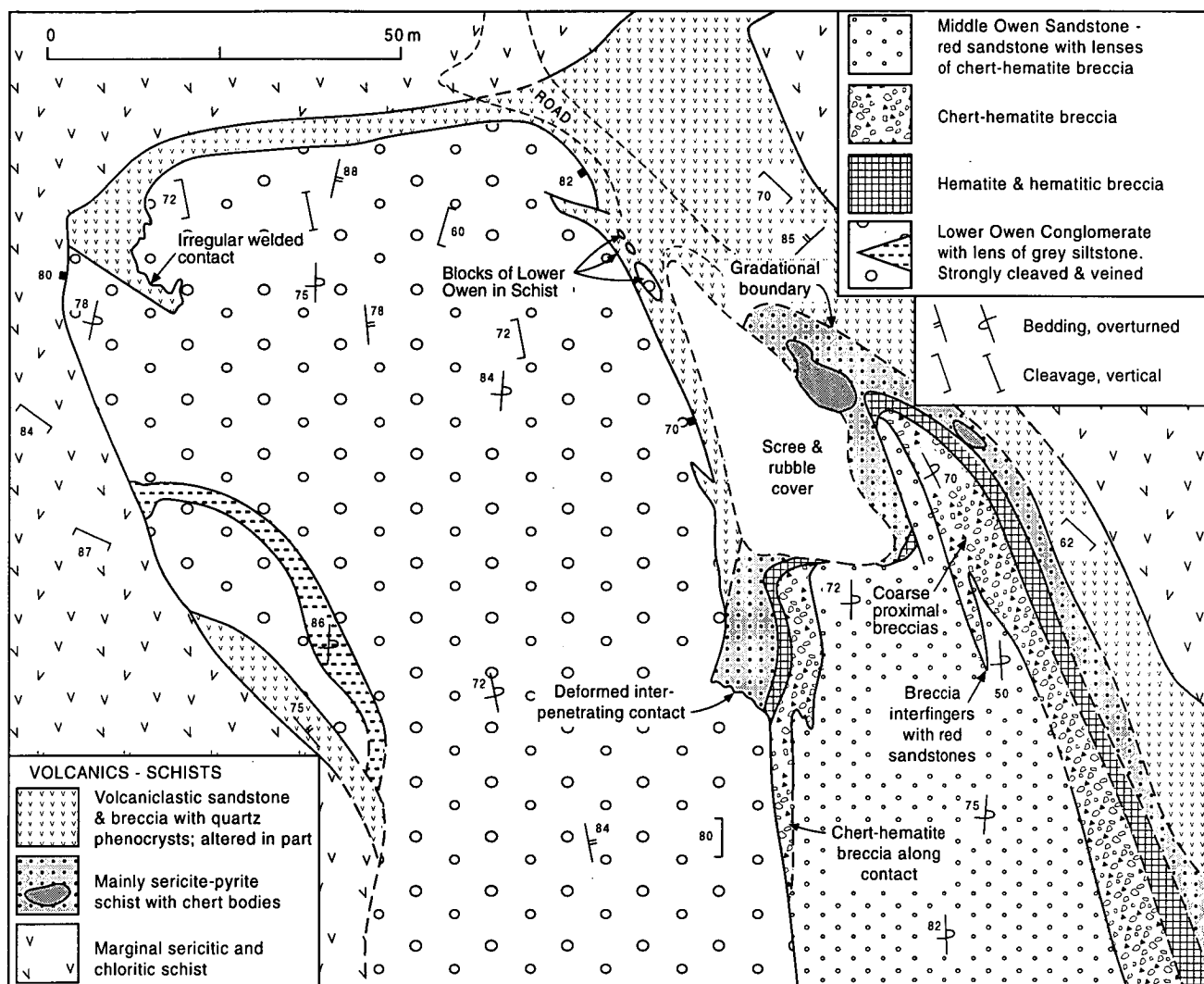


Figure 19. Detailed map of northern part of Tharsis Ridge.

to the upper conglomerate member elsewhere (Fig. 9). Towards the western edge of the exposure is an interbedded unit of buff to grey-green micaceous siltstone, 5-10 m thick, truncated at either end against the schist contact (Fig. 1, 19). The author recovered several inarticulate brachiopods of *Lingulella*-type from this unit in earlier mapping (1989). The siltstone appears to represent a small marine incursion in the upper conglomerate unit which has not been seen elsewhere.

The conglomerate outcrops show an intense sub-vertical, N-S cleavage, and are strongly fractured and quartz-veined over much of Tharsis Ridge, with over 50% vein quartz in many exposures. Many of the quartz veins have a sub-horizontal attitude, and Arnold (1985) suggests the majority are related to Devonian D2 folding.

The **Middle Owen Sandstone** is exposed along the eastern half of Tharsis Ridge, where it overlies the Lower Owen Conglomerate and is flanked down its eastern side by the schist mass of the Tharsis Trough. It is also exposed in a block just to the south of this, in the Utah tanks area (Fig. 1), where it is surrounded by schists and partly overlain by schists. The formation consists of about equal proportions of the typical red-brown hematitic sandstone, of mainly Precambrian derivation, and purplish-brown chert-hematite breccia of local volcanic derivation. The latter occurs as lenses and beds throughout the sequence (Plate 1D), as a series of lenses along the contact with the Lower Owen Conglomerate, and as a semi-continuous layer of relatively coarse breccia along the schist contact, where it interfingers with the sandstones.

A spectacular proximal version of the chert-hematite breccia outcrops at the north-eastern corner of Tharsis Ridge, adjacent to the schist contact and the schist embayment (Plate 2A, Fig. 19). The breccia here contains angular chert clasts to 30 cm long, together with irregular clasts of sericite schist, volcanoclastic sandstone and other volcanic rock types, and abundant hematite and barite. This proximal breccia is interbedded with the normal red sandstones just to the south (Fig. 19). The presence of sericitic rock types, and the pronounced angularity of many of the clasts, implies very limited transport, and suggests that the breccias were derived by weathering and spalling from the adjacent schist-chert mass at the time of deposition of the sandstones.

The **Middle Owen Conglomerate** is exposed only in a limited outcrop at the head of Whaleback Spur, where it is wrapped around by schist and faulted along its southern side (Fig. 1). It consists mostly of siliceous pebble conglomerate, is steep to moderately dipping, and has a conformable contact with Upper Owen Sandstone.

The **Upper Owen Sandstone** lies mostly to the east of the schist belt, where the 100 m-wide zone of Haulage folding and upturning is developed, partially overlapped by Pioneer Sandstone (Fig. 1). The topography is dominated by a series of anticlinal ridges and synclinal valleys reflecting Devonian D2 folds, partially modified by NW-trending cross-faults. The sequence consists of interbedded sandstone, granule-pebble conglomerate and micaceous siltstone, with abundant sedimentary structures indicative of shallow marine to tidal depositional environments. Much of the sequence is oxidised and is pink to red-brown in colour, but zones of unoxidised grey-green colour are also present, resembling the Pioneer Sandstone in some cases.

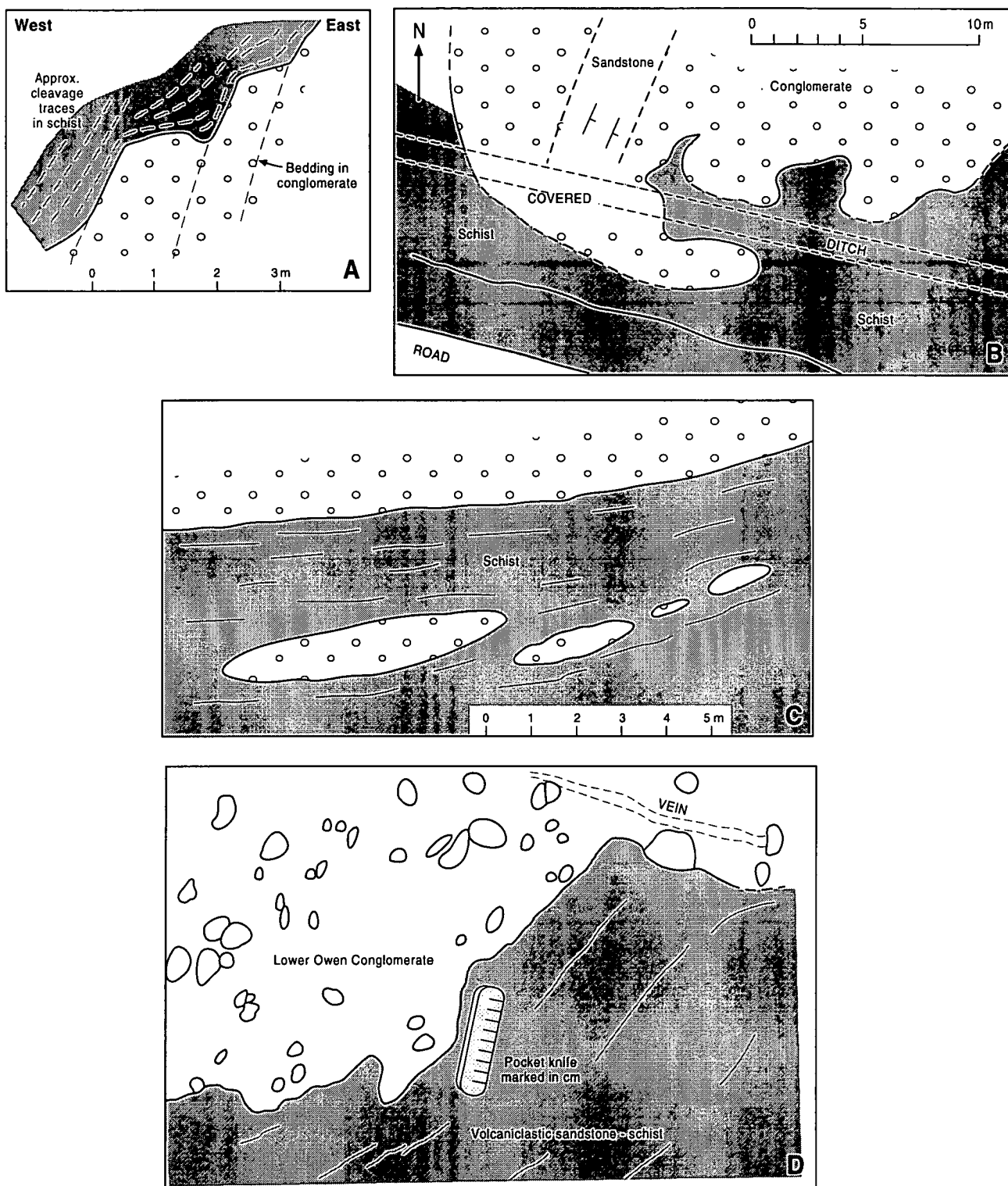


Figure 20. Field sketches showing details of schist–Lower Owen contacts in Tharsis Ridge area. (A) Cross-sectional view on west flank of ridge (see text). (B) South-west corner near cross-road. (C) North-east corner (see Fig. 19). (D) 20 m south of C.

Interbedded with the normal Upper Owen sediments are lenses and beds of chert-rich and chert-hematite-rich breccia-conglomerate (Plate 3B), some containing rounded pebbles of hematite. Beds with abundant clasts of chert up to 30 cm or more across are interbedded with the normal pink sandstone beds in the contact zone with the North Lyell chert (Plate 3C), and a coarse basal breccia with large chert blocks several m in diameter marks the contact. Elsewhere, the schist contact is marked by local lenses of chert-hematite-rich breccia-conglomerate, or by a zone or body of semi-massive hematite.

Contacts and Relationships Between Owen Group Rocks and the Schist Mass

Contacts between the schists and Owen Group rocks provide important information on the interaction of the schists with the sediments, and have been carefully mapped and studied. The bodies of hematite which occur on the contacts in places are discussed separately.

Contacts between the schists and Lower Owen Conglomerate are well exposed in several places around Tharsis Ridge. On the western flank of the ridge (382,950E; 5342,970N), south of the major cross-fault, an exposure of the 45° west-dipping contact shows it rising in a series of steps coinciding with conglomerate beds, which dip west at about 75° (Fig. 20). The schist wraps into the indentations between the beds, and locally varies from sub-horizontal to sub-vertical in attitude. The contact appears welded and tight, with small flames and indentations of schist penetrating the conglomerate in places. 'Floating' pebbles of quartzite and irregular lumps of pink sandstone derived from the conglomerate are found in the schist up to 40 cm out from the contact.

At the south-western corner of Tharsis Ridge (382,930mE; 5342,880mN), where the 'saddle' of schist crosses the Owen Group rocks, a drainage ditch above a road exposes a highly irregular, interfingering contact between conglomerate and schist, with flames of schist penetrating the conglomerate for many metres, and lobes of conglomerate resembling large load features (Fig. 20). This contact is indicative of two semi-plastic or semi-consolidated rock masses interacting rather than two fully lithified bodies. A somewhat similar contact is present at the north-western corner of the ridge (382,850mE; 5343,250mN), where schist derived from a volcanoclastic unit shows irregular penetrations and lobes against the coarse conglomerate on a tightly welded contact (Fig. 19). This section of the contact is dextrally offset on a linear NW-trending fault which does not appear to continue into the adjacent schist, suggesting it may be an early structure with some Devonian overprint.

On the eastern side of Tharsis Ridge near its northernmost point (Fig. 19), a well-exposed contact along a roadside shows several sub-rounded lenses of pink Lower Owen conglomerate, the largest about 6 m long by 1.2 m wide, lying within the schist a few metres out from the contact (Fig. 20). The contact itself is welded and quite irregular on a small scale, with pebbles of the conglomerate projecting into the schist, and small flames and lobes of schist projecting into the conglomerate (Fig. 20). Sixty metres further south, at the southern end of a schist embayment (Fig. 19), the schist contact cuts across bedding in the Lower Owen to produce a complex, deformed and inter-penetrating contact, again suggestive of interaction of two non-lithified rock masses.

These contact features are interpreted to have resulted mainly from over-riding of semi-consolidated conglomerate by semi-plastic schist during a mass emplacement phase in the Late Cambrian, as further discussed below. Devonian reactivation of the contacts must have

occurred in at least some places, but this movement appears to have been concentrated *within* the schists near the contact rather than along the actual schist-conglomerate interface.

Contacts between schists and Middle Owen Sandstone

Much of the contact between schists and Middle Owen Sandstone around the northern part of Tharsis Ridge is occupied by a zone of semi-massive hematite and hematitic breccia (Figs 1, 19), generally grading into the adjacent chert-hematite breccias above, and into hematite-altered volcanic material below. At the southern end of Tharsis Ridge (382,960mE; 5342,750mN), a well-exposed schist contact is present along the western margin of a separate block of the Middle Owen sandstones near the Utah tanks (Fig. 1). Here, the contact shows steps and waves in plan, and can be seen to shelve up and flatten out to the east in section. An isolated remnant of the schist, about 10 x 5 m in dimensions, sits discordantly on the steeply dipping sandstones in the centre of this block (Fig. 1), and appears to represent part of the sole or base of the schist mass which has over-ridden the sandstones.

This over-riding phenomenon can also be seen at the north-western corner of the Utah tanks (382,990mE; 5342,640mN), where the schist wraps completely over the top of an exposure of pink, quartz-veined Middle Owen sandstones in a small down-faulted block. Another example is found towards the southern end of the main part of Tharsis Ridge (383,020mE; 5342,880mN), where a 10 m long remnant of schist sits discordantly on steeply dipping sandstone in an area of steep topography with nearby cliffs of conglomerate and sandstone (Fig. 1). These exposures imply that the schist mass has over-ridden the Middle Owen sandstones (and Lower Owen Conglomerate) on a more-or-less horizontal surface when the sandstone beds were sub-vertically dipping - a concept which the author found initially difficult to accept.

A well exposed sole remnant of schist sitting on Middle Owen Conglomerate is preserved on Razorback Ridge, and is described later.

Contacts between schist and Upper Owen Sandstone

The contact of the Upper Owen Sandstone against the eastern margin of the schist mass is well exposed along the road into North Lyell open cut. Here the sandstone sequence abuts the large North Lyell chert body, and coarse breccias of chert fragments are present in the basal beds (Plate 3C,D). Pink Upper Owen sandstone also occurs within cracks in the brecciated upper surface of the main chert body in one exposure, indicating that sand was deposited against a collapsing wall or cliff of chert.

One of the sandstone beds containing chert clasts at this locality was mis-interpreted by Sillitoe (1984) and also Arnold (1985, p. 48 and his fig. 21) as a zone of boudinaged silicification (Plate 3C,D), hence inferring that the silicification post-dated the Owen, and that the silicification which produced the similar-looking North Lyell chert was also post-Owen. However, careful examination shows two largish (30 cm) clasts of chert wrapped around and smoothed off by the intense cleavage to resemble rounded boudins. Arnold's (1985, p. 48) interpretation of a 'transition from interbedded fine sandstone and slate of the Owen Conglomerate into silicified and hematitic rocks of the North Lyell chert' is also due to non-recognition of the sedimentary nature of the basal chert breccias and the replacement nature of the large chert body.

Some of the more silty Upper Owen beds at this locality have a soapy feel and a lustrous yellowish appearance on bedding planes and cleavage surfaces, indicating a sericite-rich

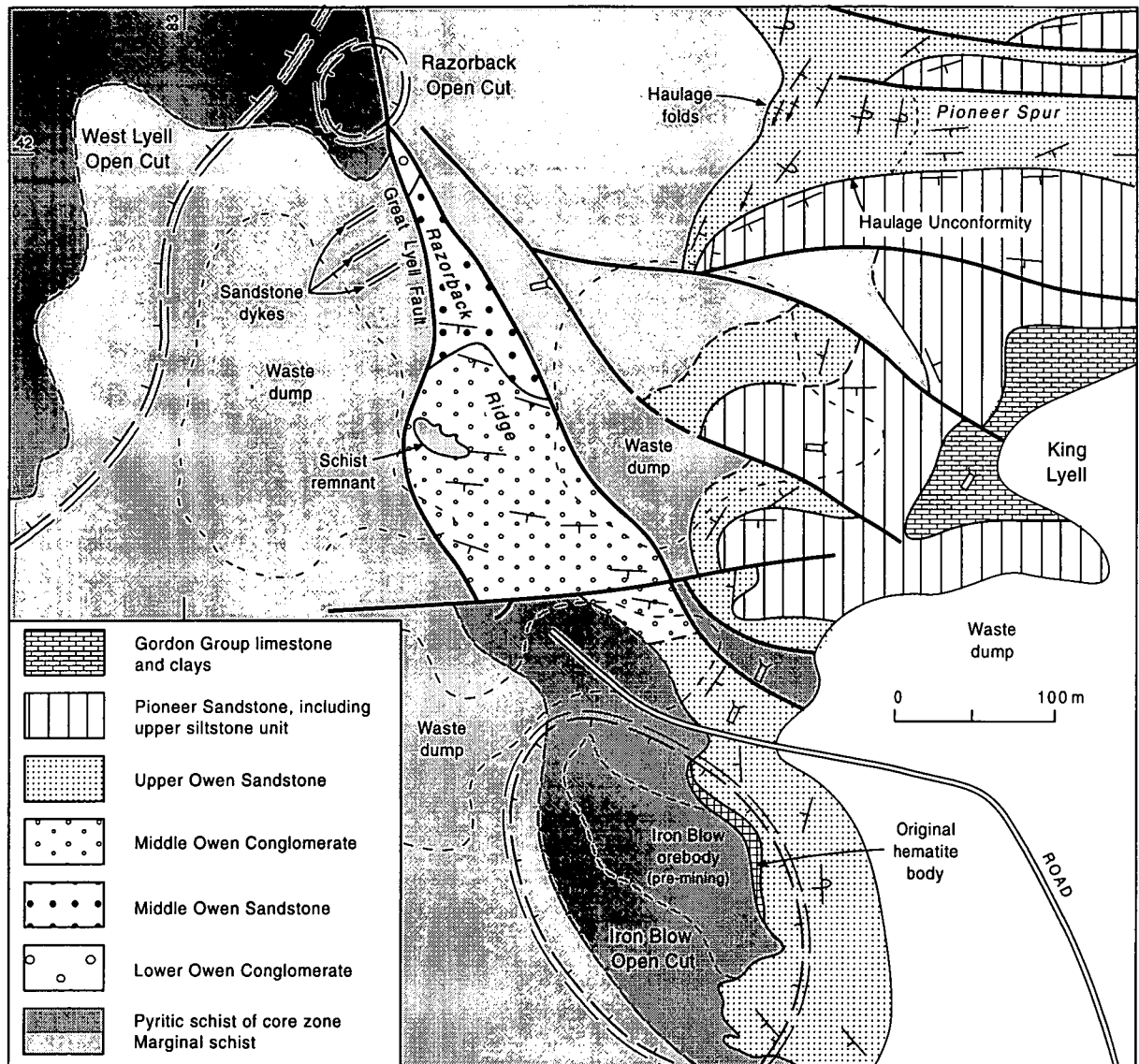


Figure 21. Simplified geological map of the Iron Blow–Razorback Ridge–Pioneer Spur area. Geology has been extrapolated under waste dumps in some cases.

composition. This is interpreted to reflect a locally-derived clastic input of sericitic material to the sediments from the schist mass (with recrystallisation during Devonian deformation), rather than a post-Owen sericite-forming hydrothermal event as implied by Berry (1990) and Hart (1992).

GEOLOGY OF THE RAZORBACK RIDGE - IRON BLOW AREA

General Geology

Razorback Ridge is a narrow, north-pointing wedge of Owen Group rocks lying more or less along strike from Tharsis Ridge and occupying a similar structural position (Figs 1, 21). The Great Lyell Fault surface lies along the western flank of the ridge, and has become highly visible in recent years due to several metres of west-side-down subsidence of the volcanic rocks into the underground workings due to block caving. The fault is traceable southwards to a major east-west cross-structure located close to the original Mt Lyell haulage line (Fig. 21), but is not evident as a surface fault beyond this. The continuation of the schist-Owen contact through the Iron Blow area is a very irregular, folded surface which wraps around the southern end of the Blow orebody and up the southern wall of the open cut before disappearing under a waste dump.

The eastern flank of Razorback Ridge is bounded by a steeply east-dipping fault which obliquely intersects the Great Lyell Fault at the northern end of the ridge, and continues south across the Haulage fault. Several other faults converge towards the northern end of Razorback Ridge, and form a fan-like structure to the south-east, displacing the schist-Upper Owen contact to varying degrees (the geology beneath a waste dump in this area has been reconstructed from maps of underground workings in the old Mt Lyell prospecting tunnel).

The Tharsis Trough schist mass extends into this area, being bounded by the Razorback Ridge to the west and the contact with the Upper Owen to the east. A narrow extension of it continues beyond the Haulage cross-fault, and disappears under a large waste dump. This southern extension of schist consists of strongly altered, pyrite-rich, sericite-silica schist, typical of the core alteration zone. Similar pyrite-sericite schist forms a narrow zone around the Iron Blow orebody just to the west (Fig. 21). This contrasts with most of the schist in the Tharsis Trough to the north, which is mainly marginal sericite schist with primary flow-banding and other textures preserved in many places.

The Owen Group rocks on Razorback Ridge strike east-west, perpendicular to the bounding faults, suggesting considerable rotation within and between fault blocks. The beds dip and face to the south at moderate angles. A sliver of Lower Owen Conglomerate is preserved at the northern tip, followed by a section of highly hematitic Middle Owen Sandstone, followed by Middle Owen Conglomerate with a high proportion of chert-hematite conglomerates. A well-preserved schist remnant sitting on the tilted conglomerate beds is described separately. The Middle Owen beds continue south of the Haulage fault, and have a concealed contact with strongly folded Upper Owen beds which wrap around the Iron Blow orebody.

Upper Owen Sandstone beds have a sedimentary-type contact with the schists along the eastern side of the Tharsis Trough, best seen in the Pioneer Spur area. Some excellent examples of Haulage folds are present on the crest of Pioneer Spur, close to the basal contact (eg Plate 4B). The Pioneer Sandstone overlaps the Upper Owen to varying degrees in the

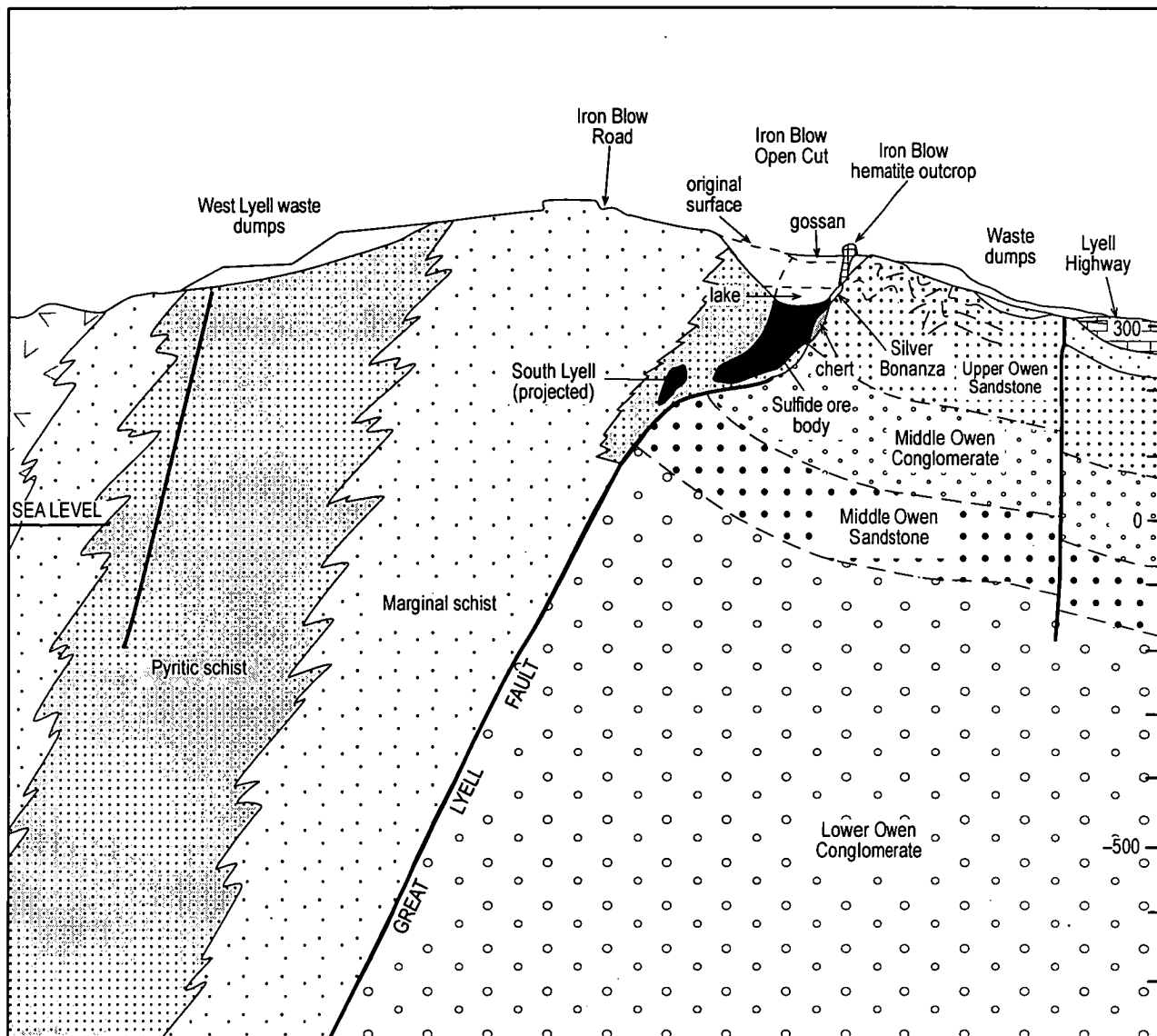


Figure 22. East-west cross-section through Iron Blow orebody, partly restored to pre-mining situation. Partly after Solomon(1967), and Arnold (1985).

different fault blocks, and rests directly on the schist mass in the block just north-west of the King Lyell workings (Fig. 21).

The Iron Blow Massive Sulphide Body

The Iron Blow sulphide deposit was discovered in about 1886 when a Tertiary gossan developed on it was tested as part of the early gold-mining operations (Thureau, 1886; Wade and Solomon, 1958). The body lies within an isolated zone of core-type pyritic felsic schist forming a small outlier against the Owen Group contact south-east of Prince Lyell (Figs 1, 21). A large projecting lens of hematite (the actual 'iron blow') was located on the contact of the sulphides with the Upper Owen Sandstone, and was removed during the gold mining and later open cut operation.

The contact between the schists and Upper Owen sediments at the Iron Blow open cut is folded and irregular in both plan and section (Figs. 21, 22), with a deep embayment where the southern part of the orebody is in contact with the sandstones. Folds in the adjacent sandstone beds appear to represent Haulage folding overprinted by Devonian folding. Middle Owen beds are present in the subsurface at the level of the lower part of the body (Fig. 22; Solomon, 1967).

The orebody was unlike any of the others on the field. It was about 200 m long and 50 m wide at surface, and extended some 250 m into the sub-surface in a 'banana' shape. As shown by the cross-section (Fig. 22), the lower part of the body rested on a flat section of the schist-Owen contact. The smaller South Lyell deposit lay some 200 m away to the south-west and was essentially identical in mineral content. Although initially considered to be a faulted off remnant of the main body (eg Gregory, 1905), further work suggested there was no fault but a 'boudinaged' or torn-off relationship (Nye, 1934; Arnold, 1985).

The sulphide body consisted mainly of massive pyrite, with only a few small intercalations of schist. Chalcopyrite was the most important copper mineral according to Nye (1934), with some bornite, chalcocite, tetrahedrite, tennantite, enargite, galena, sphalerite, hexastannite, arsenopyrite and molybdenite also present (Nye, 1934; Markham, 1968). The copper grade varied across the body, with the highest grades (around 6% Cu) towards the Owen contact and the lowest (around 0.5% Cu) towards the western side and in the deeper levels. Much of the body was actually mined as a pyritic flux for mixing with the siliceous North Lyell ores after 1903. Some pockets of the ore were rich in zinc and lead (Blainey, 1967).

Of considerable interest was the occurrence in the upper margin of the body, near the Owen contact (Fig. 22), of a number of irregular patches and shoots of very high-grade ore. The richest of these was the 'Mount Lyell bonanza' silver shoot, which yielded 852 tons of ore at 21% copper and 31,500 g/t silver from a narrow seam of stromeyerite, tetrahedrite, chalcopyrite, bornite and chalcocite (Gregory, 1905; Wade and Solomon, 1958; Arnold, 1985).

Markham (1968) described delicate banding and remnant colloform textures within the Iron Blow pyrite, and considered the ore to be of 'exhalative sedimentary type' like the Tasman Crown lead-zinc body. Cox (1979, 1981) described similar colloform textures as well as framboidal textures in pyrite and fine banding in galena-sphalerite-chalcopyrite-barite-silica ore, and also considered the body to be exhalative. Unlike the situation at Tasman Crown and

the Comstock mullock quarry, however, the Iron Blow body is hosted within schists which appear to be derived from Central Volcanic Complex rock types rather than lower Tyndall Group, since the characteristic quartz phenocrysts and polymict volcaniclastic textures are lacking. This suggests that the Iron Blow body may represent an earlier exhalative stage within the upper part of the Central Volcanic Complex, and that there may be a younging of the system, and of the exhalative horizon, to the north. Alternatively, there may have been several or multiple exhalative horizons through the long-lived system, beginning in the Central Volcanic Complex.

Chert bodies or silica heads are not a significant component of the schists in the Iron Blow area, although some chert was preserved between the sulfide body and the Owen contact (Fig. 22; Arnold, 1985). This could mean that either the cherts were eroded off before burial of this remnant of the alteration zone, or that there was less silica and chert in this part of the system than in the Comstock-North Lyell area.

The mode of emplacement of the Iron Blow body is discussed in a later section, after consideration of the emplacement of the North Lyell schist mass.

The Schist Remnant on Razorback Ridge

An excellent example of a schist sole remnant, sitting on tilted Middle Owen Conglomerate beds, is exposed on Razorback Ridge (Fig. 23). The schist mass is about 40 m long and 15-20 m wide, and consists of yellowish sericite-pyrite-rich schist, similar to material from the core of the alteration zone elsewhere. It sits discordantly on the conglomerate beds, which dip at 60-70° south and consist mostly of the chert-hematite-rich variety with interbeds of the 'normal' quartzite-clast type. Zones of vein quartz are developed along the contact in places, and there is hematite alteration and staining of the conglomerate beds in one area (Fig. 23). Several small faults affect the conglomerate beds in places, but are not traceable into the overlying schist, suggesting the faulting may be in some way related to emplacement of the schists.

Two small troughs or channels are exposed on the shelving northern contact of the schist mass, and appear to be undulations formed by the semi-plastic schist interacting with bedding in the conglomerates. The channels are somewhat asymmetrical in cross-section and show 'digging-in' along the eastern side (Plate 8A), features which suggest movement of the schist mass from NW to SE, more or less parallel to the length of the body. In detail, the contact between schist and conglomerate is welded, irregular and inter-penetrating, indicating that it was formed by interaction of two semi-consolidated materials rather than by faulting between two lithified units. The exposed part of the southern contact of the schist mass is also over-steepened as though by 'digging-in' (Fig. 23).

An unusual feature of the schist mass is the presence within it of a number of irregular masses and deformed dyke-like bodies of pink sandstone. These have been examined in thin section (OG 83, 84) and have the same distinctive texture (hematite-coated quartzite grains floating in clear quartz cement) as the Middle Owen Sandstone, which occurs just to the north on Razorback Ridge, and also forms sandstone dykes within the schists adjacent to the Great Lyell Fault (Plate 8B). The presence of deformed and folded dykes within the schist mass suggests that the mass has slumped or slid across the Middle Owen Conglomerate beds *after* dykes were initially emplaced from the Middle Owen Sandstone. Other dykes of this

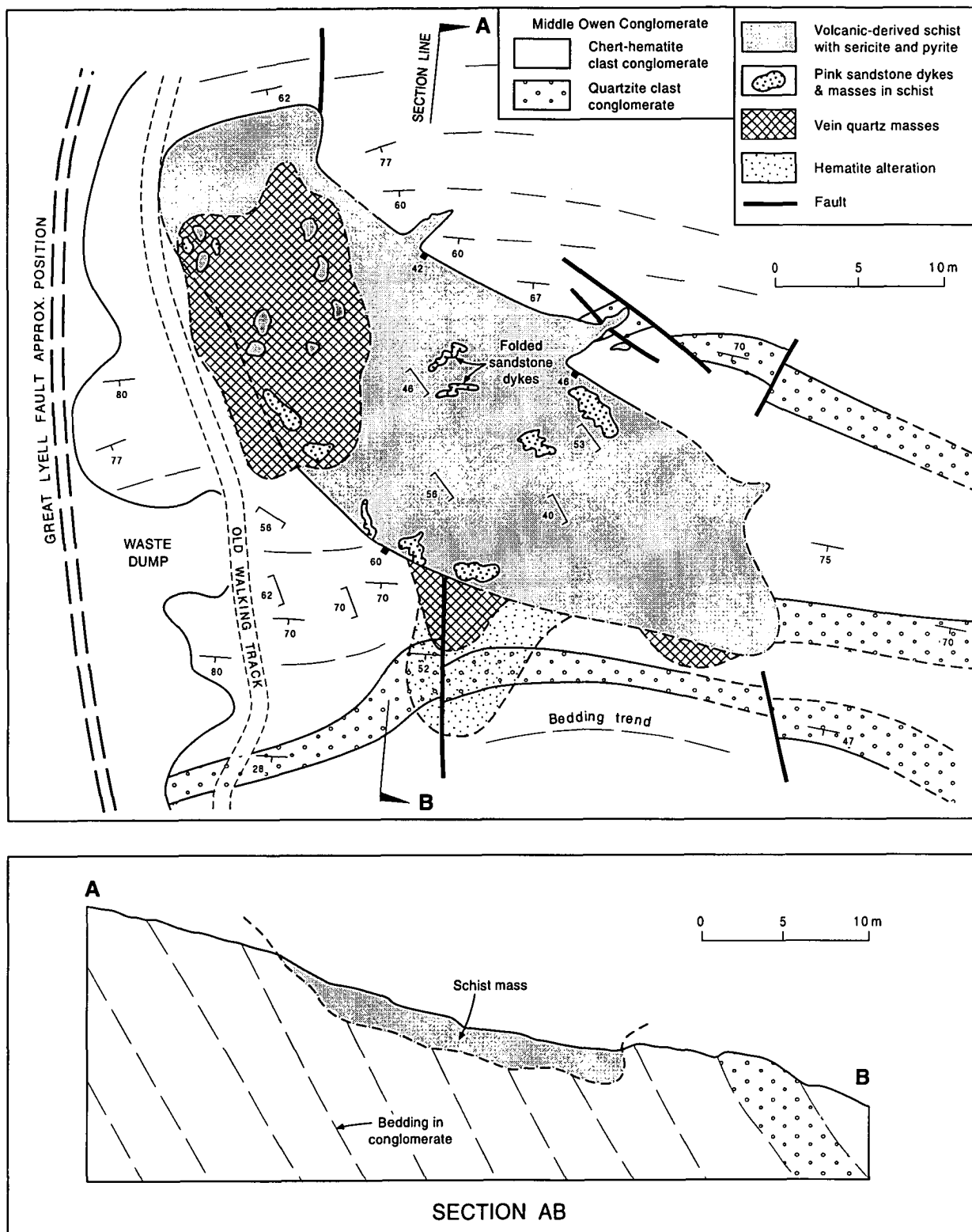


Figure 23. Geological map and cross-section of the schist remnant at Razorback Ridge (see Fig. 21). Dashed boundaries indicate areas concealed under surface rubble.

distinctive sandstone have been mapped in a number of localities within schists close to the Owen contact between the Iron Blow open cut and the Copper Estates area (Fig. 1).

NATURE AND ORIGIN OF THE HEMATITE-BARITE BODIES BETWEEN NORTH LYELL AND THE IRON BLOW

General Description

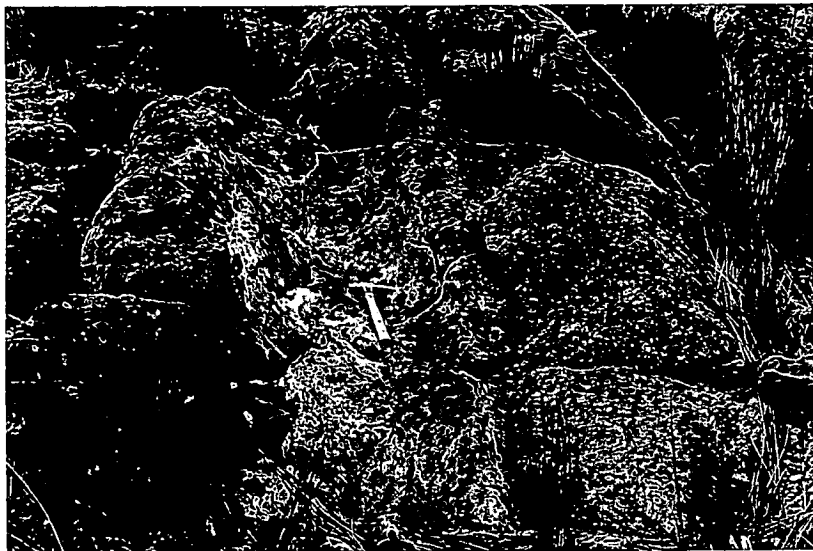
Discontinuous bodies of massive to semi-massive purplish-red hematite, usually with abundant blebs of barite and lenses of chert-hematite breccia, occur along the schist-Owen contact between North Lyell and the Iron Blow. Similar hematitic breccias are present along the contact on the eastern flank of Tharsis Ridge and in the Copper Estates- Moores Creek area (Fig. 1). The original Iron Blow was one such body, but was removed during early mining operations and is now represented by loose blocks on the waste dump and some remnants in the bottom of the Iron Blow pit (Fig. 21).

The largest hematite body is that exposed on the North Lyell road at the entrance to the Lyell Tharsis open cut. It is about 16 m thick, and extends along strike to the south for about 400 m (Fig. 1). A smaller body was located on the northern side of the North Lyell chert body (Figs 1, 16), as evident from old plans, drill intersections, and residue on a nearby waste dump. The Iron Blow body was about 100 m long, up to 15 m thick, and extended about 60 m into the subsurface (Solomon, 1967). It consisted almost entirely of hematite and barite (Plate 8C), with little or no chert or breccia facies. It was in direct contact with the massive pyrite body on its western side, and appears to have been a gossan-like development on that body.

Figure 24 summarises the major features of the hematite bodies, and gives a cross-sectional reconstruction of their relationship to the schist mass and the Owen sediments. The bodies typically show a gradational base through strongly hematite-altered schist into schist with irregular hematitic veins penetrating downwards for 5-10 m. The hematite alteration overprints the normal sericite-chlorite-silica-pyrite alteration. The adjacent chert at North Lyell is brecciated and veined with hematite to a depth of 20 m or more, and the hematite-jasper veining seen in the Comstock chert is considered analogous.

The massive to semi-massive hematite forming the main Lyell Tharsis body sits at and just above the schist contact, and appears to partially or completely replace the Upper Owen sediments and some of the schist. Remnant beds and lenses of pink Upper Owen sandstone and hematitic shale after micaceous siltstone are present within the hematite, and help to give it a crudely bedded appearance. Lenses and beds of breccia rich in irregular clasts of hematite, chert and other altered volcanic materials in a hematite-barite-rich matrix are typically intercalated with the massive hematite (Plate 8D), and form the dominant lithology in some areas. There is typically a gradation out into less hematitic chert-hematite breccias, and these breccias typically finger out into the normal sandstones of the Owen sequence.

Irregular blebs and veins of coarse-grained barite are prominent in parts of the hematite masses, and at Lyell Tharsis appear to be concentrated in irregular zones which cross-cut bedding. The blocks of Iron Blow hematite show abundant barite blebs in narrow zones which appear to be parallel to remnant bedding in the hematite (Plate 8C). Thin sections of some of the chert-hematite-rich breccias from within the Owen sequence away from the hematite bodies show clasts of hematite with included blebs of barite (eg Plate 2D), as well as significant amounts of barite in the matrix, implying that the barite was an early introduction to



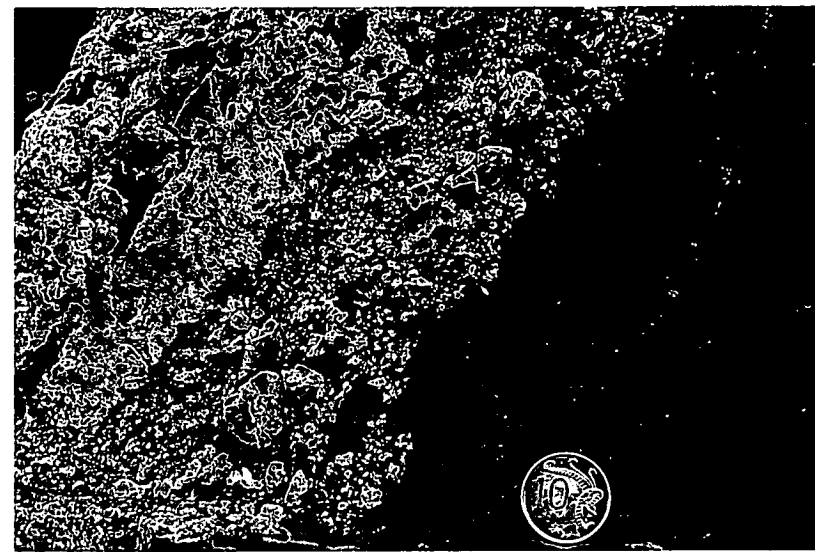
(a) View of basal channel structure at contact of schist sole remnant on Middle Owen Conglomerate beds, Razorback Ridge. Main schist mass is at bottom of photograph. Orange-coloured schist has irregular, inter-penetrating contact with conglomerate. Note overhanging ridge structure on right hand side where schist has 'burrowed' into semi-consolidated conglomerate.



(c) Block from original Iron Blow hematite body, showing barite blebs (white) and probable bedding textures.



(b) Dyke of pink Middle Owen-type sandstone within sericite schist at north-west end of Iron Blow open cut



(d) Part of hematite body with layer of chert-rich breccia, 100 m south-east of Lyell Tharsis open cut.

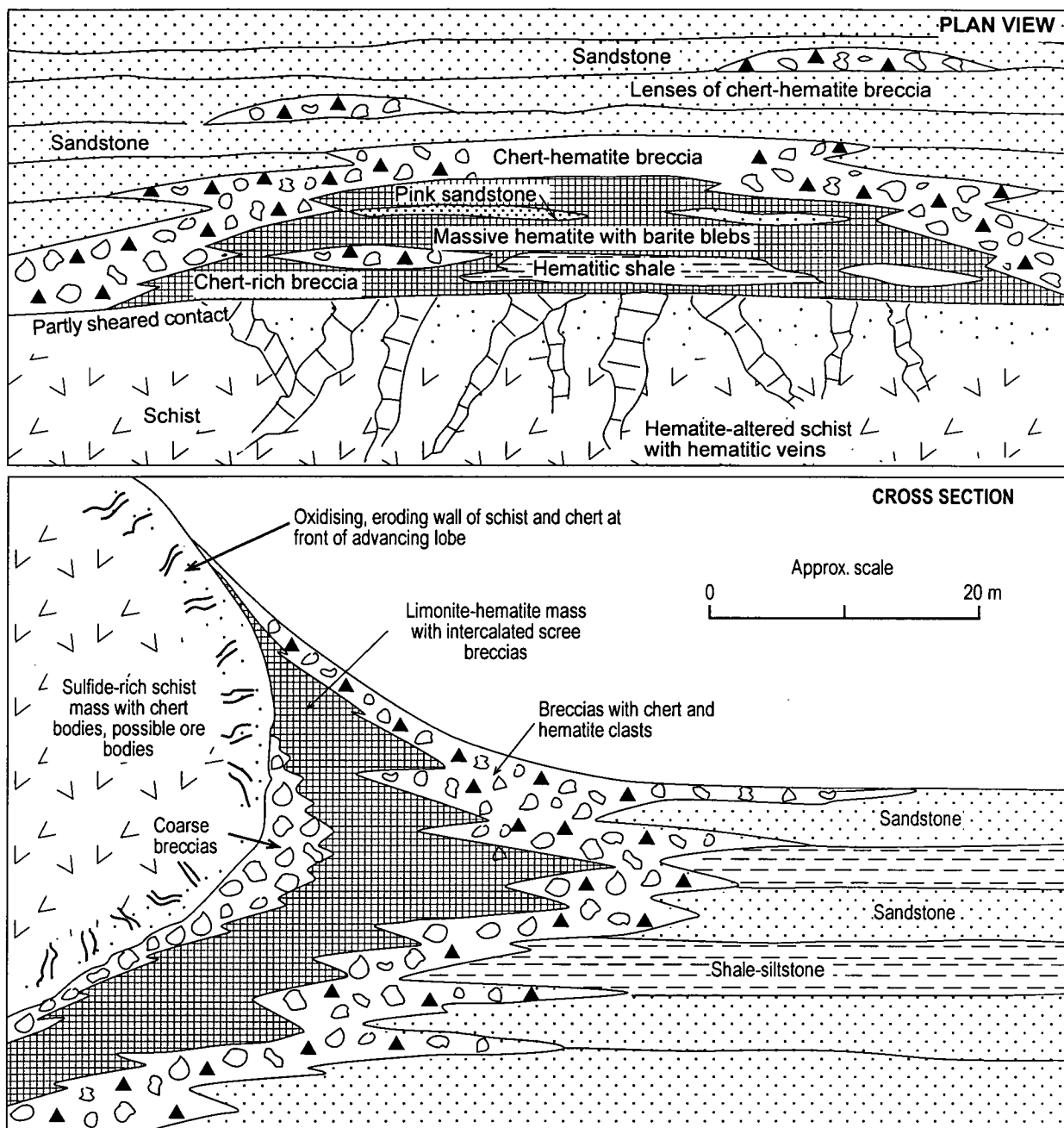


Figure 24. Diagrammatic plan view and cross-section showing typical features of hematite bodies and associated chert-hematite breccias, and relationship to schist mass and Owen Group sediments.

the hematite, and that the environment of the hematites and associated breccias was more or less saturated with barite. The clastic nature of the hematite-barite material in Owen sediments implies that it was formed as a product of Cambrian oxidation and erosion and associated processes rather than by some later hydrothermal event.

Relationship to Owen Group sediments

The fingering out of the hematite bodies and associated hematite-rich breccias is clearly demonstrated in two North Lyell drill holes, NL 1101 and 1102 (Fig. 17). These holes were drilled in 1985 from either side of the Lyell Blocks area to test for extensions of the Blocks mineralisation at depth (Beddows, 1985). Hole NL 1101 was collared in Pioneer Sandstone and drilled westwards through the Lyell Blocks workings in Pioneer and Gordon Group clays, then through Upper Owen Sandstone rich in hematite and chert-hematite breccias, finally bottoming in Middle Owen Conglomerate. An upper hematite-barite unit, approximately 30 m thick, shows semi-massive hematite, patches with crustiform or botryoidal intergrowth of hematite, jasper and barite, and complex breccias of hematite, chert, jasper and barite. A large block of schistose volcanic material, 7 m across, showing hematite alteration overprinting a sericite-altered feldspar-phyric texture, occurs just below this hematite unit, suggesting proximity to the schist contact. A lower hematite unit, some 43 m across, shows evidence for hematite replacement of coarse volcanic-derived talus-type breccia in part, as well as replacement of Owen-type siltstone. Barite is common as large bladed crystals and smaller blebs, and broken clasts of bright red jaspery material are prominent. Oolite-like textures of hematite-rimmed rounded bodies, 5-15 mm across, are present in one zone.

Hole NL 1102 was drilled eastwards through the North Lyell chert body (76 m), and penetrated a 5 m-wide hematite body followed by Upper Owen Sandstone rich in chert-hematite breccias, followed by Pioneer Sandstone. It then re-entered Upper Owen Sandstone, passing through interbedded sandstones and chert-hematite breccias followed by the upper hematite-barite body (40 m), followed by red sandstones and granule conglomerates, before passing through the North Lyell Fault and bottoming in Lower Owen Conglomerate. The main hematite body shows abundant coarse barite and bright red jaspery material, as well as some schistose volcanic clasts in places. Also seen in several places are clasts of hematite-veined chert essentially identical to the hematite-altered phases of the North Lyell chert. A chert clast with leiseegang-type iron oxide banding truncated at the clast margins was also noted, providing further confirmation that oxidation and hematisation occurred prior to deposition in the Owen sediments.

As shown in Figure 17, the drilling indicates that the hematite-barite bodies at North Lyell extend up to 200 m out from the schist contact, and are interbedded with the other facies of the Upper Owen, including chert-hematite breccias and normal sandstones.

A zone of hematite development is also present along the schist-Middle Owen Sandstone contact on the north-eastern flank of Tharsis Ridge (Figs 1, 16, 19). The zone is typically only 1-5 m thick, and is dominated by breccia textures rather than massive hematite. Barite is abundant in the zone, and irregular clasts of sericite-altered and cherty volcanic material are usually present, together with abundant clastic hematite in a hematite-rich matrix. The hematite-rich zone grades out into chert-hematite breccias which are interbedded with the normal red sandstones. In some places, the intense hematite development extends into the schist, overprinting the earlier sericite alteration and in some cases producing a crudely banded

hematite-sericite rock. Shearing is evident in the hematitic schists along this steeply-dipping zone, which has been referred to as the Tharsis Fault (Fig. 17).

Mode of Origin of the Hematite Bodies

The available evidence demonstrates that the hematite bodies formed contemporaneously with sedimentation of the Middle and Upper Owen beds. The hematite appears to have formed as a result of oxidation of the sulphide-rich mass of schists and chert, and replacement of the adjacent Owen siltstone and sandstone, where Owen sediments lapped against the disintegrating mass. The sedimentary facies of the Owen beds indicate that this occurred in shallow seawater and in tidal to partly subaerial conditions. Considerable brecciation of the chert bodies accompanied the oxidation, allowing hematite to penetrate up to 20 m or more into the chert bodies, and there was considerable mixing of clastic chert into the hematite masses. There was considerable erosion, disintegration and reworking of the oxidised schists and cherts into the Owen sediments, and coarse talus-like breccias of chert, schist and hematite fragments accumulated at the base of the slope at times. Barite was produced in great quantities at the same time as the hematization, and permeated the hematite bodies and associated breccias. Clasts of hematite with included blebs and crystals of barite were re-deposited into the Owen beds.

Previous Interpretations and Theories of Origin

The hematite deposits were of considerable interest to early workers, and the 'Iron Blow' outcrop figured prominently in early discussions of the Mt Lyell district (Blainey, 1967). Arguments over the origin of the hematite and of the adjacent massive pyrite deposit began after the first visit by a geologist (Thureau, 1886, 1889; Johnston, 1889; Power, 1891; Peters, 1893; Montgomery, 1893), and have continued almost to the present day. Some confusion is evident in early discussions because the hematite and pyrite of the Iron Blow were both referred to by the same name. Although it was generally accepted that the hematite was related to oxidation of the pyrite, the age of this oxidation event and the relationship to the more recent gossan on top of the body were not resolved.

A detailed study of the hematite bodies was made by Solomon (1967). He described the hematite-chert breccia within Middle Owen Conglomerate near Comstock (probably the same as the 'jasper bed' of this report), the large body at North Lyell, which he showed as interfingering within Upper Owen beds, and the original Iron Blow deposit. He noted that pebbles of fractured and hematite-veined chert in the Middle Owen Conglomerate were identical to the Comstock chert, proving that both the chert and hematite were pre-Upper Owen in age. He also noted that the North Lyell chert was similar to the Comstock chert except for being more brecciated and fractured, and that it contained veins of hematite, some of which showed botryoidal texture which had been modified by the Devonian cleavage. He described similar botryoidal textures, modified by Devonian cleavage, from the hematite body at North Lyell. He noted the coincidence of the three main occurrences of hematite with the three main areas of sulphide concentration on the Mt Lyell field, and concluded that the hematite bodies were 'gossans or limonitic screes developed during Ordovician weathering of adjacent sulphides'.

These observations and conclusions are entirely in accord with those of the present study. However, a revision of the North Lyell interpretation was made in a later paper (Solomon et

al., 1987), when the North Lyell chert body was considered to be a replacement of Owen Conglomerate, and the hematite-barite body was attributed to possible post-Owen (Devonian) metasomatism. The high-grade bornite orebodies at North Lyell were included in this postulated Devonian event. This somewhat surprising revision of good field-based conclusions was probably related to the interpretation of Sillitoe (1984) and others of the North Lyell chert as a post-Owen silicification phenomenon, based on the mis-interpretation of chert clasts in basal Upper Owen beds, and of conglomerate-like brecciation textures in the chert, as previously discussed.

This interpretation of the North Lyell chert and hematite bodies as Devonian hydrothermal products was further embraced by Hart (1992), who related the hematization to a redox front on the Great Lyell Fault, where upwelling reduced fluids reacted with oxidised connate waters from the Owen Conglomerate. The interpretation was later modified (Hart, 1993) when clasts of hematite were identified at the base of the Pioneer Sandstone, and a Late Cambrian-Early Ordovician hydrothermal event was considered responsible.

The present study has clarified the relationship between the volcanic-related chert bodies and bornite ores, of Middle Cambrian age, and the hematite bodies and the Owen Group sediments of Late Cambrian age. A separate hydrothermal event does not seem necessary to account for the hematite-barite bodies, which appear to have developed by surface oxidation processes on the sulphide-rich schists during a period of exposure and erosion. Considerable heat may have been generated during the rapid exposure and oxidation of so much fresh sulphide, however, and some residual heat from the original hydrothermal system may still have been affecting the rocks. Hence the oxidation processes may have been quite intense, with seawater contributing to the chemical reactions. As discussed by Solomon (1967), there was probably an intermediate phase of limonite and/or goethite formation before the hematite was produced, although the abundance of clastic hematite in the Owen sediments suggests that hematite production happened fairly rapidly.

There are also questions relating to the origin and significance of the barite. That in the Iron Blow hematite may have been derived from the underlying pyrite deposit, which also contains significant barite (Johnston, 1889). The sulphur isotopes (+36 to +41‰) and strontium isotopes of the Iron Blow barite indicate a Cambrian age (Solomon et al., 1988; Whitford et al. 1986). The origin of the large amounts of barite at North Lyell are less obvious, and the sulphur isotope values so far known are lower (+21 to +26‰) than those at the Iron Blow but similar to those from veins and blebs of barite in the Prince Lyell deposit (Walshe and Solomon, 1981). Values for the barite in clasts in the Owen Group rocks have not been determined.

Further studies of the hematite-barite bodies are required to clarify the processes involved and investigate the mineralogical relationships. It is noted that somewhat similar bodies of hematite occur at the contact of the Middle Owen Sandstone and underlying Lower Owen Conglomerate at the eastern end of the Mt Lyell range, some 3 km east of the schist contact, and in possibly equivalent positions in local erosional channels carved in coarse Lower Owen-type conglomerate on the Tyndall Range (Corbett and Jackson, 1987). Hence, the possibility exists of a widespread period of intense oxidation and hematite development during Owen Group sedimentation which could provide a useful stratigraphic mapping guide.

MODE OF EMPLACEMENT OF THE SCHIST MASSES AT NORTH LYELL, THARSIS TROUGH AND IRON BLOW

Expansion and Upward Mobility of the Altered Rocks

There seems little doubt that much of the Mt Lyell alteration-mineralisation system was eroded and beheaded in the Cambrian, mostly during the time of Owen deposition. The cover of middle and upper Tyndall Group rocks was removed during deposition of the Lower Owen, and the chert-rich upper part of the alteration zone was exposed, oxidised and eroded into the Middle and Upper Owen units. Some sections from this upper part of the zone were preserved when they collapsed or rolled into the Owen basin from the Great Lyell Fault scarp, but the bulk of the chert-rich zone appears to have been eroded off. Its detritus is evident as the abundant clastic chert within the Middle and Upper Owen formations (spread throughout the West Coast Range), and the oxidation products are seen as the abundant hematite in the same formations and on the schist-Owen contact. Softer products such as the abundant sericite were presumably broken down to clays and incorporated mainly into siltstones and mudstones, although some sericite is seen in basal Upper Owen sandstone beds at North Lyell.

The uplift responsible for the erosion seems to have been centred on the alteration zone in the mine area, since the cover of Tyndall Group rocks is intact beyond Comstock, where drilling suggests the alteration zone tails off. Hence a local driving force rather than a regional one seems likely.

Even before the Owen sedimentation began, there is evidence that the top of the alteration zone was being pushed up on to the seafloor and eroded during lower Tyndall Group time. This is suggested by the abundance of clastic chert and siliceous alteration material in the breccias and conglomerates of the lower Tyndall at Comstock, and by the fact that relatively unaltered limestone and other rocks sit directly on the Comstock chert body in places. The presence of clasts of sulphide in many of the breccias suggests that some exhalative sulphide deposits sitting above the chert were also eroded as a result of local uplift after deposition.

A further indication of uplift of the alteration zone at Comstock is provided by the upturning and overturning of the Tyndall Group cover rocks in the area (eg Figs 12, 13B), a feature which appears somewhat at odds with the general intensity of Devonian folding in the area, eg dips of 40–45° N in Owen beds on the northern flanks of Mt Lyell across the Great Lyell Fault (Corbett et al, 1989).

One possible explanation for the upward expansion and mobility of the altered rock mass could be found in the nature of the main alteration processes, and particularly in the degree of hydration involved. As recognised by Edwards (1939), in discussing the origin of the Lyell Schists, the two main alteration processes involved have been conversion of feldspar (in this case mainly albite) to sericite, and of ferromagnesian minerals to chlorite.

Edwards (1939) noted that sericitisation is essentially a process of hydration, in which the feldspar takes up from 5 to 6% by weight of water and heat is liberated. If other things remain unchanged, the volume of the feldspars is increased by 10 to 15%. Chloritisation is also essentially a process of hydration, in that pyroxenes contain from 0.1 to 1% by weight of water, and amphiboles from 0.5 to 3%, whereas chlorites carry 12 to 13% by weight of water. If other things remain unchanged, the volume of the ferromagnesian minerals would be increased by about 20% by chloritisation.

In the alteration-hydration process, therefore, if nothing was removed from the rocks at the same time, the volume of feldspar-rich and ferromagnesian-rich rocks would have increased by something like 10-20%. It is likely, however, that there was considerable removal of elements from the system, such as alkalis, iron, magnesium, etc, and much redistribution of silica, so that the overall volume result of the entire alteration process is difficult to estimate. Detailed chemical studies and mass balance analysis would be necessary to quantify this, and are outside the scope of the present study. The observation remains, however, that the Mt Lyell alteration zone consists of at least 6 cubic km of rocks in which the dominant constituents are sericite and chlorite, with quartz and pyrite as the other most important minerals. Unless there has been very large-scale removal of constituents, which is possible but for which there is no definitive evidence, the overall impression is that sericitisation and chloritisation have been the most volume-significant processes.

Edwards (1939) actually attributed the schistosity in the altered rocks to the expansion resulting from the hydration processes, and noted (p. 84) that because of the constraints imposed by the surrounding unaltered rocks.... "much of the expansion probably took place upwards, and it may be noted in this respect that frequently the sericite pseudomorphs after the feldspar phenocrysts have been drawn out into lens-like shapes, with their longest axes parallel to the dip of the cleavage directions....".

Although most of the cleavage formation at Mt Lyell has been attributed to the Devonian deformation, occurring long after the alteration which produced the original schists (eg Williams, 1993), the simple observations on alteration and expansion made by Edwards (1939) provide a possible, though unconfirmed, explanation for the expansion-related phenomena which have been described and deduced. It would seem likely that some degree of expansion could have accompanied the sericite-chlorite alteration from earliest times, pushing the altered materials upward towards the seafloor. This would explain the erosion of the upper parts of the Comstock chert body during Lower Tyndall time. Burial of the alteration zone by Middle and Upper Tyndall rocks could have produced a metastable situation, and as the overburden was stripped off it seems likely that there was a renewal of expansion and upward movement. This would have resulted in the chert-rich upper part of the system being exposed at the seafloor and eroded, and provides an explanation for the 'extrusion' of large masses of this material from the fault scarp into the Owen basin.

The North Lyell Corridor Mass

The available evidence indicates that this mass was emplaced by 'extrusion' or collapse of a large body of schist from the vicinity of the Great Lyell Fault scarp just to the west, the schist mass moving slowly into the margin of the Owen basin during sedimentation of the Owen beds. The interpreted events and processes involved in this emplacement are shown diagrammatically in Figure 25, and involve three main stages: (1) erosional unroofing of the alteration zone during Lower Owen deposition; (2) collapse and extrusion of rocks from the alteration zone into the Owen basin during Middle and Upper Owen sedimentation, accompanied by erosion and oxidation; and (3) uplift of the Tharsis Ridge shoulder and down-warping of the schist trough during and after emplacement.

As previously noted, hydrothermal activity in the Mt Lyell system was probably focussed on the Great Lyell Fault zone, and finally waned and ceased during deposition of the lower

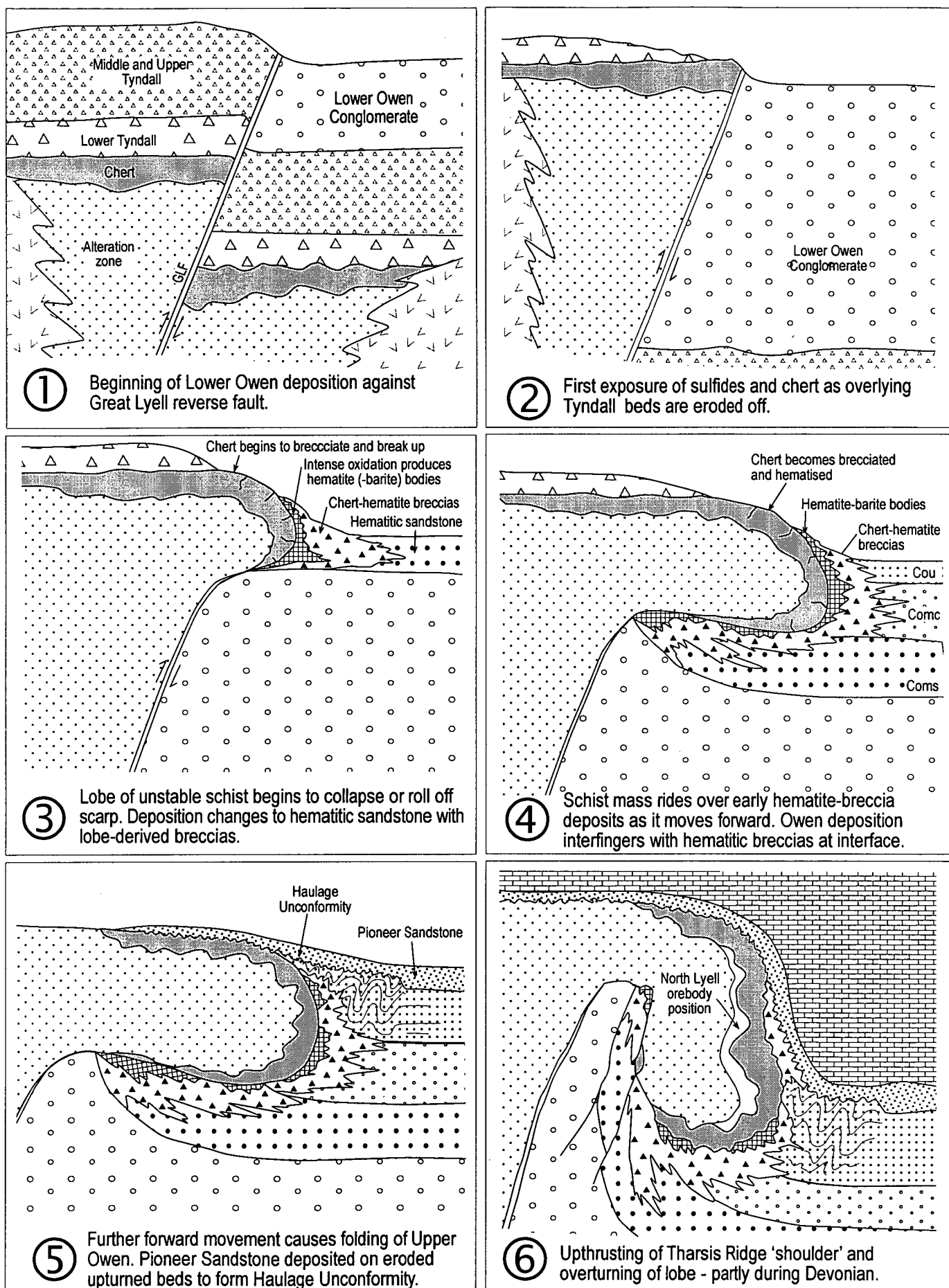


Figure 25. Deduced model for emplacement of schist mass at North Lyell (cf Figs 17, 18).

Tyndall Group. The alteration processes appear to have resulted in expansion of the rock mass, perhaps mainly because of the hydration involved, and this expansion was mainly relieved in an upward direction, resulting in the altered rocks pushing on to the seafloor and being partially eroded. In the Comstock area, this was followed by burial of the alteration zone beneath the middle and upper parts of the Tyndall Group to a depth of 300-400 m. This burial of a large mass of highly altered and hydrated rocks appears to have resulted in a metastable situation, and some initial uplift probably occurred even during Tyndall Group sedimentation, such that the depth of cover over the mine area may have been significantly less.

Owen Group sedimentation then commenced with deposition of the Lower Owen Conglomerate on the downthrown eastern side of the west-dipping fault. In the mine area, above the alteration zone, this deposition was accompanied by uplift and erosion of the Middle and Upper Tyndall rocks from the western side of the fault, and there is clear evidence that by Middle Owen time the cherts of the upper part of the alteration zone were exposed and being oxidised and eroded. The eroded middle and upper Tyndall material appears to be present in the Lower Owen sediments as relatively inconspicuous volcanic quartz grains and quartz-feldspar porphyry clasts.

The exposure of the sulphide- and chert-rich alteration zone appears to have resulted in, or was accompanied by, a change in configuration of the Owen basin, and marks the change from the coarse fluvial conglomerates of the Lower Owen to the shallow marine-deltaic sandstones of the Middle Owen Sandstone. The sandstones were red-coloured from the abundant hematite being fed into the basin as the sulphides were oxidised, and contemporaneous erosion of the chert bodies produced abundant chert detritus. Initially at least, the large chert 'cap' bodies may have protected the underlying parts of the alteration zone from significant erosion, and may have provided a degree of cohesion to the mass as it moved forward.

The large mass of schist and chert from the upper part of the alteration zone, with a number of included ore bodies, appears to have rolled or crept forward off the scarp at this stage. The forward motion may have resulted from the inability of the mechanically weak sericite-rich schists to maintain a steep scarp face, combined with the expansionary pressure built up within the schists as a result of the alteration. The mass must have moved slowly enough to retain considerable coherence, and although difficult to classify, must have had properties somewhere between a slump sheet and a small nappe.

The large upper chert body was much brecciated and eroded during the movement, but its size and competency may have been critical factors in preserving the overall shape and integrity of the mass as is now evident at North Lyell (Figs 16, 17, 18). The chert body seems to have folded over on itself as it advanced, producing a ragged, synclinal fold structure. Early-formed hematite and contact breccia deposits, such as those now exposed at the north-eastern corner of Tharsis Ridge, were apparently over-ridden by the lobe as it advanced, and some small masses of Lower Owen conglomerate (and some loose cobbles) were dragged off the substrate and incorporated into the schists in places. Some partially-altered lower Tyndall Group rocks were probably incorporated into the mass, and seem to be represented by the remnants of quartz-phyric volcanoclastic sandstone-schist around the northern end of Tharsis Ridge. However, no representatives of the likely exhalative ore deposits were preserved.

Deposition of Middle Owen Sandstone, Middle Owen Conglomerate and Upper Owen Sandstone continued against the growing wall of the schist mass as it slowly advanced forward

several hundred meters. Hematite bodies were developed along the contact as the sulphides were subjected to intense oxidation, and erosion of these bodies, and of the adjacent cherts, produced abundant lenses and aprons of chert-hematite breccia which interfingered with the Owen sediments. There was further advance after deposition of the Upper Owen beds, perhaps associated with a tectonic reactivation of the fault as part of a more regional event, resulting in compression, upturning and folding of the sandstone beds in the 100 m wide Haulage fold zone along the contact, as discussed below. The Pioneer Sandstone transgressed across the folded beds to produce the Haulage Unconformity, and overlapped on to the schist mass.

The stage at which the Tharsis Ridge was uplifted to its present position is uncertain, as is the reason for this uplift. The fact that the preserved sole remnants of the schist mass, which are sub-horizontal at present, rest on strongly tilted Owen beds suggests that considerable tilting and possible uplift of the substrate beds may have occurred during the emplacement process. There may also have been considerable downwarping of the schist mass as it 'ploughed' or 'burrowed' into the Owen beds. Further uplift and downwarping undoubtedly occurred during the Devonian deformation. Faulting along the northern and southern margins of the 'corridor' may have commenced in Cambrian time, but a major uplift on the North Lyell Fault late in the Devonian orogeny resulted in Lower Owen rocks being brought to present surface level.

Subsequent erosion of the covering schists has exposed some of the higher parts of the Tharsis Ridge and shoulder structure of Owen Group rocks, and left 'saddles' of schist and scattered small 'sole' remnants of schist sitting on steeply-dipping Owen beds.

Emplacement of the Tharsis Trough Mass

The schists filling the Tharsis Trough appear to have been emplaced in the same general way as the deeper mass at North Lyell, although for the most part the preserved filling is of marginal schist rather than core zone schist. This suggests that the core zone material from this area, with its complement of potential orebodies, was eroded away at some stage either during the emplacement process or subsequently.

The schist mass represented by the sole remnant at Razorback Ridge had apparently been intruded by sandstone dykes before moving or collapsing off the scarp. As it ploughed across the upturned conglomerate beds it produced shallow, asymmetrical channels or troughs on the contact, and appears also to have caused small displacements and faults in the bedding. This mass consisted of strongly altered pyrite-sericite schist like that from the core of the alteration zone.

Formation of the Haulage Fold Zone

The zone of Haulage folding and upturning along the schist-Upper Owen contact between North Lyell and Pioneer Spur, and its relationship to the Haulage Unconformity beneath the Pioneer Sandstone, have already been described. The localisation of the zone along the schist contact, the uncleaved 'soft-sediment' nature of most of the folds, the west-to-east transport direction indicated by the overturning, and the post-Upper Owen pre-Pioneer age of the deformation as indicated by the Haulage Unconformity, all point to the folding being related to further eastward movement of the schist mass. This late phase of movement and schist 'extrusion' from the Great Lyell Fault may have been associated with a more widespread

tectonic event which is reflected in unconformities beneath Pioneer Sandstone correlates in the general Queenstown-Zeehan area (Corbett and Turner, 1989), although most such unconformities represent the summation of movements during all of Owen Group time.

Further evidence that the schist mass was emplaced during Owen time is provided by the fact that Pioneer Sandstone can be seen to rest directly on the schists in a downfaulted block at King Lyell (Figs 1, 21), indicating that the sandstone had transgressed beyond the Upper Owen beds and on to the upper surface of the schist mass, as shown in the reconstruction in Figure 25). This is probably also the case at North Lyell, where a wedge of Pioneer Sandstone and Gordon Group clays along the northern side of the open cut rests on the underlying schists on an irregular sheared surface which has been designated as the 'Blocks Fault' but appears to be a sheared unconformity surface. These exposures confirm that the schist mass was in place within the Owen basin when the Pioneer Sandstone was deposited.

The zone of upturned, compressed and folded sandstone beds appears to have formed a 'bulge' on the seafloor, and most of the basal conglomeratic part of the Pioneer Sandstone was deposited on the downslope side of this bulge. The grey sandstone facies of the Pioneer transgressed across the truncated beds and covered at least part of the schist mass. There may also have been some further forward movement of the schist mass *after* deposition of the Pioneer Sandstone, at least in some areas. This is indicated by the arrangement revealed by drilling at Gormanston, where the schist-volcanic mass overlies a recumbently folded zone of Pioneer Sandstone and Gordon group clays, with indications (eg extensive breccia textures in the volcanics) that some collapse of the mass has occurred in relatively recent times, perhaps as a result of Tertiary weathering of the Gordon Group limestones to soft clays. A somewhat similar structure appears to be present at the Tasman Crown mine at Comstock (Figs 12, 13A), where the lobe of schists and Tyndall Group rocks carrying the Tasman Crown sulphide body appears to over-ride Pioneer Sandstone in a puzzling fashion.

Mode of Emplacement of the Iron Blow Sulphide Body and Associated Schist

The folded and irregular nature of the contact of the Iron Blow body against the Upper Owen sediments, the presence of a hematite-barite gossanous body on the contact, and the location of the deposit on a flattened part of the Owen contact coinciding with the Middle Owen beds, all point to a similar history of emplacement to that deduced for the North Lyell schist mass. In this case, however, there does not appear to be any equivalent of the Tharsis- Razorback Ridge structure developed, the available drilling suggesting just a major flattening of the Owen contact at about the level of the Middle Owen Sandstone associated with a forward bulge in the schist mass (Fig. 22).

Three stages in the interpreted emplacement history are shown in Figure 26. After unroofing of the alteration zone on the upthrown western side of the Great Lyell Fault during Lower Owen deposition, the mass of sericite-rich schist began to collapse or 'extrude' from the fault scarp into the Owen basin. Considerable erosion and oxidation of the sulphides occurred during the process, forming the hematite body on the contact. It is suggested that supergene enrichment processes operating at this time on the upper part of the orebody, where there may have been some lead-zinc mineralisation, produced the pockets and lenses of bonanza grade copper-silver ore.

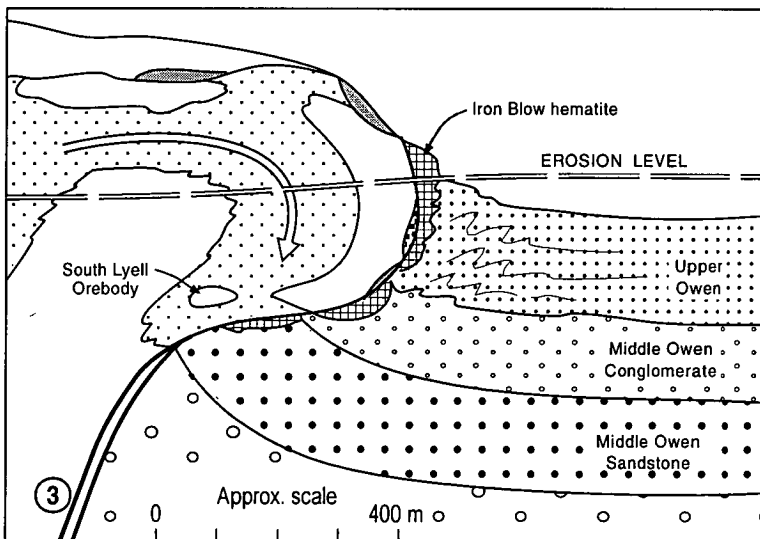
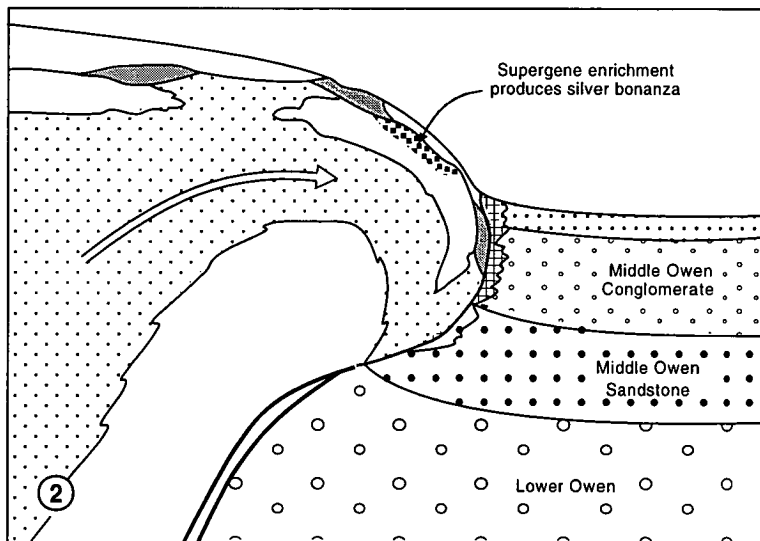
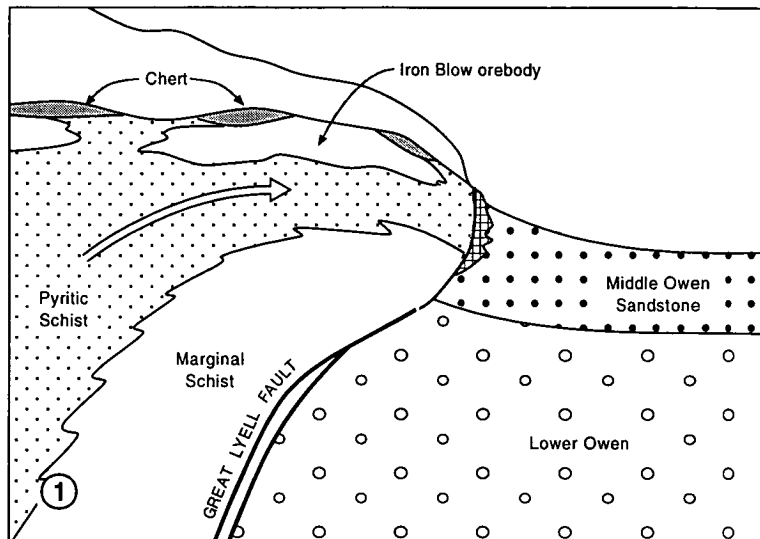


Figure 26. Proposed model for emplacement of Iron Blow sulphide body, formation of bonanza silver lodes, and formation of hematite body (cf Fig. 22).

The forward rolling motion of the schist mass caused rotation of the originally horizontal orebody into a subvertical position as it ‘bulldozed’ into the sandstones, in a manner similar to that of the North Lyell chert and associated orebody. The considerable weight of the massive sulphide body may have contributed to the deformation. The South Lyell lens probably became detached within the schists as the larger body rolled or collapsed forwards. Subsequent erosion has removed the connection of the pyritic schists to the main schist belt, and also the top of the orebody (and probably several other such bodies).

Previous Interpretations of the North Lyell- Tharsis Ridge- Tharsis Trough Structure

The origin and significance of the mineralised schist mass at North Lyell, and of the associated conglomerate mass at Tharsis Ridge, have exercised and puzzled geologists since the form of the structure first emerged from mapping and underground workings. Interpretations applied to the structure have ranged from an intrusive contact through sedimentary interfingering and slumping, to purely structural origins, with no consensus apparent.

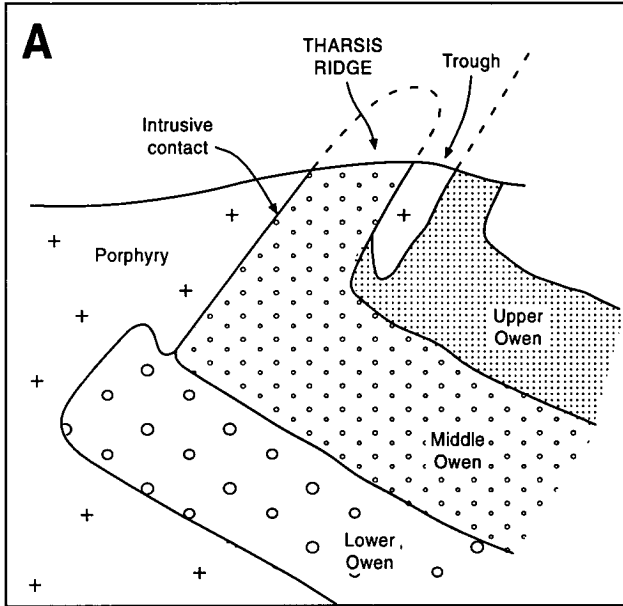
Early replacement or facies change models

Connolly (1947) provided the first coherent interpretation, when he considered the schist to be a Devonian porphyry which had intruded and partially replaced the conglomerate, particularly along the top of the Middle Owen formation (Fig. 27A). Wade and Solomon (1958) also considered that the schist trough was partly an intrusive-replacement phenomenon of the Middle Owen (Fig. 27B), although they recognised that the schists were mostly of Cambrian age and suggested that the structure was partly due to interfingering of volcanic and siliceous facies during Owen time, with only local ‘metasomatic replacement’ at the contact. Elms (1960, unpublished) supported a model of sedimentary interdigitation of volcanics and conglomerate to produce the original embayment in the Middle Owen, followed by folding and faulting in the Devonian to produce the ridge and trough structure (Fig. 27C).

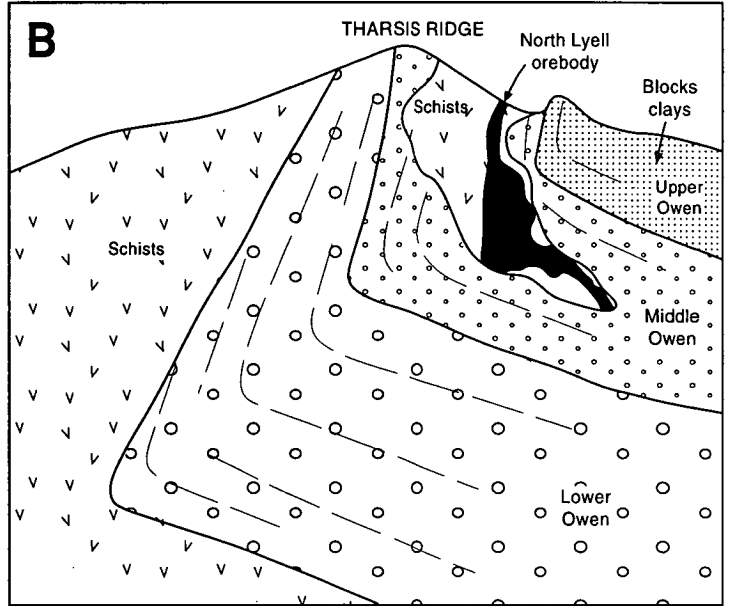
Early sedimentary- slumping models

An explanation involving remobilisation of Cambrian volcanics into the Owen, in the form of a large slump mass, was proposed by Solomon (1969) and re-iterated by Walshe and Solomon (1981). This model (Fig. 28) envisioned locally-derived hematitic breccias being deposited at the western margin of the Owen basin during Middle Owen time, followed by slumping of a large mass of volcanics into these breccias in Upper Owen time, causing folding of the sandstones and subsequent production of the Haulage Unconformity. Devonian folding was considered responsible for upturning and overturning of the western margin to produce the Tharsis Ridge structure. This model has much in common with the one proposed here, although it does not consider the influence of the Great Lyell Fault and has the ‘slumping’ as a discrete and presumably rapid event.

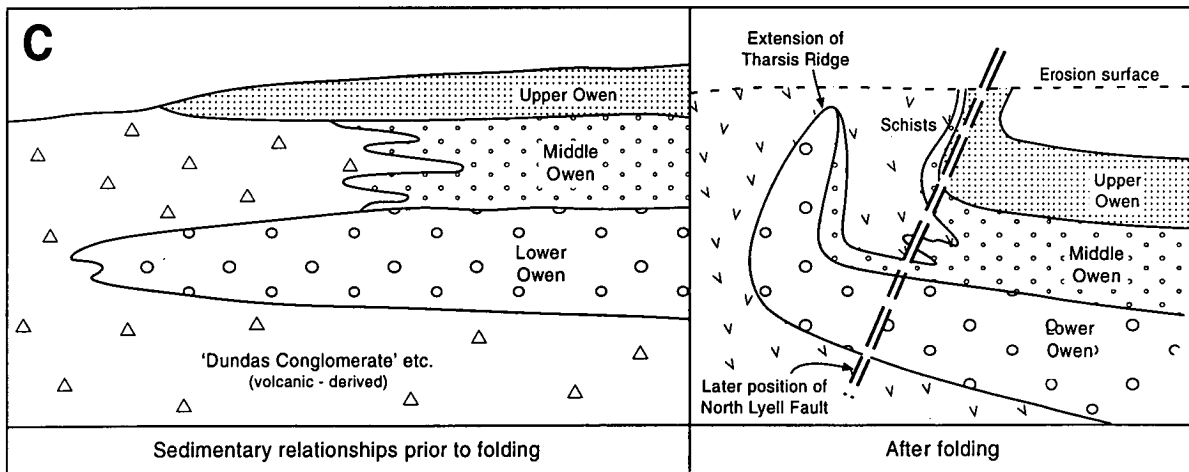
The slumping model was further refined by Bryant (1975), who suggested a slow-moving ‘slab’ or nappe-like body of volcanics had been involved (Fig. 28), which had behaved semi-coherently to preserve most of the internal volcanic stratigraphy. Again, it was considered that the slab had slumped into a pre-existing mass of hematite-chert breccias (deposited as a ‘facies variant’ of the Middle Owen Conglomerate), rather than producing the breccias as it eroded, as indicated in the present study, and that the event occurred in the Upper Owen. Some difficulty in integrating the Great Lyell Fault is evident in the model, which shows it dipping east at all times, but overall the model is an excellent reconstruction and accords with that proposed here in most of the important aspects.



Connolly, 1947: Porphyry intrusion into Owen after folding.



Wade and Solomon, 1958: Local metasomatic replacement of Owen after folding and schist development.



Elms, 1960: Original interfingering of volcanics and conglomerate results in schist embayment in Middle Owen after folding.

Figure 27. Early replacement–facies change models for Tharsis Ridge and Trough structure.

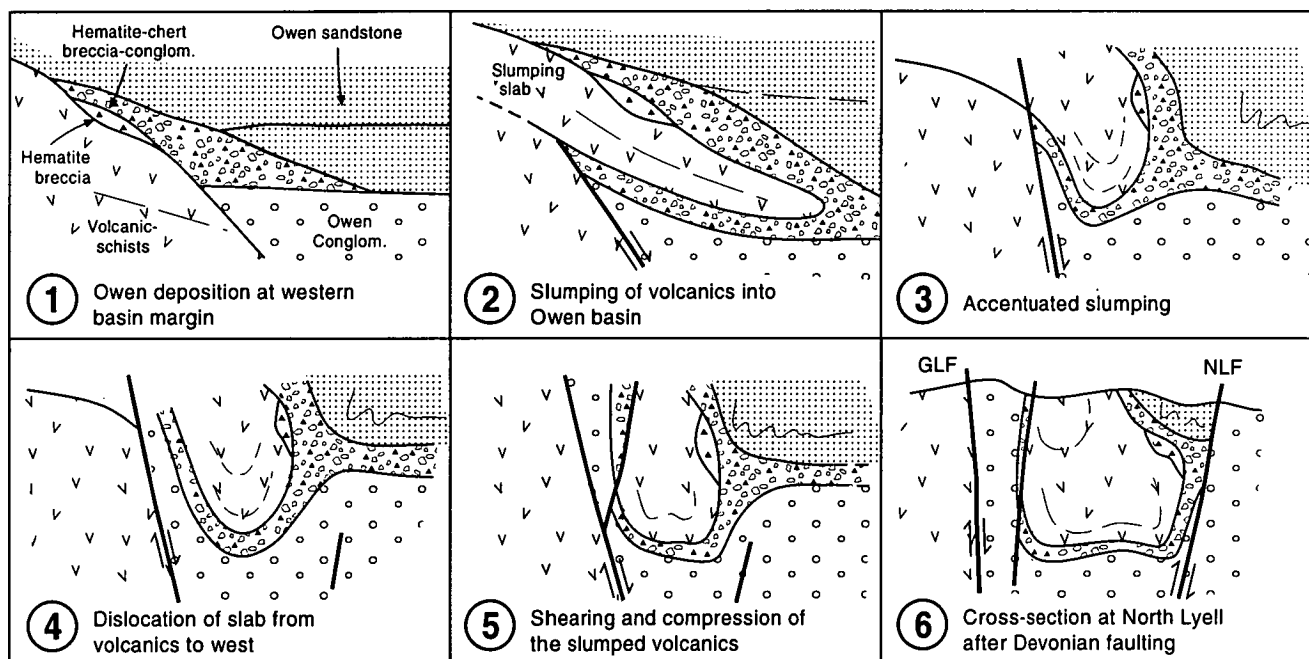
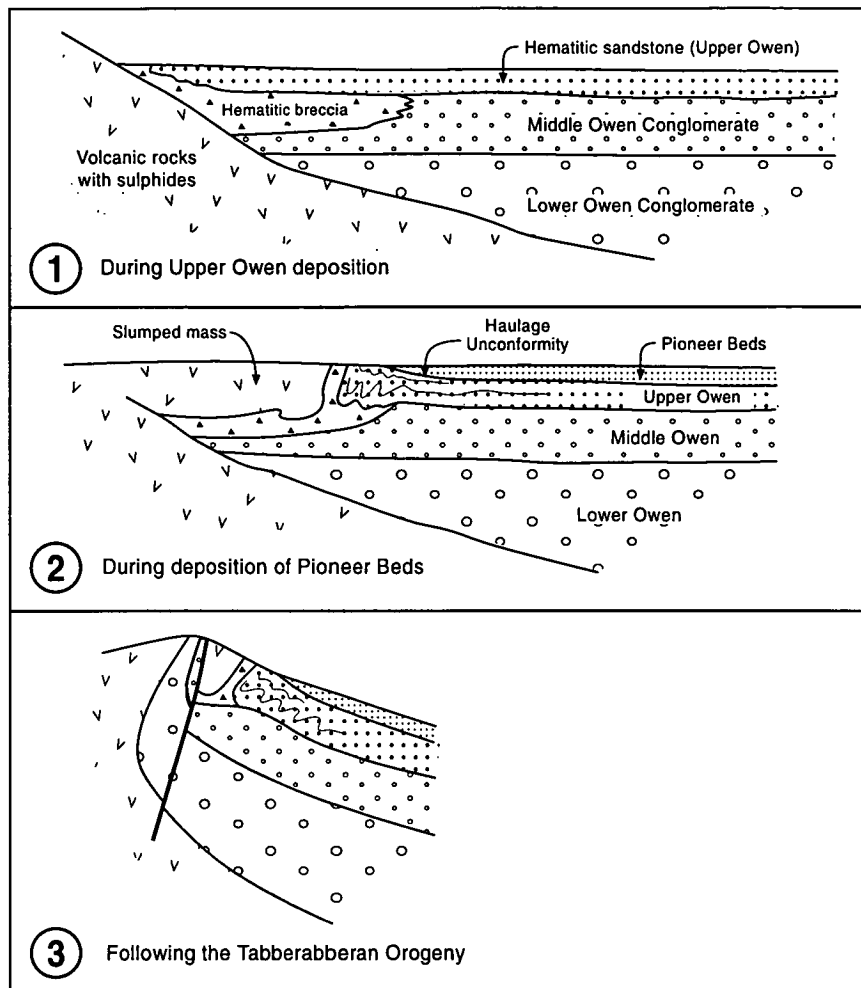


Figure 28. Early sedimentary-slumping models for North Lyell Corridor-Tharsis Trough. Top: Solomon (1969). Bottom: Bryant (1975).

Structure-based models

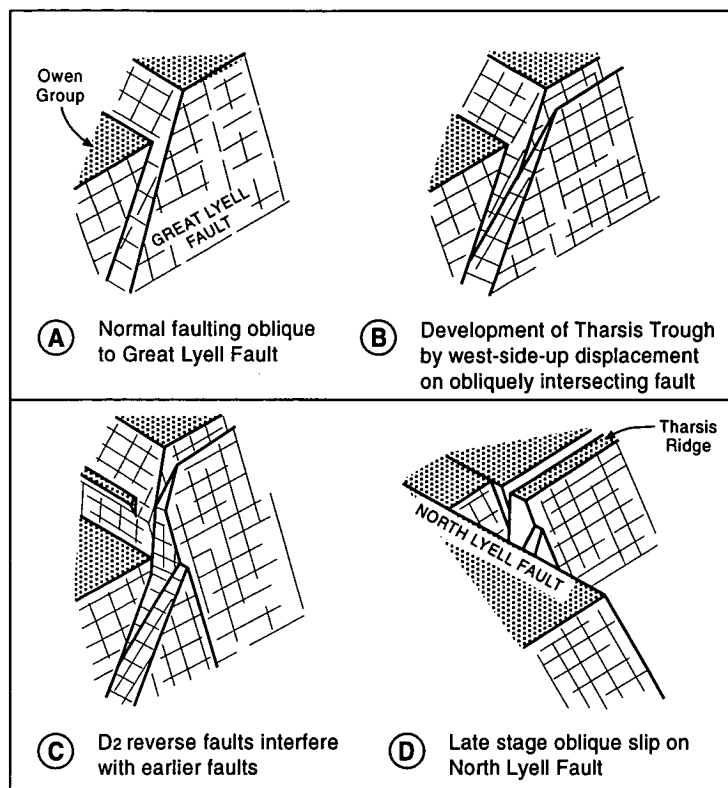
A series of structure-based interpretations for the ridge and trough structure, involving combinations of faults and folds, mostly of Devonian age, superseded the sedimentary models through the 1980's and 1990's. The first of these was by Cox (1981), who postulated a variety of movements on a combination of post-Owen faults at different intersection angles to the Great Lyell Fault to produce a fault-bounded wedge of volcanics with Owen Group rocks on three sides (Fig. 29). This purely structural interpretation takes no account of the sedimentary nature of many of the contacts, of the development of hematites and hematite-chert breccias on the contacts and their interbedding with Owen Group rocks, nor of the clear evidence for emplacement of the schist mass prior to deposition of the Pioneer Sandstone.

Arnold's (1985) relatively simple structural explanation (Fig. 29) is based on folding of the Great Lyell thrust fault surface to produce the Ridge and Trough structures, and associated drag-folding of the Owen beds to produce the Haulage folds. This model again takes no account of the sedimentary nature of the schist-Owen contacts along the eastern side of the structure.

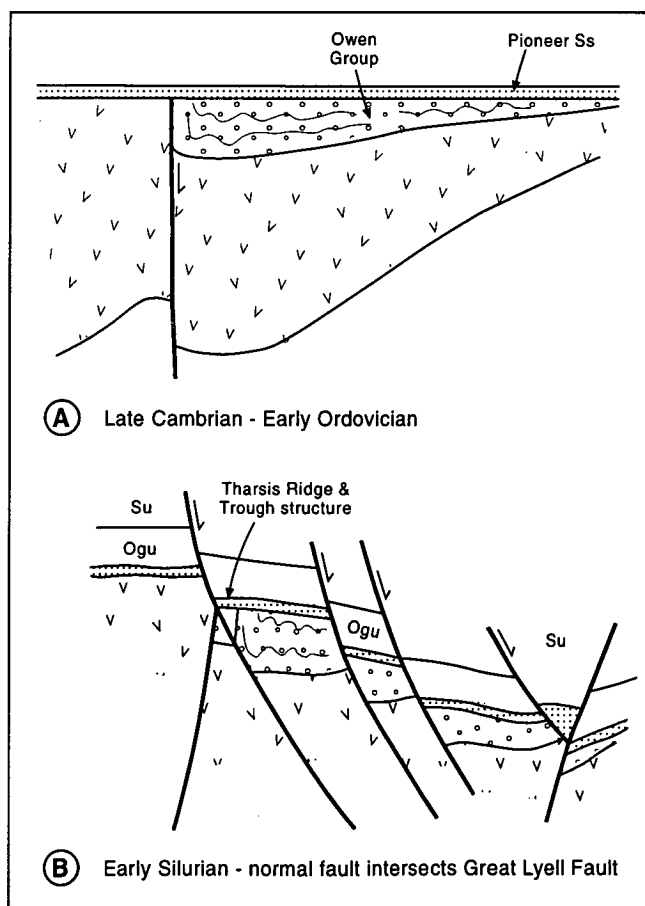
A model by Berry (1990) has two intersecting listric normal faults at the margin of the Owen basin with a rotated block of bedded Owen between them which defines the Haulage zone and produces the Haulage Unconformity (Fig. 29). A low-angle Devonian thrust intersects these faults, and Devonian D1 folding of this structure produces the ridge and trough arrangement. While this interpretation allows for hematite development at the original Owen margin, it does not accord with evidence for emplacement of the schist mass prior to Pioneer Sandstone time, when the Haulage folds were also formed, and does not consider the interactive nature of the contacts. It also relies on an east-dipping margin for the Owen basin when the available evidence indicates a west-dipping margin formed by the Great Lyell Fault.

A problem raised by Berry (1990) regarding the origin of the Haulage folds and the Haulage Unconformity is that several of the most accessible exposures of the unconformity show Pioneer Sandstone dipping east at 45-65°, overlying Upper Owen beds dipping west at 70-80°, with an angular discordance of about 40° between the two (eg Plate 4C). Rotation of the Pioneer beds to their horizontal 'depositional orientation' thus gives a relatively shallow dip (40°) to the east for the underlying beds, rather than the steep to overturned westerly dips expected from a schist emplacement model. A possible explanation for this anomaly is that folds in the still-unconsolidated Upper Owen beds were tightened, on the same steep axial planes, and the Pioneer beds were tilted, during further movement of the schist mass in the Ordovician.

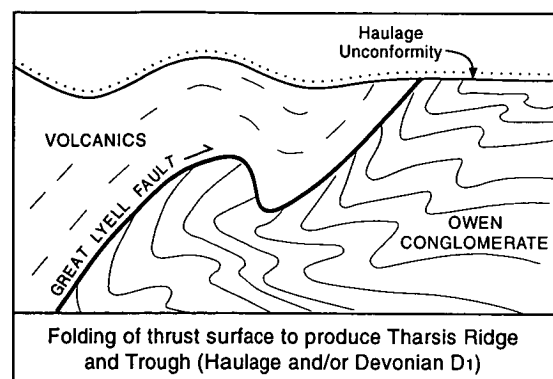
Another interpretation of the ridge and trough structure is contained within a general tectonic model of the Owen basin by Williams (1993). In this model (Fig. 29), subsidence movements on a sub-vertical Great Lyell Fault are responsible for the Haulage folds and the subsequent Haulage Unconformity. A second normal fault intersects the Great Lyell Fault in the early Silurian and displaces the schist-Owen boundary to produce the Tharsis Ridge and Trough structure. As with the other structural models, this simplistic model takes no account of the sedimentary nature of some of the contacts, nor of the pre-Pioneer age of emplacement of the schist mass.



WILLIAMS 1993



ARNOLD 1985



BERRY 1990

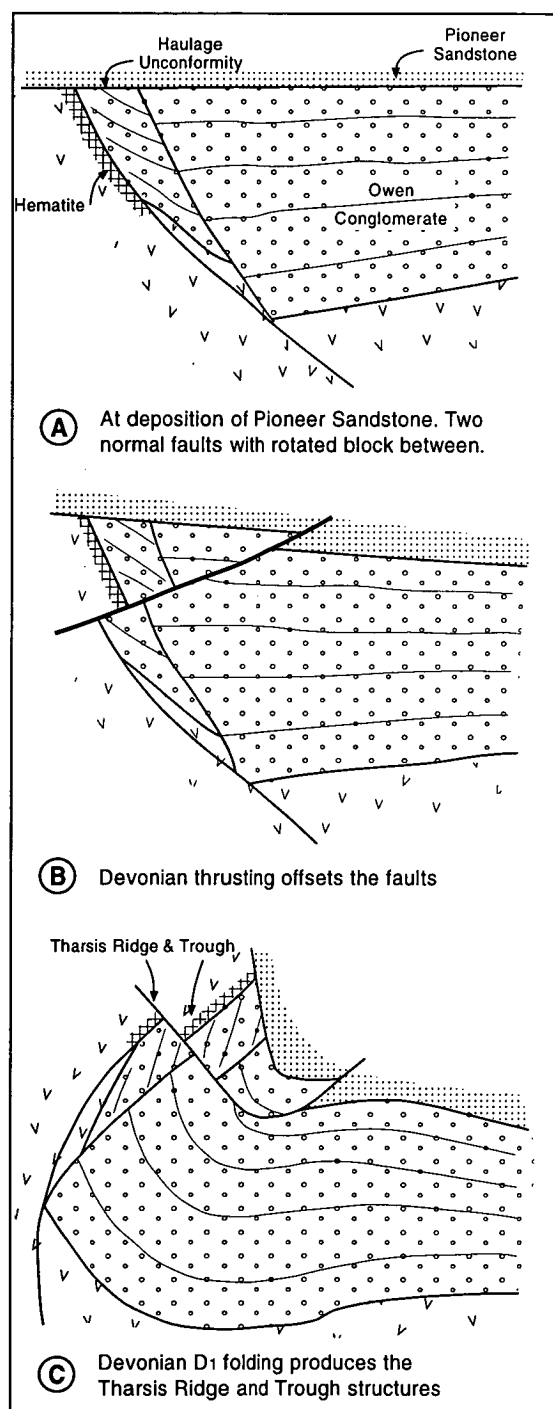


Figure 29. Structure-based models proposed for Tharsis Ridge and Trough by Cox (1981), Arnold (1985), Berry (1990) and Williams (1993).

RECONSTRUCTION OF THE MT LYELL ALTERATION- MINERALISATION SYSTEM

General Features

A diagrammatic reconstruction of the Mount Lyell hydrothermal system is shown in cross-section in Figure 30, and in longitudinal section in Figure 31. Much of the top of the system has been removed by erosion, and the erosion levels for the present time and for Upper Owen time are indicated in Figure 31.

The alteration system is dominated by a core of pyrite-rich sericite-chlorite-silica schists with pyrite content ranging from 1 or 2% up to 20% or more. This core zone grades laterally to marginal zones of pyrite-poor sericite and chlorite schists, as shown in the cross-section. Within the core zone, there is a marked vertical zonation from an exhalative zone at the top through a silica cap zone with very large chert bodies to a zone of abundant smaller chert bodies or silica heads, followed by a deeper zone of mainly pyrite-sericite-chlorite schists in which siliceous alteration is relatively sparse. The presence of magnetite-apatite lenses and veins at Prince Lyell suggests that such features indicative of input from magmatic fluids might be more prominent in the deeper levels.

As shown by the longitudinal section, the silica cap zone and the zone of silica heads were probably continuous from the northern limit of the system at Comstock at least as far south as the North Lyell area, where the large schist mass preserved within Owen beds contains a cap-like chert body and numerous smaller chert bodies. There is only sparse evidence to indicate whether, and in what form, these zones may have continued further south- only a small amount of chert is preserved at the Iron Blow, but some large eroded blocks of similar brecciated chert are present at Copper Estates, suggesting that some form of chert-rich upper zone was present in this southern area.

The present erosion level exposes the deeper levels of the system in the Prince Lyell- Royal Tharsis area, the lower part of the silica heads zone at Western Tharsis, and the upper part of the silica heads zone and the silica cap zone at Comstock, indicating an overall northerly plunge. This plunge is interrupted by the North Lyell Fault, which brings the deeper levels up again at Cape Horn.

The pyritic core zone has a maximum width of about 600 m in the Prince Lyell area, where the maximum concentration of ore lenses is also located (Fig. 1). The bulk of the schists in the core zone are sericite-dominated, but chlorite-rich schists are common in places and appear to be derived from andesitic precursors. Observations at Comstock suggest that intense sericite-pyrite-silica alteration has overprinted earlier chloritic alteration in places. The abundant pyrite occurs as disseminations, veinlets, blebs and solid bands within the schists. The massive pyrite in some of the bands is very fine-grained and pale yellow, with internal fine banding suggestive of open space deposition. Some of the pyrite has been recrystallised and remobilised into veins and lenses in the Devonian, and this pyrite tends to be bright yellow and coarse-grained.

The Exhalative Zone and Associated Mineralisation

The exhalative zone in the lower Tyndall Group is preserved only at Comstock (and possibly on the buried downthrown side of the Great Lyell Fault, as suggested in Fig. 5), and has apparently been removed by erosion over most of the Mount Lyell field. The Iron Blow sulphide body appears to represent a section of a slightly deeper exhalative horizon from

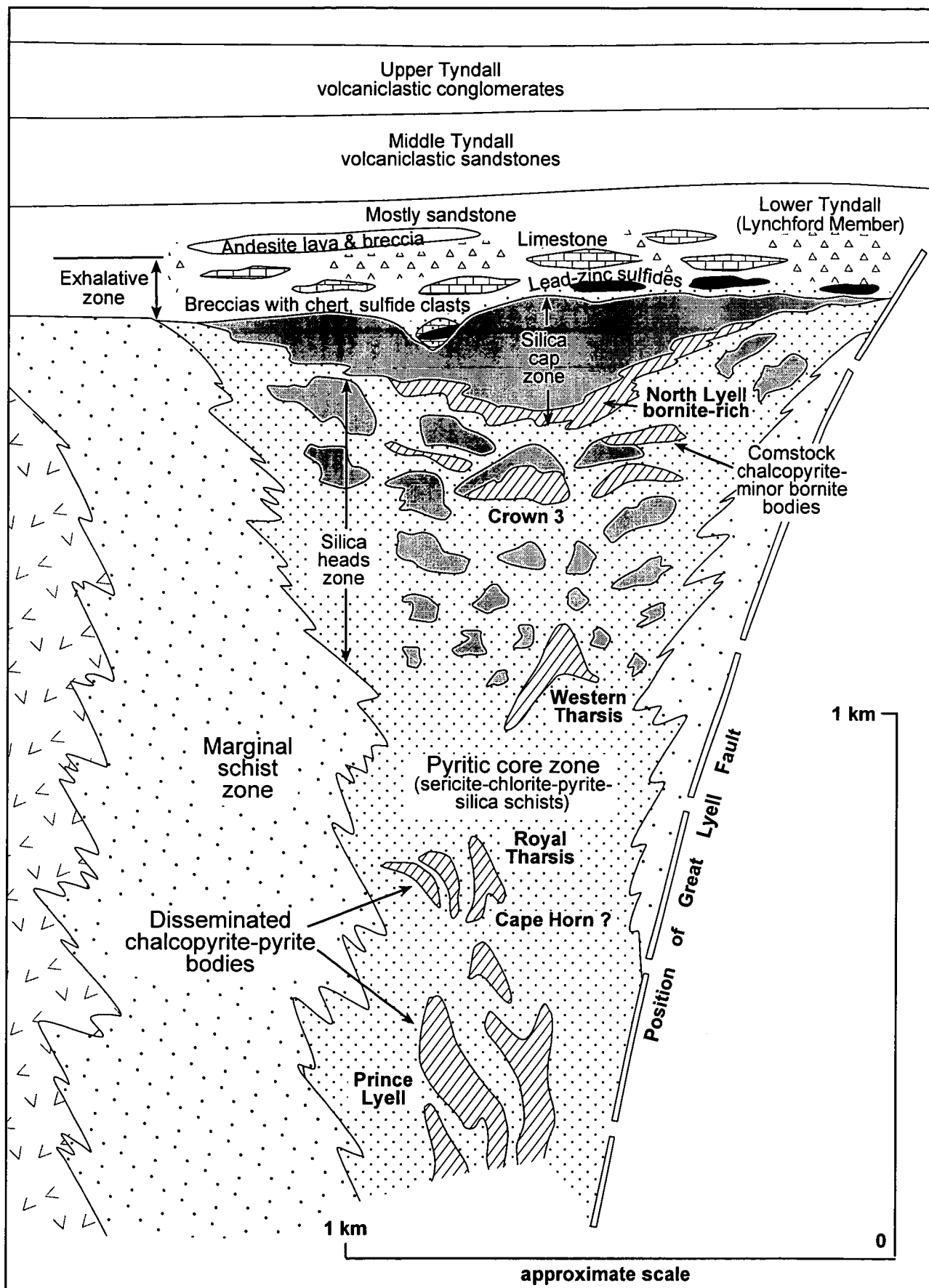


Figure 30. Cross-sectional reconstruction of the Mt Lyell alteration-mineralisation system. Upper part of system is composite of Comstock and North Lyell. Original shape of many of the orebodies is speculative.

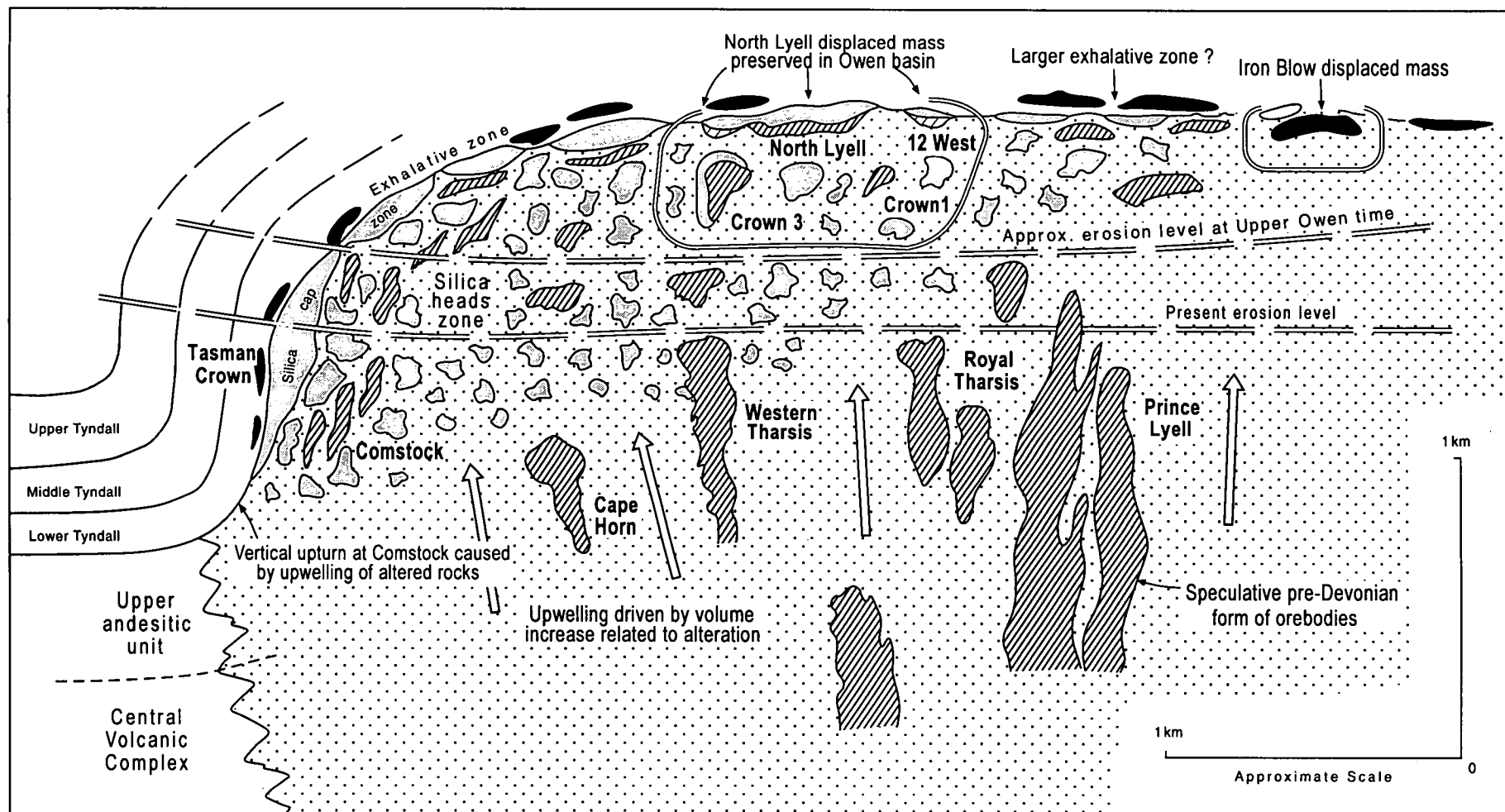


Figure 31. Diagrammatic longitudinal section of reconstructed Mt Lyell system as it might have looked without erosion. The preserved masses with orebodies at North Lyell and Iron Blow are indicated, and the approximate erosion levels at Upper Owen time and at present time are indicated.

further south in the system. The zone lies immediately above the irregular upper surface of the large chert body at Comstock, and abundant erosional detritus from this chert is present in the clastic breccias which characterise the zone. Some contemporaneous erosion of the upper part of the alteration system has thus occurred, perhaps removing some exhalative products, and this probably reflects some contemporaneous upwelling of the alteration zone rocks on the Great Lyell Fault. Some sericite-pyrite-silica alteration extends above the chert and into the basal Tyndall Group rocks in places.

Exhalative lead-zinc massive sulfide bodies so far identified are fairly small, the largest (Tasman Crown) being 90 m long, 5 m wide, and 50 m deep (top truncated). One of the bodies is closely associated with a lens of brecciated limestone, with banded sulfides in the interstices of the breccia, suggesting a close relationship between exhalative vents and at least some of the limestone lenses. The limestone lenses, many with fossils, persist in the stratigraphy above the zone of obvious alteration and mineralisation, suggesting they may have been related to waning hot spring activity over the site.

Silica Cap Zone and Associated Bornite-Rich Mineralisation

The very large bodies of cherty silica at Comstock and North Lyell appear to represent cap-like bodies formed at or near the top of the alteration zone, reaching thicknesses of 100-200 m and extending many hundreds of m along and across strike. Their size suggests that they would have formed a locally effective seal to fluid outflow for at least part of the later life of the system, and the extensive brecciation within the bodies may in part have been caused by over-pressured hydrothermal fluids.

The bodies for the most part appear to be replacements of original andesitic to felsic volcanics, with a few remnants of original porphyritic textures seen in places. Only preliminary trace element studies have yet been done (MacDonald, 1991; Hart, 1993; W.Herrmann, personal communication, 2001), and this remains a useful topic for further work. Possible sedimentary or sinter-type textures may be preserved at the top of the Comstock body, but most such 'pseudo-conglomerate' textures appear to be the result of brecciation and cataclasis.

Extensive hematite-jasper-barite alteration and veining of the chert at North Lyell and Comstock appears to be mainly related to a period of exposure, oxidation and erosion of the upper part of the system during Owen Group time in the Late Cambrian. This period probably saw the removal of most of the chert-rich top of the system and its erosion into the Owen sediments, evident as large volumes of chert detritus in Middle and Upper Owen units throughout the West Coast Range. Only the displaced mass preserved by burial within Owen sediments at North Lyell, and the distal edge of the system preserved at Comstock, remain to indicate the abundance of cherty silica which once capped the Mount Lyell system.

Mineralisation associated with the Comstock chert body includes base metal sulphides within chert breccias, mainly near the top of the body, and elevated gold levels towards the upper and lower margins. The poorly-known 'Eastern orebody' at North Lyell may also have been of this type. The extraordinary North Lyell orebody of high-grade bornite-chalcopryite ore (average grade 5.4% Cu) was located near the base of the chert, with irregular extensions into the chert and adjacent schist. Minor (but significant) bornite was associated with the Comstock chalcopryite-pyrite ore lenses, which were located a short distance below the main chert body, and with the Western Tharsis deposit, near the base of the silica heads zone, suggesting a

possible continuum. Minor bornite has also been recorded from all of the other orebodies, including Prince Lyell.

The origin and significance of the bornite mineralisation at North Lyell have been subject to some debate. Both Markham (1968) and Bryant (1975) concluded from mineragraphic studies that bornite and chalcopyrite had crystallised simultaneously from the one system. However, Walshe and Solomon (1981) and Solomon et al. (1987) argued that a more acid, oxidised and copper-rich fluid was required for the bornite than for the disseminated chalcopyrite ores, and suggested that this was probably a late-stage fluid circulating within the upper part of the system and leaching copper from the pre-existing chalcopyrite mineralisation. They noted that the sulfur isotopes from the North Lyell ores are generally lower (range -6 to +2, average -2.6 %) than those from the pyrite-chalcopyrite ores (range +3 to +10, average +7.0 %), lending support to the case for different fluids.

Huston and Kamprad (2000, in press), however, have argued that the bornite mineralisation at Western Tharsis formed as a later 'high- sulphidation' phase of the same hydrothermal event which produced the pyrite-chalcopyrite mineralisation. However, they relate this event not to the Cambrian volcanism but to a later, post-volcanic Ordovician event, based on the mis-interpretations of Hart (1993) and others regarding the silicification and hematite-barite alteration at North Lyell.

It is suggested that the concentration of bornite at North Lyell could be largely a matter of the original position of the North Lyell mineralisation within the overall hydrothermal system. The present study suggests that the North Lyell mass was originally located close to, but stratigraphically above, the Western Tharsis area (Figs 1, 30, 31), where the upward-moving ore fluids may have been partially trapped beneath a siliceous cap. The bornite-producing 'high- sulphidation' phase appears to have been relatively late in the system, after most of the silicification had occurred, and a late-stage magmatic event or resurgence, perhaps related to granite intrusion (and to the magnetite-apatite lenses seen at Prince Lyell), may have been an important influence, as suggested by Large et al. (1996).

The North Lyell mass appears to have collapsed into its present position during Owen time, taking its cargo of orebodies with it, and represents one of the very few segments of the rich upper-central part of the system (the Iron Blow body is probably another) which was preserved from the extensive erosion which took place on the upthrown side of the fault during Owen time (Fig. 31). The Comstock mine is in a stratigraphically similar situation, and contains a little bornite, but is located at the lateral edge of the system where fluid temperatures and concentrations may have been waning. The fact that the Comstock ore lenses declined in grade with depth (Wade, 1957) supports this interpretation. It seems likely that the main bornite-bearing deposits in that area have been removed by erosion.

Silica Heads Zone and Associated Mineralisation

The zone of silica heads appears to have extended some 500-600 m below the silica cap, with some scattered patches of siliceous alteration below this. The average size of the bodies decreases from 30 m or more in the upper levels to less than 10 m in the deeper parts. Numerous smaller lenses and bands of silica accompany the larger bodies, and there is a gradation from massive silica bodies through partly schistose bodies with bands of sericite and pyrite, to inter-banded chert-sericite-pyrite schist. Many of the bodies, particularly in the upper

levels, are rich in pyrite, and some also carry chalcopyrite. Some of the bodies at North Lyell show a fine-scale breccia texture, somewhat similar to that in the main North Lyell chert, and carry abundant pyrite, and in some cases chalcopyrite, in the interstices, suggesting that much of the mineralisation post-dates the silicification and brecciation.

The four main chalcopyrite ore lenses at Comstock, several of those at North Lyell, and at least part of the Western Tharsis deposit, occur within the silica heads zone. Minor but significant bornite was associated with some of these bodies. Remnants of ore in the Comstock open cut suggest that some of the ore was hosted within siliceous bodies, and at North Lyell, the Crown Lyell 3 orebody was mainly hosted in a large silica head. The Crown Lyell 1 and Lyell Tharsis low-grade bodies were hosted mainly within strongly chlorite-altered andesitic units near the contact of the core zone with zones of marginal schist.

Sub-Silica Heads Zone and Associated Mineralisation

The major part of the copper mineralisation preserved at Mt Lyell appears to lie below the original zone of silica heads, and is centred on the large Prince Lyell deposit, which extends deep into the system and is open-ended at depth. Analogy with the Western Tharsis-North Lyell situation suggests that a large amount of material has been eroded from the upper levels of the system above Prince Lyell during Owen Group time.

The original shape of the Prince Lyell and similar ore lenses, prior to Devonian deformation, is of some interest, but is difficult to determine. The present lenses are greatly elongated in the down-plunge direction (depth at least three times length), parallel to the main Devonian D2 schistosity and stretching lineation (Cox, 1981), and are elongated in plan view parallel to this NW-trending schistosity (length about five to ten times width). A rough concordance between ore lenses and the steeply dipping to overturned lithological contacts is evident in the Prince Lyell- Western Tharsis area (Figs 1, 4), suggesting that the lenses were deposited more or less parallel to stratigraphy, and may have been influenced by lithological variations. However, it is also notable that the ore lenses are elongated roughly parallel to the Great Lyell Fault surface, and that the alteration zone is also broadly parallel to this structure in depth (eg Figs 4, 5, 6). It is likely that the alteration zone has always been sub-parallel to the Great Lyell Fault and therefore steeply dipping. Whatever their original shape, the ore lenses have probably been subject to considerable sub-vertical shearing and stretching throughout their history, firstly as a consequence of the upwelling of the altered rocks, possibly related to expansive alteration processes, in the Middle and Late Cambrian, and later as a result of compressive deformation of the area during Devonian folding.

THE GEOLOGICAL HISTORY OF THE MT LYELL AREA - SYNTHESIS AND DISCUSSION

The geological history of the Mt Lyell area as deduced from the present study may be considered in terms of 5 major phases: (i) the major hydrothermal period, when the main mineral deposits and alteration zone were formed; (ii) the cessation of hydrothermal activity and cover by Tyndall Group rocks in the late Middle Cambrian; (iii) uplift and unroofing of the alteration zone during deposition of the Lower Owen Conglomerate, probably in the early Late Cambrian; (iv) exposure, oxidation, erosion and mass collapse of the alteration zone rocks into the Owen basin during Middle and Upper Owen time in the Late Cambrian; and (v)

cover of the collapsed masses and Owen Group by Pioneer Sandstone and Gordon Group in the Ordovician.

1. The Main Hydrothermal Period

A large, deep-penetrating hydrothermal system, probably influenced by a Cambrian granite body at depth, appears to have operated during eruption and deposition of much of the upper part of the Central Volcanic Complex in the Queenstown area. The system was at least 6 km long and was focused on the Great Lyell Fault, a fundamental structure possibly related to the western edge of the Tyennan Precambrian block. A basalt-rich substrate to the Mt Read Volcanics (poorly exposed in a small 'window' at Miners Ridge) probably contributed copper and gold to the fluids. The alteration system appears to have been the largest of a number of such systems, including that at Henty mine, along the 40 km strike length of this fault. The system had a seafloor exhalative zone during at least part of CVC time, as evident from the large Iron Blow massive pyrite-chalcopyrite deposit, and it is possible that multiple exhalative zones were buried as volcanism and exhalative activity interacted. The youngest exhalative deposits are in the lower part of the Tyndall Group at the northern margin of the system at Lyell Comstock, and consist of small lead-zinc-rich massive bodies.

Large amounts of cherty silica were deposited in the upper levels of the system, extending from near the exhalative interface to some 500-600 m depth. This patchy silicification is now evident as numerous 'silica heads' ranging from less than a metre to 50 m or so across, culminating in very large silica masses at the top. These large upper bodies must have formed a relatively impermeable 'cap' to the system at some stages, and were brecciated and mineralised with base metals and gold to varying degrees.

Pyrite was deposited as an abundant and ubiquitous mineral throughout the system, forming up to 50% of the schists in places. Chalcopyrite was concentrated in zones which usually coincided with pyrite-rich zones, and which may have been partly related to fluid flow and partly to more permeable horizons in the volcanics. Bornite was concentrated in the upper levels of the system, more or less coinciding with the silica-rich zones. Maximum bornite deposition appears to have been under the chert cap in the North Lyell area, where zones and patches of massive bornite were found. Only minor bornite was present at this level at the margin of the system at Comstock.

The North Lyell area was originally above the general Western Tharsis area, suggesting that the minor bornite now seen at Western Tharsis represents the 'roots' of the main bornite mineralisation in the higher levels. Pyrophyllite and other minerals indicative of 'high-sulphidation' conditions are associated with the bornite at Western Tharsis (Huston and Kamprad, 2000, in press) and North Lyell (Bryant, 1975), suggesting that the bornite zones represent parts of the system in which fluids were more acid, oxidised and sulphur-rich, and probably had a stronger magmatic component (Sillitoe et al, 1996). It seems most likely that the 'high-sulphidation' bornite-bearing phase represents a continuation of the overall mineralising episode, perhaps related to a resurgence of intrusive activity, rather than a separate event, but this remains to be established.

Some significant longitudinal variation is apparent in the Mt Lyell system, although a great deal has been lost through erosion. There are distinct similarities between Comstock, at the northern margin, and North Lyell, in the central part, in terms of silica heads and chert cap, but notable differences in terms of mineralisation, particularly the amount of bornite present. The

Iron Blow sulphide body gives us a tantalising glimpse of the upper exhalative part of the system a bit further south, but we are left wondering what might have been present above it- were there any lead-zinc massive bodies in lower Tyndall equivalents?- and below it- were there any bornite-rich North Lyell-type deposits? Further south again, we appear to have only the 'roots' of the system preserved in the Glen Lyell- Copper Estates area, with a few boulders of chert breccia in Moores Creek to suggest that an upper high-sulphidation zone might have been present.

The alteration of the approximately 6 cubic km mass of volcanic rocks appears to have resulted in a significant volume increase, since there is clear evidence of upwelling and beheading of the schist mass over time. A possible explanation is provided by the hydration and consequent volume increase associated with the ubiquitous sericitisation and chloritisation. Most of this expansion probably took place upwards, resulting in upwelling of the altered rocks on to the seafloor during the later stages of the hydrothermal activity, with consequent erosion of some of the chert cap into the lower Tyndall Group sequence, and further upwelling after the system was buried by middle and upper Tyndall rocks.

2. Cessation of Hydrothermal Activity and Cover by Tyndall Group

Gradual waning of hydrothermal activity is indicated in the lower Tyndall sequence at Comstock, where the intense sericite-chlorite alteration dies out at the level of the massive sulphide bodies, but the limestone lenses and zones of carbonate alteration persist for another 100 to 150 m in the section. The limestones, with their fossil biota, probably represent areas where warm springs exhaled on the seafloor. The question of water depth at this time remains unresolved- although there was considerable mass-flow deposition of coarse clastics, suggesting sufficient water depth to generate gravity flows, there is also the possibility of a nearby shoal area induced by the upwelling of the main part of the alteration zone just to the south, which probably formed the source of much of the chert and other detritus.

The middle and upper Tyndall Group cover is of the order of 350 to 400 m thick in the Comstock mine area, but thickens notably to the order of 700 m or more at Zig Zag Hill, 2 km to the north-west (White and McPhie, 1996). The Comstock section is notably thinner than any of the other measured sections illustrated by White and McPhie (op. cit.), a fact which supports the deduction herein that the Tyndall Group cover rocks may have thinned over the upwelling core of the alteration zone at the Mt Lyell mines area. There appears to be no way of establishing what thickness of Tyndall Group cover may have existed, because of the subsequent erosion. A largish remnant of probable lower Tyndall material, partially converted to sericite schist, is wrapped around the north-eastern end of Tharsis Ridge, and a smaller remnant of similar quartz-phyric material is present at the Owen contact near Whaleback Spur, but no middle or upper Tyndall rocks are seen in the main mine area.

3. Uplift and Unroofing of Alteration Zone During Lower Owen Deposition

The erosion of much of the Mt Read volcanic edifice to produce the conglomerates of the upper Tyndall Group was followed by a major influx of coarse siliceous gravel, derived from the Precambrian quartzites to the east, marking the beginning of Lower Owen deposition. Most of the Lower Owen sediment, which was up to boulder grade, was carried by large braided river systems, presumably on large alluvial fans. Deposition was accompanied by rapid and continuing east-side-down subsidence on the Great Lyell Fault, such that at least 1200 m

of conglomerate accumulated against the fault, thinning markedly to the east to virtually zero some 4 to 5 km away.

As the Lower Owen accumulated, the cover of Tyndall Group rocks was stripped off the alteration zone on the western side of the Great Lyell Fault. Some of this eroded material is evident as volcanic quartz and quartz porphyry detritus in the Lower Owen along the fault, although very little of the Lower Owen section is available for examination.

4. Exposure, Oxidation, Erosion and Mass Collapse of the Alteration Zone Rocks

The dramatic change at the contact between the coarse fluvial Lower Owen Conglomerate and the red, labile-rich shallow marine Middle Owen Sandstone in the mine area coincides with the first appearance of detrital chert, hematite and altered volcanic material in the Owen sediments. This material is clearly derived from the alteration zone, and indicates that the alteration zone, with its abundant sulphides and chert bodies, had just been unroofed and exposed to erosion, and was feeding detritus into the sediments from the west. But it appears that normal erosion processes could not keep pace with the rapid rise of the great volume of altered rocks, and large masses or lobes began to 'extrude' or 'collapse' off the scarp into the edge of the Owen basin and to interact with the Owen sediments.

This unusual behaviour is attributed, in part at least, to residual expansionary pressure within the schists from the alteration-hydration process. This alteration process was also heat-generating, and may well have been ongoing within the central part of the zone during the unroofing stage. Thus the situation may have been one of rapid rise and exposure of still-hot, sulphide-rich rocks made up largely of a mobile sericite-rich 'matrix' carrying numerous bodies of brittle chert and some masses of pyrite and other sulphides beneath a large blocky cap of chert. It is perhaps not unexpected that much of this material extruded sideways from the fault scarp, and that there was intense oxidation of it.

The details of the collapse process are difficult to envisage and difficult to reconstruct. The preserved contacts against Lower Owen sediments indicate semi-plastic schist masses moving over partly consolidated gravel layers, forming intricate 'soft-sediment' type contacts in places and dragging off slabs of conglomerate and loose pebbles. The presence of some lower Tyndall-like rocks 'plastered' against the Lower Owen contact at the northern end of Tharsis Ridge suggests that younger units became 'grounded' against the Owen in places and were over-ridden by older ones as the mass moved forwards. Original contacts appear to have become blurred and obscured by intermixing and shearing. Extensive slippage on shear surfaces and faults also appears to have happened. The complexity was compounded as the mass continued to move forwards over lenses of the rubbly hematite-rich breccia deposits which had formed along the contacts and been interbedded with the normal Owen sediments.

The large chert mass at the top of the zone at North Lyell has obviously been a major controlling influence on the final form of the corridor mass. Although somewhat broken and attenuated, the chert has a folded form in both plan and section which suggests that it has rolled over on itself in caterpillar fashion while retaining considerable cohesion. This mass also acted to protect the underlying schists from erosion, and its presence is probably the main reason that the rich North Lyell orebodies were preserved rather than eroded. Elsewhere along the Tharsis Trough zone to the south, with the exception of the Iron Blow segment, the chert

bodies were either not present or were removed, as was the ore-rich upper part of the alteration zone, leaving mainly marginal schists.

The collapse or extrusion of schists into the Owen basin appears to have taken place along virtually the full 6 km strike length of the alteration zone, from Copper Estates in the south to Comstock in the north. In the northern and southern areas, the phenomenon was apparently not associated with formation of a distinct ridge or 'shoulder' of Owen group rocks as was the case in the central part between Tharsis Ridge and Razorback Ridge. Instead, the schists appear to have 'bulged' forwards across the Middle Owen beds, with associated flattening of the contact surface (generally referred to as a 'flattening of the Great Lyell Fault'), as is seen at the Iron Blow (Fig. 22). The reason for formation of a 'shoulder' structure of Owen Group rocks is uncertain, but may be related to the size of schist mass emplaced. A somewhat similar feature is observed in some diapirs, where the 'head' of the diapir expands and the 'neck' area (where pressure is presumably lower) contracts and there is in-faulting of the host rocks to fill the gap (eg Dalgarno and Johnson, 1968; Drew et al, 1994). It is unlikely that the initial 'extrusion' was synchronous in all areas, but this would be difficult to establish.

The total amount of forward movement achieved by the schist masses was not great, the corridor mass at North Lyell terminating some 400 to 500 m from the Great Lyell Fault scarp (Fig. 1), and that at the Iron Blow seemingly only travelling 150 m or less (Fig. 22). The amount of further movement involved in producing the Haulage fold zone in the Upper Owen beds was probably only a matter of a few tens of metres. In some places, dykes of Middle Owen Sandstone which had been injected into the schist mass adjacent to the Great Lyell Fault contact (possibly by infilling of temporary tensional cracks) were carried within the extruded masses across the Owen beds.

The intense oxidation effects related to the uplift and exposure of the altered and mineralised rocks in the Late Cambrian are well preserved and exposed in places, and are deserving of further study to clarify the processes and conditions involved. At Comstock, the Comstock chert body was cut by numerous hematite-jasper-barite veins, accompanied by brecciation and hematite-jasper alteration, and many of the limestone lenses were hematite-altered. The veining is presumably a deeper-level expression of the surface hematite formation seen in the North Lyell- Iron Blow area, and drill holes at Comstock might reveal the depth to which the hematite alteration penetrated. Study of the veins might indicate the temperatures involved and the sources of the fluids. The abundance of barite associated with the hematite in the North Lyell- Iron Blow area, both within the in-situ bodies and within clastic detritus derived from them, is quite remarkable. This raises the question as to how much of it is residual (ie derived simply from weathering of the associated bedrock and sulphide bodies) and how much might be related to fluid movements associated with the oxidation episode.

The occurrence of hematite (with some barite, eg OG 10) at the top of the Lower Owen at the eastern end of Mt Lyell, and of hematite channel fills at a stratigraphic level possibly corresponding to the top of the Lower Owen across the Tyndall Range, suggests there may have been a regional oxidation and erosional event linked to the exposure of the alteration zone at Mt Lyell.

5. Cover by Pioneer Sandstone and Gordon Group

A period of erosion or non-deposition appears to have followed the formation of the Haulage fold zone, during which the folded beds were eroded and there was considerable reworking of Owen beds generally. Much of the erosional detritus accumulated on the eastern flank of the folded mass in the form of the basal pebbly conglomerates of the Pioneer Sandstone sequence. Much of this pebbly sediment probably came from upwarped Middle Owen Conglomerate beds, and the presence of blocks of Middle Owen Sandstone in the base of the Pioneer indicates that that unit was also eroded.

The Pioneer Sandstone progressively overlapped the folded Upper Owen beds and the flanks of the schist masses, but whether it overtopped the highest parts of the schist zone is uncertain. The present distribution of the Pioneer beds is well out on the flanks of the anticlinal zone of schists west of the Great Lyell Fault (eg at Comstock and Queenstown township).

There was almost certainly some further movement of the schist masses after deposition of the Pioneer Sandstone, to account for the situation at Comstock, where mineralised schist and Tyndall Group rocks apparently overlie the Pioneer and Upper Owen, and at Gormanston, where a similar situation exists. Post-Pioneer erosion of the still-exposed schists could account for at least some of the copper clay mineralisation, and perhaps even some of the lead-zinc mineralisation, in the associated Gordon Group calcareous beds.

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APPENDIX 1. SUMMARY OF THIN SECTION DATA

Owen Group series : OG 1-OG 103

- OG 1** - Lower Owen Conglomerate, eastern end of Mt Lyell - grey sandstone bed near base of formation. Abundant volcanic detritus, partic. quartz & qtz porphyry grains. Some metaquartzite grains. Foliated micaceous matrix.
- OG 2** - Lower Owen - sandstone bed 52 m above base. Mostly metaquartzite grains, some tourmaline, strong cleavage cross-cuts bedding, outlined in micaceous matrix material.
- OG 3** - Lower Owen - pink sandstone bed at 67 m. Mostly metaquartzite grains, some tourmaline.
- OG 4** - Lower Owen - pink sandstone with white pebbles, lower part of Siltstone-Sandstone Unit. Abundant mica flakes to 1 mm. Jumbled appearance of grains. Mostly PE derivation.
- OG 5** - Lower Owen - graded sandstone bed within grey siltstone of Siltstone-Sandstone Unit. Mica-rich (~10%), mostly PE derivation, jumbled appearance, some tourmaline.
- OG 6** - Lower Owen - graded sandstone bed in Siltstone Unit as above. Mica-rich (~15%), dominantly PE derivation, some tourmaline. Has flame structure of micaceous silt.
- OG 7** - Lower Owen - grey siltstone from Siltstone Unit. Quartz-mica-rich.
- OG 8** - Lower Owen - sandstone bed within planar-bedded facies. 'Invasive' matrix of fine mica-sericite wraps around most clasts and through cracks. Mostly PE, some tourmaline.
- OG 9** - Lower Owen - sandstone within upper channel facies. 5-10% micaceous matrix has been forced through rock and into cracks. Mostly PE derivation.
- OG 10** - Hematitic unit at base of Middle Owen Sandstone, eastern end Mt Lyell - mostly opaque hematite with blebs of clear barite, sericite-barite, and some quartz.
- OG 11** - Hematitic sandstone, base of Middle Owen Ss, eastern end Mt Lyell - extraordinary texture & composition- seems to be entirely volcanic grains floating in cement of hematite and secondary quartz (much of it with graphic-type texture). Virtually no quartzite grains, although some tourmaline. Striking rock similar to Middle Owen Ss at mine area, and to sandstone dykes at mine.
- OG 12** - Pink ss near base of Middle Owen Ss - bioturbated- rich heavy mineral band with abundant zircon & tourmaline grains. Mostly quartz grains of uncertain origin.
- OG 13** - Conglomeratic sandstone in lower part of Middle Owen Ss - mostly PE derivation, coating of opaque hematite on most clasts. Large intraclast of hematitic mudstone. Lot of secondary quartz cement.
- OG 14** - Pebbly sandstone within MOSs - has abundant clasts (~50%) of fine chert up to 3 mm, some with fine sericite looking like schist from volcanics area, and some with remnant quartz phenocrysts - also some volcanic-type quartz grains. Also has PE grains. Lot of hematitic cement.
- OG 15** - Cross-bedded sandstone within MOSs, with leiseegang banding- abundant chert clasts (70-80% of large clasts)- also volcanic quartz grains.
- OG 16** - Grey sandstone in central part of MOSs, eastern end Mt Lyell- very clean, well-sorted ss, not much obvious matrix- many sutured boundaries. Some volcanic quartz but mostly PE derivation.
- OG 17** - Pink sandstone within MOSs - most grains in contact but much pore space filled with dusty material. Some chert clasts but mostly PE grains. A few bands rich in opaque grains.
- OG 18** - Pink sandstone in upper part of MOSs, eastern end Mt Lyell - very fresh, clean, well sorted, many sutured boundaries and quartz overgrowths. Hardly any mica. A few chert grains, but mostly PE derivation.
- OG 19** - Pebble conglomerate near top of MOSs, eastern end Mt Lyell - pebbles are of various quartzite types, incl. one with internal tourmaline crystals and veinlets. Quartz overgrowths and some dusty sericitic matrix between grains, but very little mica. Sparse volcanic grains only.
- OG 20** - Pink sandstone bed within Middle Owen Conglomerate, central bluff of Mt Lyell- fair amount of volcanic detritus, incl chert and chert-sericite clasts- also PE detritus. Most grains have coating of opaque dust. Interstices mostly filled with secondary quartz. Several detrital apatites?
- OG 21** - Coarse sandstone within conglomerate bed in Middle Owen Congl at 87 m on central bluff- about 60% volcanic detritus, incl quartz grains, chert, chert-altered feldspar porphyry, quartz porphyry, spherulitic lava (CVC type). Also some PE grains. Hematite and quartz in interstices.
- OG 22** - Conglomerate from MOCongl at 86 m - large pebbles are mixed PE and volcanic types, but smaller ones are mainly volcanic, with variety of types, incl quartz phenocrysts and quartz porphyry, chert, chert-sericite alteration, chert breccia, spherulitic lava, isolated spherulites, snowflake lava.

- OG 23** - Siltstone near top of MOCongl, central bluff - dark, hematitic, abundant shreds of mica. Strong flattening foliation parallel to bedding is crossed by slaty-type cleavage. Sandstone band is made up largely of angular chert and volcanic quartz grains, with some of quartzite.
- OG 24** - Conglomerate bed near top of MOCongl - clasts are roughly 50% volcanic, 50% PE.
- OG 25** - Siltstone in Upper Owen Sandstone, central bluff of Mt Lyell - alternating fine ss and micaceous siltst laminae 2 mm thick -some bioturbation- grains fairly angular, lot of chert, some Qtzite, lots of shreds and flakes of white mica.
- OG 26** - Rippled sandstone, lower part of Upper Owen Ss, central bluff - quartz grains floating in 'sea' of overgrowth quartz- original grain boundaries marked by films of hematitic dust. Much volcanic quartz and chert, but also some quartzite grains.
- Og 27** - Grey sandstone 'marker' bed in Upper Owen - abundant overgrowth quartz between grains. Some chert and volcanic quartz grains, also some Qtzite.
- OG 28** - Pink sandstone with mud pellets near top of Upper Owen, central bluff - much overgrowth quartz between grains- Qtzite, chert, volcanic detritus mixed. Much bioturbation.
- OG 29** - Dark sandstone from top of strongly bioturbated bed, Upper Owen - irregular mixing of coarse and fine material due to bioturbation- plenty of overgrowth quartz, with much hematitic material also. Lots of volcanic grains, partic embayed quartz phenos.
- OG 30** - Pink sandstone with current lineation, Upper Owen - very well sorted, fine-grained. Dark hematitic cement between grains, except in sandier laminae where quartz overgrowths dominate. Small muscovite flakes common. Mixed Qtzite-chert-volcanic grains, notable angularity.
- OG 31** - Conglomerate with mudstone intraclasts, Upper Owen - rounded pebbles of Qtzite, chert, smaller clasts of chert, mudstone, dark hematitic material. Lots of quartz overgrowths. Band rich in heavy minerals- opaque grains, zircon, tourmaline.
- OG 32** - Typical granule-pebble conglomerate of Upper Owen - pebbles mostly alteration-type chert, some Qtzite, a few of hematite. Sandy matrix shows lot of overgrowth quartz.
- OG 33** - Coarse sandstone near base of congl bed, Upper Owen - rich in chert and volcanic clasts, some Qtzite. Secondary hematite overprints quartz overgrowths.
- OG 34** - Pink sandstone with muddy laminae, Upper Owen - well sorted clean sandstone, mixed detritus. Some zircon and tourmaline grains.
- OG 35** - Dark pink sandstone at top of Upper Owen section, western bluff of Mt Lyell - fairly clean, well sorted, with moderate amount of overgrowth quartz. Coatings of dusty to solid hematite on most grains. Also blebs of hematite. Mostly volcanic grains.
- OG 36** - Conglomerate from Middle Owen Conglomerate, western bluff of Mt Lyell - volcanic-rich (60-70%), with abundant clasts of volcanic quartz, also alteration-type chert, volcanic rocks, also Qtzite, vein Qtz.
- OG 37** - Sandstone bed in Middle Owen Congl, western bluff - mixed Qtzite and volcanic clasts about 50:50.
- OG 38** - Pink sandstone in Lower Owen, above Cape Horn - about 40% volcanic detritus (mainly volcanic quartz grains, very minor chert), 60% PE Qtzite. Some fine micaceous matrix and much overgrowth quartz. Lacks the hematitic coating around grains.
- OG 39** - Hematite-rich sandstone at base of Middle Owen Sandstone above Cape Horn- fractured, veined and partly replaced by hematite. Some large blebs of replacement hematite have inclusions of barite and sericite. There is much volcanic quartz, some Qtzite, only very rare chert grains.
- OG 40** - Conglomerate at hematite zone at base of Middle Owen Sandstone, above Cape Horn - most large clasts are of Qtzite, but smaller grains mostly volcanic quartz and altered volcanics, incl some chert. Abundant volcanic quartz and volcanic rock frags. Hematite has replaced much of cement.
- OG 41** - Sandstone within siltstone unit in Lower Owen, west side of Tharsis Ridge - micaceous fine ss, fairly well sorted - 20-30% mica, some of it coloured and pleochroic. Some tourmaline & zircon grains.
- OG 42** - 'Sandstone'- like rock within volcanics, west side of Tharsis Ridge - actually a spherulitic lava with siliified spherulites- also much chlorite.
- OG 43** - Pink barite at contact of Lower Owen Congl and Middle Owen Ss, northern part of Tharsis Ridge - all coarse barite except for thin vein of sericite-chlorite.
- OG 44** - Chert clast from chert-hematite-barite breccia near contact of Middle Owen Ss and schists, NE corner of Tharsis Ridge - shows uncleaved cryptocrystalline chert texture mostly, cut by quartz veins- also has numerous irregular blebs of barite through it, also one remnant quartz phenocryst. Part of breccia matrix attached is strongly foliated granular-textured, with quartz grains in shredded chlorite-sericite with fibrous quartz and hematite.
- OG 45** - Large chert clast from same breccia as above - cryptocrystalline chert texture, numerous blebs of barite, much disseminated fine hematite.

- OG 46** - Similar chert clast to above - cut by numerous coarser veins of recrystallised quartz, some with blebs of barite. One remnant quartz phenocryst in chert.
- OG 47** - Lower part of chert-hematite breccia at Middle Owen Ss- schist contact, NE Tharsis Ridge - excellent breccia texture of chert-sericite-altered volcanic frags & rounded clasts in dark hematite-rich murky matrix rich in small sericite blebs. Remnant volcanic textures in some clasts. Looks very proximal.
- OG 48** - Chert body or small silica head in schist at contact with MOSs, NE Tharsis Ridge - variably crystalline chert with patches of sericite, cut by irregular hematite-chlorite veins.
- OG 49** - Part of matrix to chert-hematite breccia with pink sandstone bands within Middle Owen Ss, NE Tharsis Ridge - good sandstone texture mostly, with hematitic matrix- lot of volcanic quartz, some chert and cherty-altered volcanic clasts. Hematite-sericite veining.
- OG 50** - Sandstone layer in above breccia, NE Tharsis Ridge - close-packed sandstone texture of quartz grains in hematitic matrix. Some chert clasts.
- OG 51** - Chert body or silica head on SW rim of Crown 3 open cut - fairly uniform chert texture except for dark blebs which appear to be hematite after original feldspars.
- OG 52** - Conglomerate unit in Upper Owen, 20 m above base, above Cape Horn - poorly sorted mixture of chert clasts (to pebble size), volcanic quartz grains, and quartzite grains in hematitic cement (replacing quartz overgrowths?). Lot of zircon grains in places. Also some rounded hematite grains.
- OG 53** - Pebble conglomerate in Middle Owen Sandstone, above Cape Horn - about equal proportions of quartzite and volcanic-derived grains. Many large embayed quartz grains.
- OG 54** - Sandstone bed in Middle Owen Conglomerate, above Cape Horn - has clast composition of about 10% quartzite, 45% volcanic quartz, 40% chert/volcanic. All in fine dusty sericite-rich matrix (~15%) showing strong cleavage.
- OG 55** - Jasper clast in pebble conglomerate in Middle Owen Conglomerate, above Cape Horn - consists of quartz and hematite, shows excellent colloform textures, some unusual textures include quartz rods rimmed by hematite.
- OG 56** - Conglomerate bed rich in jasper and hematite clasts, Middle Owen Congl, above Cape Horn - abundant clasts of volcanic quartz, some of quartzite, as well as jasper and hematite. Hematite clasts mostly have inclusions of barite- up to 50% barite. There are large blebs and bladed crystals of barite throughout this rock, some in clasts and some in matrix- must be clastic.
- OG 57** - not collected
- OG 58** - Chert clast conglomerate-breccia in Middle Owen Sandstone near schist contact, NE Tharsis Ridge - clasts of chert and chert-hematite material have poorly defined boundaries, are separated by areas of quartz grains, in very abundant (~50%) hematitic matrix.
- OG 59** - Sandstone interbedded with chert-hematite breccia, Middle Owen Sandstone, NE Tharsis Ridge - well-sorted ss, mostly qtz grains with sutured overgrowths of dusty qtz.
- OG 60** - Interbedded sandstone and chert-hematite breccia, Middle Owen Sandstone, NE Tharsis Ridge- good granular sandstone separates irregular chunks of chert and chert-hematite rock, also clasts of hematite. Abundant hematite in matrix between sand grains.
- OG 61** - Clast of hematite in above breccia - consists of hematite with abundant small to large blebs of barite through it, also small amount of colourless micaceous mineral (sericite?) in some of the blebs.
- OG 62** - Matrix of 'jasper bed' in Middle Owen Conglomerate, above Cape Horn - mostly a large complex chert-hematite clast, with only a small remnant of matrix.
- OG 63** - Chert clast from 'jasper bed', MOCongl, above Cape Horn - large chert clast with many blebs of barite.
- OG 64** - Jasper clast from 'jasper bed', MOCongl, above Cape Horn - consists of intergrown quartz, barite and hematite.
- OG 65** - Hematite clast with matrix, 'jasper bed' as above - clasts of quartz-hematite-barite (with large bladed barites in some cases), also clasts of quartz, volcanic quartz, chert, lots of clasts of barite (to coarse sand-granule grade), a few clasts of qtzite, some rounded zircon grains. Foliated yellowish sericitic material between grains.
- OG 66** - Clast of volcanoclastic sandstone from 'jasper bed', as above - mostly cherty matrix material with scattered quartz phenocrysts, sericitic blebs (after feldspar?), patches of hematite.
- OG 67** - Hematite clasts and matrix, 'jasper bed', as above - good sandy matrix, with larger clasts of chert, cherty-altered volcanic with porphyry texture, quartzite, chert-hematite, quartz, snowflake-textured lava, hematite-barite-chert, hematite, and some large clasts of barite. Sand grains are mainly volcanic qtz, some chert, barite etc.
- OG 68** - not sectioned
- OG 69** - Jasper clast from 'jasper bed', as above - intergrown quartz, hematite and much barite.
- OG 70** - Chert-rich conglomerate bed in Upper Owen, above Cape Horn - close-packed sandstone matrix, lots of chert clasts, also qtzite clasts, quartz, spherulitic lava, some rounded zircon grains.

- OG 71** - Cross-bedded sandstone in Upper Owen, above Cape Horn - about equal mixture of chert and qtzite clasts, plus many volcanic qtz grains. Most grains have hematite coating, which extends into pore spaces where filling is clear quartz overgrowths.
- OG 72** - Conglomeratic sandstone bed with mudstone intraclasts and chert clasts, Upper Owen, above Cape Horn - large intraclasts to 1cm + of dark micaceous-hematitic mudstone, some of which are cherty textured.
- OG 73** - Hematite unit with chert clasts, schist-Owen contact, NW of Batchelors Quarry - appears to be a hematite-altered chert breccia, with some remnant quartz phenocrysts visible.
- OG 74** - Hematite unit with sandy layers, NW of batchelors Quarry - most of rock is Owen-type sandstone impregnated with hematite. Some chert-breccia material on one side. Some blebs and veinlets of barite.
- OG 75** - Sandstone layer in hematite-siltstone unit at schist contact, Lyell Tharsis area - dominated by secondary hematite-barite textures, incl zones of colloform growth and zones of fine brecciation. Some primary quartz phenocrysts, patches of chert texture.
- OG 76** - Barite zone in hematite unit, Lyell Tharsis area - mostly secondary textures in hematite and barite, with patches of fibrous green/brown pleochroic mineral like pumpellyite.
- OG 77** - Hematite unit with fibrous/colloform veins of hematite, Lyell Tharsis - hematite veins have selvages rich in green fibrous mineral, which also occurs in blebs and patches. Sericite and barite also present.
- OG 78** - Chert-hematite breccia-congl in Upper Owen, Pioneer Spur - large clasts of hematite and chert-hematite, some with blebs of the green pumpellyite-like mineral. Much hematite in matrix.
- OG 79** - Sandstone unit within Pioneer Sandstone, east end Pioneer Spur - unusual bimodal texture of large clasts of qtzite and altered volcanics, and fine sand (with mica flakes), with dark matrix which streams between the larger grains - bioturbated?
- OG 80** - Pink sandstone clast with attached matrix in basal Pioneer Sandstone (looks like MOSs) - clast has extraordinary texture dominated by clear overgrowths around grains with dark rims - very like MOSs and ss dykes of same stuff. Surrounding ss is coarse grained jumble of qtzite and volcanic grains with hematite coatings extending into qtz-filled interstices.
- OG 81a** - Sandstone lens at base of upper channel facies, Lower Owen, east end Mt Lyell - all clasts are qtzite. Matrix (~10%) is mostly sericite-muscovite.
- OG 82** - Pink sandstone in upper channel facies, Lower Owen, east end Mt Lyell - mostly subangular qtzite grains with ~15% matrix or pore space consisting of sericite, qtz overgrowths and dark hematitic dust.
- OG 83** - Dyke of pink sandstone in schist, west side of Razorback Spur - distinctive texture of well-sorted fine sand with quartz grains marked by hematite-dusted margins separated from one another ('floating') by abundant overgrowth quartz. Looks like Middle Owen Sandstone.
- OG 84** - Irregular dyke of pink sandstone within schist outlier on west side of Razorback Ridge - has same distinctive texture as OG 83, with qtz grains floating in sea of overgrowth qtz.
- OG 85** - Pink sandstone dyke with pyrite within schist outlier, west side of Razorback Ridge - contact of sandstone against schist is fairly sharp but some sand grains have separated into schist. Ss has same distinctive texture as above. Strong cleavage has caused elongation of grains. Blebs of pyrite through the ss. Schist has ovoid blebs of mosaic qtz, mixed with sericite, minor chlorite, pyrite.
- OG 86** - Iron Blow hematite, dump sample - intergrown hematite and barite, with some patches of massive hematite. Much hematite is well crystallised, with elongate crystals intergrown with barite.
- OG 87** - Iron Blow hematite, dump sample - mostly massive hematite with patches of barite, some intergrown hematite-barite. Some fibrous/micaceous mineral stained brown but looks like sericite-muscovite.
- OG 88** - Pyritic schist from fault block on SW side of King Lyell valley - mostly fine cherty silica with disseminated pyrite. Some relict feldspar texture, possible amygdales?
- OG 89** - Pyritic ore from Iron Blow mine, dump sample - pyrite with blebs of barite.
- OG 90** - Galena-rich ore from Iron Blow mine, dump sample - also has barite.
- OG 91** - Sandstone dyke in schist, SE of South Lyell shaft - clean qtz sandstone with abundant overgrowth qtz, some fine sericitic matrix material also. Similar to other dykes- like MOSs.
- OG 92** - Sandstone within Middle Owen Ss, foot of Mt Owen Road - lot of qtzite clasts, some large clear volcanic qtz's, rounded tourmalines, sericite in matrix.
- OG 93** - Hematite body at schist-Owen contact, embayment south of Lyell Highway - barite mixed with hematite as blebs and intergrown, also sericite blebs.
- OG 94** - Hematite body at schist-Owen contact, as above - small white blebs are all sericite in this case, no barite?
- OG 95** - Chert-pyrite 'boudin', at small adit, schist embayment south of Lyell Highway - all cherty silica, some very fine sericite, one small bleb of barite.

- OG 96** - Schistose Owen congl at schist contact, embayment south of Lyell Highway - very schistose congl, with Qtzite clasts and grains separated by zones of sericite and cherty silica, some pyrite. Some lenses of chert-like material of uncertain origin.
- OG 97** - Sandstone lens within Lower Owen (?) at western end of Owen Spur - quartzite-dominated pebbly ss, lots of sericitic matrix btwn clasts. Also scattered large muscovite flakes. Typical Lower Owen?
- OG 98** - Conglomerate at Lower Owen-Middle Owen transition (?), west end of Owen Spur - large Qtzite clasts, some good chert clasts also, some with remnant feldspar-porphyry texture. Hematite replaces sericitic matrix in places.
- OG 99** - Pink sandstone at Lower Owen- Middle Owen transition, west end Owen Spur - well sorted, even grained, all grains with thin hematite coating, lot of overgrowth Qtz but moderate amount of sericitic matrix also. Scattered chert grains. Fairly like MOSs.
- OG 100** - Green siltstone in lower part of Middle Owen Ss, foot of Mt Owen road - has extraordinary concentration of tourmaline grains floating in ashy fine siltstone. Also some opaque grains.
- OG 101** - Hematite layer on base of sandstone bed in Middle Owen Ss, west end of Owen Spur - hematite completely replaces matrix and parts of many grains of this coarse ss- fine congl consisting mostly of Qtzite clasts.

Comstock series : CO 20-27, 35-36

- CO 20** - Comstock Chert with pseudo-conglomerate texture, block in glacials - congl texture marked by patches of slightly different chert texture with rim of hematite staining and, in some cases, flecks of chlorite. Suggests derivation from andesite breccia?
- CO 21** - Comstock Chert with hematite breccia texture, block in glacials - marked contrast btwn clean, fine gr'd chert 'clasts' and coarse mucky hematitic-partly chloritic matrix zones. Complex history?
- CO 22** - 'Quartz-rich sandstone' (altered andesite?) near dam, above Comstock - abundant Qtz-filled large amygdales, large chlorite blebs (some after phenocrysts). Very altered andesitic lava.
- CO 23, CO 24** - Pseudo-clasts of Qtzite-like rock from above 'sandstone', near dam - uniform intergrown Qtz grains with overgrowths, some interstitial sericite. Looks like the pink sandstone dykes from Razorback Ridge area, but origin uncertain.
- CO 25** - Quartz-bearing rock near 'sandstone' above - remnant porphyritic texture in feldspar and ferromags, with large Qtz-filled amygdales. Similar to CO 22 - very altered andesite.
- CO 26** - 'Sandstone' as for CO 22 - interlocking Qtz grains, with patches of hematite. Qtz is rose-coloured.
- CO 27** - Quartz-rich rock east of dam above Comstock - Qtz-filled amygdales and smaller Qtz blebs in sea of chlorite. Very altered andesite.
- CO 35** - Quartz-feldspar porphyry within Lower Tyndall Group, lower level of Mullock Quarry - good Qtz-feldspar-biotite porphyry, with remnant flow banding. Much of the feldspar is still preserved as feldspar. Large embayed Qtz phenocrysts, large feldspar phenocrysts and glomerocrysts, large biotite flakes partially to completely altered to chlorite. Swirly groundmass texture. Could this be related to ignimbrites on Zig Zag Hill?
- CO 36** - Quartz-feldspar porphyry, Mullock Quarry - similar to previous but more sheared.

Anaconda- Western Tharsis series : AWL 1-11

- AWL 1** - Chlorite-fleck schist near old walking track to Comstock, above Western Tharsis - very chlorite-rich, has rounded Qtz-filled amygdales. Lots of chlorite blebs and flecks, mainly after ferromag phenocrysts. A few apatite crystals. Highly altered andesitic lava.
- AWL 2** - Cherty schist, near old track as above - mass of cherty silica surrounds blebs of chlorite and/or sericite, with abundant pyrite xals. A few remnant feldspars. Could be very silicified andesite, but too far gone to be sure.
- AWL 3** - Even-textured schist with quartz, same area as above - remnant large feldspars, rounded spherulite-like Qtz blebs, some pyrite. Overall granular appearance. Previously a felsic lava?
- AWL 4** - Massive andesite-like rock within schists, Western Tharsis - good remnant ferromag phenocrysts replaced by chlorite, and feldspars replaced by sericite, in groundmass of interlocking Qtz and feldspar (now sericite).
- AWL 5** - Chert body or silica head, slope above Western Tharsis - consists of cherty silica with abundant stumpy crystals of Qtz-like mineral with higher relief - probably topaz. Also small patches of coarse sericite.
- AWL 6** - Chlorite schist, upslope from Western Tharsis - much secondary cherty silica, as well as chlorite flecks after ferromags. Probably after andesite.

- AWL 7** - Pink schist just NW of Western Tharsis - abundant secondary hematite along cleavage planes, cracks, and as clumps of crystals, many are elongate to bladed and translucent red in places. This overprints a quartz-sericite schist with remant qtz phenocrysts. All the qtz is faintly pleochroic from rose pink to white?
- AWL 8** - "Knobbly" schist near Western Tharsis portal, close to marginal schist zone - blebs of carbonate abundant, overprinting earlier sericite-qtz. Coarse snowflake textured feldspar-rich rock (all feldspar now seems to be qtz) with abundant sericite as pressure beards around most grains. Patches of coarser recrystallised qtz. Some small qtz phenocrysts.
- AWL 9** - Pyritic siliceous chist, near Western Tharsis road - coarse cherty silica with fairly abundant fine sericite and crystalline pyrite.
- AWL 10** - Siliceous schist near Crown Lyell road - mostly chert with remnant qtz phenocrysts. Also patches of stubby crystals of qtz-like mineral- probably topaz.
- AWL 11** - Hard siliceous zone within cherty schist, below Crown Lyell road - consists of interlocking qtz grains with overgrowths, patches of sericite.