Reconnaissance Economic Geology Studies for 1996, North Pilbara NGMA Project

by

David L. Huston

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AUSTRALIAN
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DAVID L. HUSTON

Australian Geological Survey Organisation, G.P.O. Box 378, Canberra, ACT 2601

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Abstract

Economic geology-related field work for the North Pilbara NGMA project during 1997 involved discussions with clients, deposit visits and preliminary research on volcani-hosted massive sulphide deposits of the Whim Creek group in the west Pilbara. The following deposits and districts were visited: the Panorama district, the Lynas Find gold district and the Klondyke gold district. Descriptions of the former deposits are presented herein, whereas a description of this latter desposit is reported elsewhere. As a result of these visits and discussions with the University of Western Australia, AGSO is supporting three honours student projects in 1997 (research outlines appended).

Studies of deposit in the Whim Creek Group indicate that the lower to central part of the Cistern Formation host most known deposits. The Whim Creek deposit, which is the only major exception, occurs in the overlying Rushall Slates. The more significant mineral occurrences in the Whim Creek belt appear to be localised along syn-sedimentary structures. The ACL prospect, which is the smallest VHMS prospect in the Whim Creek belt, is the only deposit that does not appear to be associated with syn-sedimentary faulting.

Paragenetic studies of the Mons Cupri deposit suggest five stages of mineralisation, as follows: siderite-sphalerite-pyrite-galena-quartz → silica → chalcopyrite-pyrite-chlorite-quartz → siderite-quartz±pyrite±sphalerite. Textural relationships suggest that most of the ores are epigenetic, and definitive evidence of syngenetic mineralisation is relatively sparse. This suggests that most, if not all, ore formed as sub-seafloor replacement.

Introduction, purpose and extent of field work

Between late May and early July 1996, work was undertaken by the author to establish a program of economic geology research for the North Pilbara NGMA project. Exploration companies were visited in Perth and field activities were undertaken in the west and central Pilbara with the following aims: (1) to discuss with clients their current and planned activities in the Pilbara, (2) to undertake preliminary geological studies (geological excursions, core logging and alteration mapping) of the Whim Creek volcanic-hosted massive sulphide (VHMS) district, and (3) to visit significant mineral deposits in the west and central Pilbara. The purpose of this report is to describe the geological setting of mineral deposits visited during the 1996 field program and to propose a work program on economic geology topics for the 1997 field season.

Discussions with clients

Prior to arriving in the field (late May) and after leaving the field (early July), a number of Perth-based exploration companies, the GSWA and the University of Western Australia were visited to discuss their activities and to develop a research program that best fits our client's needs. The following companies were visited:

- Sipa Resources Ltd/Outukumpu Australia (P. Morant and M. Doepel): Discussed exploration efforts in the Strelley VHMS district. Viewed company data and samples from the Kangaroo Caves and Sulphur Springs VHMS deposits.
- Dominion Mining/Straits Resources (T. Poustie): Discussed plans to establish a oxide leach operation at the Whim Creek and Mons Cupri deposits in early 1997. Established a research program around these deposits to incorporate semi-regional (1:10 000 scale) alteration mapping and detailed studies of the mineralisation and host rocks at these

two deposits. Presented core logs to the company and aquired unpublished reports and 1:2 000 and 1:10 000 scale geologic maps of the area.

- Lynas Gold NL (T. Davies): Discussed exploration efforts and structural/stratigraphic controls on Au mineralisation in the Pilgangoora Syncline. Developed a research plan for an Honours thesis on the Lynas Find deposits for which the author will co-supervise and AGSO will provide analytical support (Appendix A).
- Dragon Mining NL (M. Hoyle): Discused exploration efforts in the Tozer Well Syncline and Mt Hall areas to the south of Roebourne. Discussed potential research topics, including the Orpheus prospect. Dragon Resources expressed an interest in aquiring digital processed Landsat data.
- Resolute-Samantha Resources (P. Bailey, B. Keillor, H. Anderson): Discussed exploration efforts and models for Radio Hill-type Ni-Cu deposits.
- Great Southern Mines NL (P. Verbeek): Discussed exploration efforts in the central and east Pilbara. Great Southern Mines offered AGSO access to contract mapping and air photo interpretations of the Coongan (1:25 000; John Martyn) and Kelley (1:40 000; M E. I'ons) Volcanic belts. This mapping indicates extensive faulting and includes some alteration mapping.
- Ray Butler: Discussed the geology of the Salt Creek deposit and obtained permission to log drill core.
- Geological Survey of Western Australia (A. Hickman, I. Williams, T. Griffin, R. Rogerson, G. Williams): Discussed GSWA's mapping program in the Pilbara, and their plan to establish a mineral occurrence/deposit data base for Western Australia.
- University of Western Australia (D. Groves, E. Mikucki, C. Brauhart): Discussed the progress of Brauhart's Ph.D. mapping in the Strelley belt and how AGSO can assist with analyses.

The author also visited the Pilbara Mining and CRA exploration offices in Karratha:

- CRA Exploration (M. Christie): Discussed CRA exploration activities and prospects. Previously CRA had been exploring for VHMS deposits with little success. At the time of the visit they were actively exploring for gold, had established a significant resource at the Klondyke prospect and had encouraging stream sediment and soil geochemistry from the Western Shaw belt. Since this visit, CRA has closed its Karratha office and is presently winding down exploration in the Pilbara.
- Pilbara Mining (M. McKeesick): Discussed exploration activities in the Whim Creek belt and the geology of the Salt Creek and adjacent ACL prospect, and obtained drill core logs for recent drilling at both prospects.

Visits to exploration camps and mine sites are discussed separately below.

Preliminary geologic studies of the Whim Creek belt

Owing to time restrictions, limited original research was undertaken. Most research was undertaken on VHMS deposits and their environments within the Whim Creek Group in the west Pilbara. Field investigations involved logging drill holes from the Mons Cupri (two holes), Whim Creek (one hole), Salt Creek (two holes) and ACL (three holes) deposits, and preliminary alteration mapping around the Mons Cupri and Whim Creek deposits.

Regional geology

Prior to undertaking these studies, the author was introduced to the Whim Creek Group by Hugh Smithies of GSWA. The following descriptions are based on this introduction supplemented by published literature and observations made by the author. Figure 1 summarises the geology of the Whim Creek area based on Smithies' mapping (pers. comm., 1997), and Figure 2 illustrates stratigraphic relationships in the region.

The Whim Creek Group overlies unconformably a strongly foliated and lineated amphibolite and the Caines Well Granite Complex, which contains two distinct medium- to coarse-grained phases: (1) mesogranite with well developed, folded, gneissic fabric, and (2) leucogranite with a generally weak foliation. The distribution of these phases may be distinguished using radiometric and Landsat imagery. Both phases contain pegmatite and quartz-tourmaline veins, which cut the folded gneissosity and weak foliation, respectively. Along the Sholl shear zone, a gneissic fabric parallels the shear, and folds indicate a dextral motion. The gneissic phase of the Caines Well Granite Complex intrudes and contains inclusions of the amphibolite.

The Mons Cupri Volcanics and the Warambie Basalt unconformably overlie the Caines Well Granite Complex (Fig. 2). Using the revised stratigraphy of Smithies, the Mons Cupri Volcanics are divided into two separate units: the underlying Mount Brown Rhyolite, which consists of massive feldspar- and rarely quartz-phyric flows and domes, and the overlying Mons Cupri Epiclastics, which consists mainly of felsic epiclastic rocks derived from the Mount Brown rhyolite. The Warambie Basalt, which consists of massive amygdaloidal and vesicular flows interbedded with reworked mafic volcaniclastics, conventionally is considered to be the basal unit of the Whim Creek Group (e.g. Barley, 1987). However, the Mons Cupri Epiclastics contains basaltic clasts, and basal part of the Warambie Basalt contains cobbles and pebbles of Mount Brown Rhyolite, Caines Well Granite Complex and the amphibolite. A possible resolution to this dilema is that the deposition of the Warambie Basalt and the Mount Brown Rhyolite overlapped in time.

The Mons Cupri Volcanics and the Warambie Basalt are conformably overlain by the Cistern Formation, which Smithies redefined to include the coarse fragmental rocks that underlie the Mons Cupri deposit; these rocks had previously had been included in the Mons Cupri Volcanics (Miller & Gair, 1975). The Cistern Formation is a polymict, dominantly felsic, unit comprised mainly of felsic epiclastic rocks, with local vitric tuff and basaltic flows. The felsic epiclastic rocks vary from volcanic with volcanic and granite clasts to fine-grained arkosic sandstone. The vitric tuff units are locally welded (H. Smithies, pers. comm., 1997), which indicates a subaerial environment for deposition of at least part of this unit.

The Rushall Slate (aka the Whim Creek Slate; Miller & Gair, 1975; Reynolds et al., 1975) conformably overlies the Cistern Formation, and consists of gray to black shale, siltstone and minor sandstone. The Rushall Slate is disconformably overlain by the Louden Volcanics, which consist of massive to locally pillowed, spinifex textured komatiitic andesite. The Louden Volcanics are unconformably overlain by the Negri Volcanics, which consist of massive variolitic basalt flows, with minor mafic intrusions. Barley (1987) and several company geologists have grouped the Louden Volcanics into the the Negri Volcanics.

The Caines Well Granite Complex is intruded along or near its margins by the mainly gabbroic Millindinna Complex (Fig. 1). Mapping by Texas Gulf Australia Ltd (Smith, 1975) also indicates the presence of intrusive gabbros within the Whim Creek Group.

Geology of the Whim Creek deposit

The Whim Creek deposit (Figs. 3 and 4) occurs within a 3 km wide, ovoid basin of the Rushall Slate. The deposit occurs along a 0-20 m thick, 5 km long mineralised horizon that occurs 100-150 m stratigraphically above the contact with the underlying Mons Cupri Volcanics (Reynolds et al., 1975). The Cistern Formation is not recognised in the stratigraphy of the Whim Creek deposit.

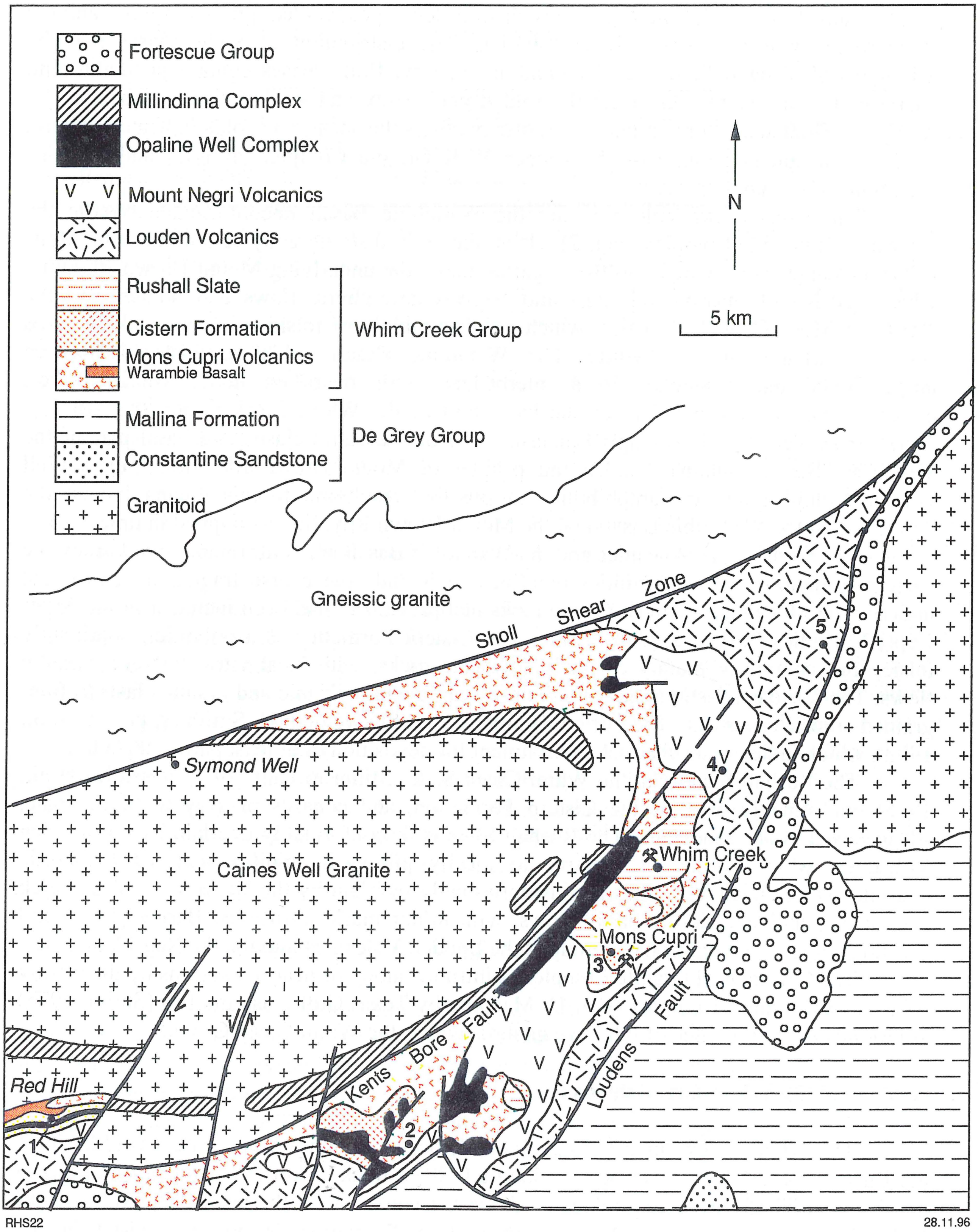


Figure 1. Geology of the Whim Creek Group (courtesy H. Smithies).

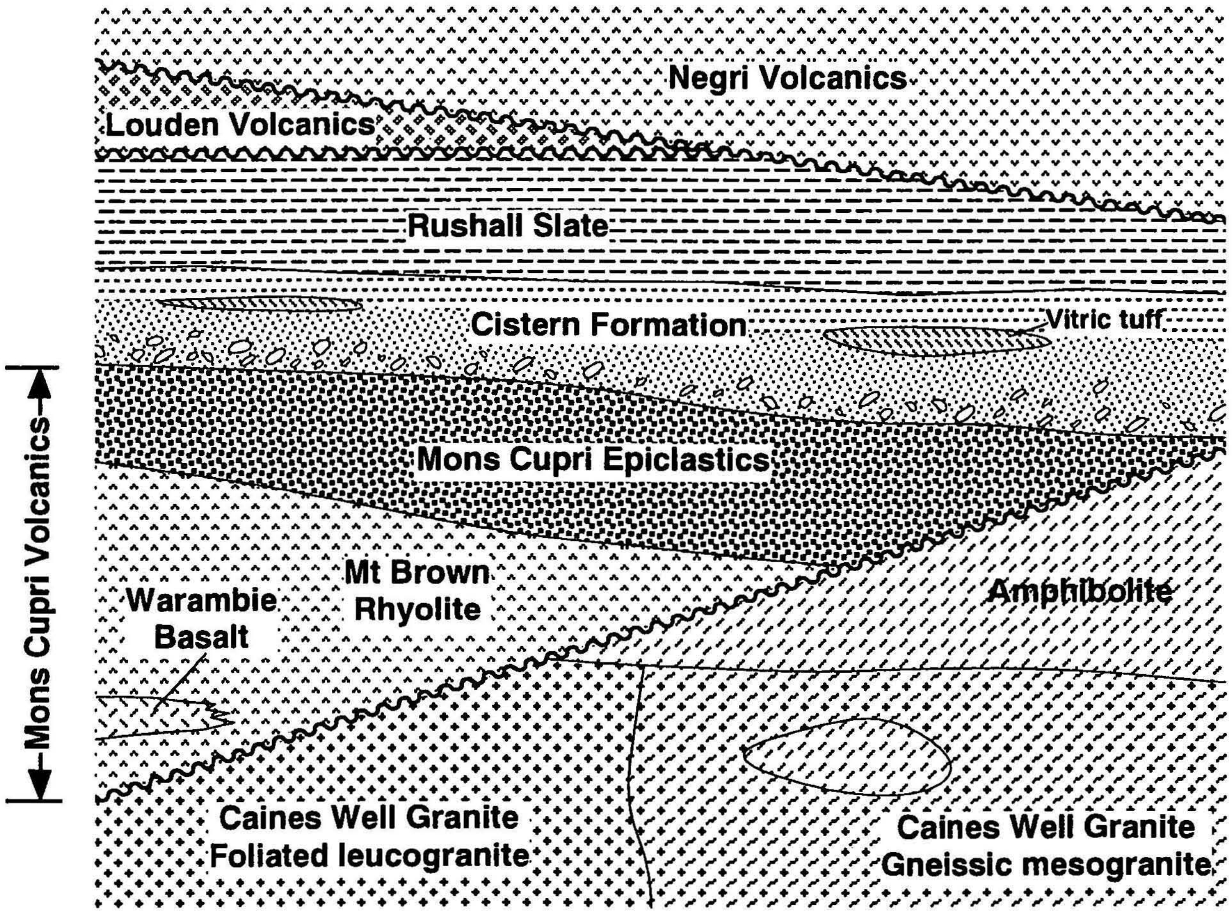


Figure 2. Schematic diagram showing the relationships between units within the Whim Creek Goup (based on discussions with H. Smithies, 1996).

Host rocks

The rocks in the immediate hanging wall and footwall of the Whim Creek deposit consist almost exclusively of shale and siltstone that becomes chloritically altered towards the ore lens. The mineralised horizon is characterised by a more complex lithological assemblage consisting of variably chloritised and silicified shale, "felsite" and sandstone. The origin of the "felsite", a massive, silicified rock, is controversial. Reynolds et al. (1975) emphasised that this unit is either cherty slate or chert. However, in drill core (Fig. 5), this rock type occurs as silicified, massive aphyric bodies that contain sulphide veinlets, or as clasts within breccias. At surface, the "felsite" has a complex, irregular relationship with silicified sandstone (Fig. 6a), which is suggestive of a peperite. The sandstone superficially resembles parts of the Cistern Formation exposed at Mons Cupri. The mineralised horizon that hosts the Whim Creek deposit appears to contain a significant volcanic component, which distinguishes it from the host Rushall Slate.

Mineralisation

The Whim Creek ores, which are dominated by pyrite, pyrrhotite, chalcopyrite, sphalerite and minor galena, form a lens that dips 20-25° to the northeast and is bounded by two northeast trending normal faults. Along the margin of the ore lens, the ore horizon pinches from 10-14 m to 1.5-3 m. The ore lens is divided by an aniclinal arch into two ore shoots: the east shoot, which is enriched in pyrrhotite, and the west shoot, which is enriched in pyrite and sphalerite (Reynolds et al., 1975).

Inspection of surface exposure and drill core indicates that much of the ore occurs as 0.1-0.5 m thick massive sulphide bands and stringers within silicified "felsite". Most, if not all, of the (ex)massive sulphide zones observed are discordant, even if only weakly so (Fig. 6b). Crosscutting vein relationships observed in drill core suggest the following very preliminary, vein paragenesis: pyrite-sphalerite → pyrite-chalcopyrite-chlorite → pyrite. At surface, the primary sulphide assemblages have been oxidised to Fe-oxides, malachite and azurite, and the gangue and wall rocks have been extensively kaolinitised. In drill hole WSD004, a thin chalcocite-pyrite zone is developed at 27-28 m above a pyrite-chalcocite-chalcopyrite zone at 28-39 m, which, in turn, overlies a pyrite-chalcopyrite zone at 39-45 m. Below this zone (45-48 m), the core lacks sulfide and is only weakly altered.

Reynolds et al. (1975) described three primary zones within the ore lens (Fig. 4): (1) an upper zone consisting of finely banded (2-4 mm), fine-grained (<1 mm), massive pyrite-sphalerite, (2) a central zone consisting of coarser-grained (>1 mm), massive pyrite/pyrrhotite-chalcopyrite, and (3) a lower zone consisting of disseminated chalcopyrite. Lack of exposure and drill core availability prevented observation in this study of the fine-grained, banded upper zone, which Reynolds et al. (1975) interpreted to be syngenetic. Studies of additional samples are required to determine the relative importance of syngenetic versus epigenetic processes in the formation of the Whim Creek deposit.

Geology of the Mons Cupri deposit

The Mons Cupri Volcanics, which include the Mount Brown Rhyolite and the Mons Cupri Epiclastics, underlie the Cistern Formation (Figs. 3 and 7). The Cistern Formation, which hosts ore at the Mons Cupri deposit, is a distinctive unit consisting mainly of massive to poorly bedded conglomerate, conglomeratic sandstone and sandstone. This unit is conformably overlain by the Rushall Slates, the basal part of which is locally termed the

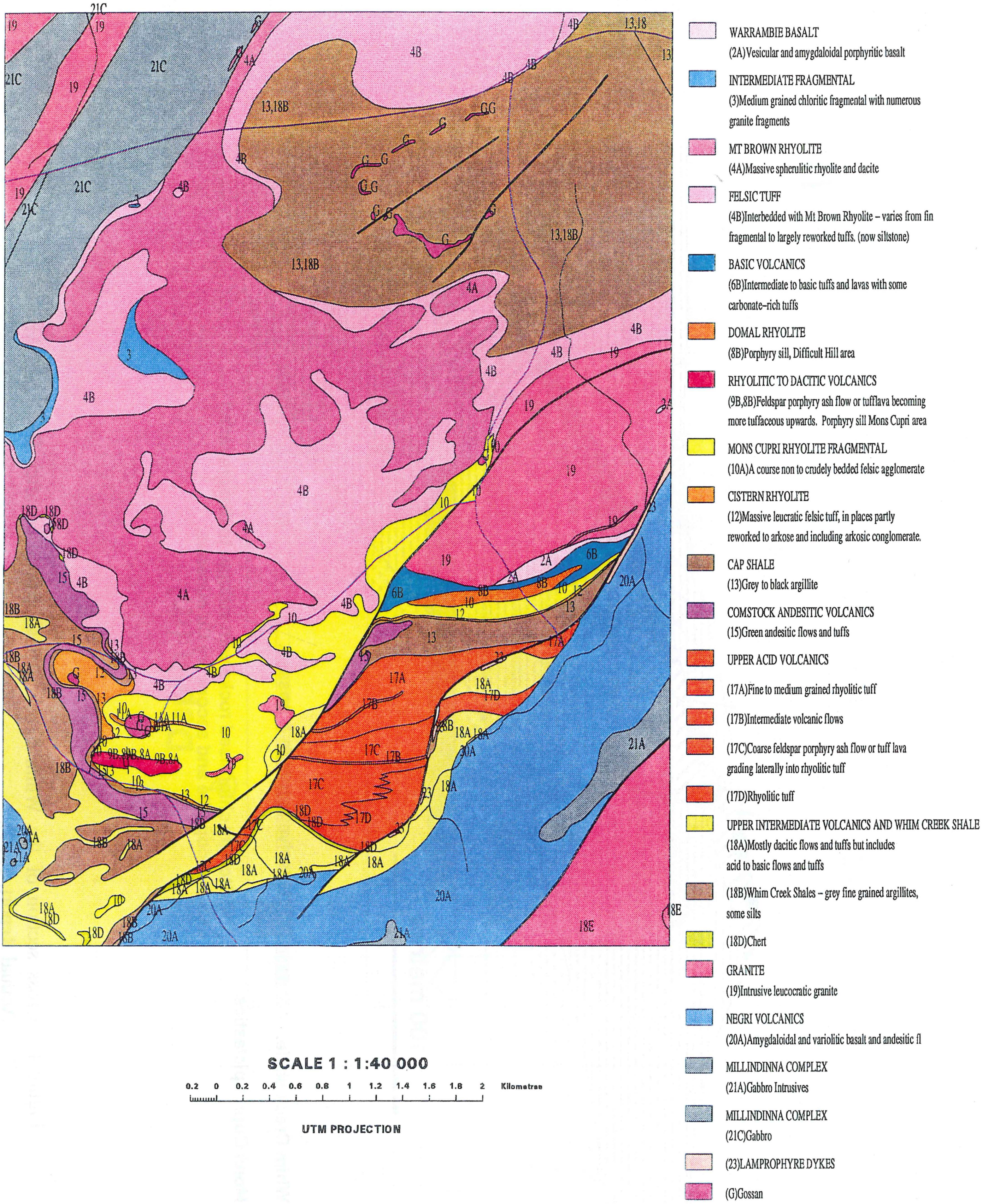


Figure 3. Geology of the Whim Creek Mons Cupri area (from compilation of company mapping by M. E. Smith).

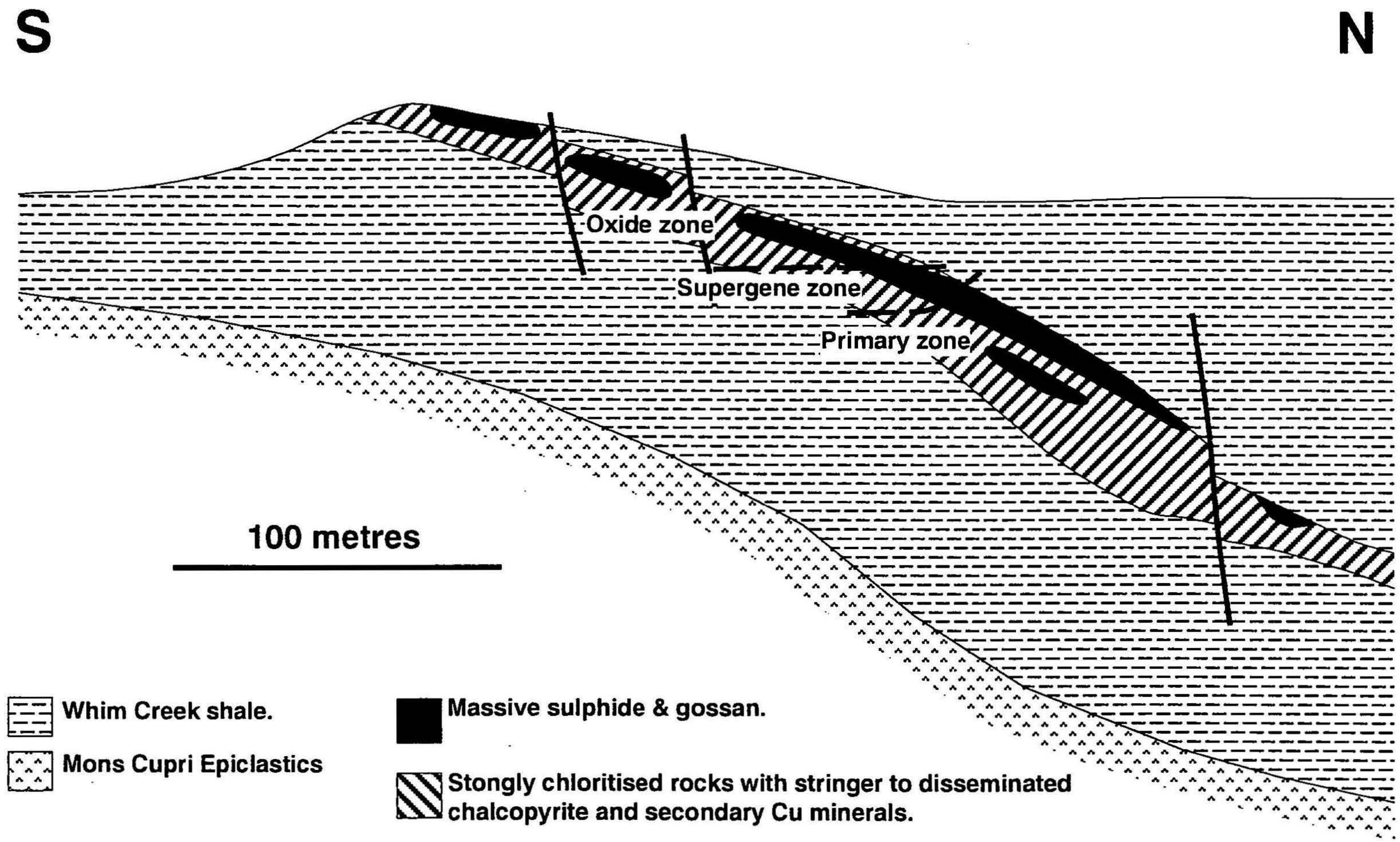


Figure 4. Cross section of the Whim Creek deposit (modified after Dominion Mining Anuual Report, 1996).

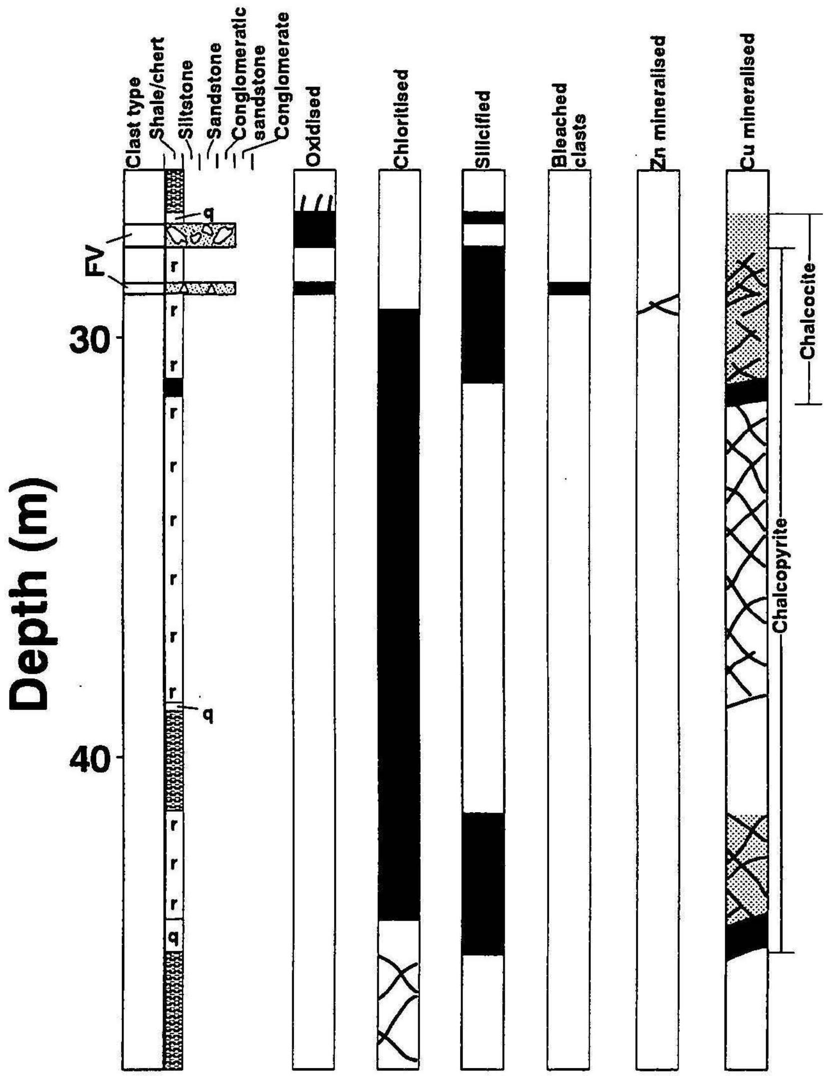
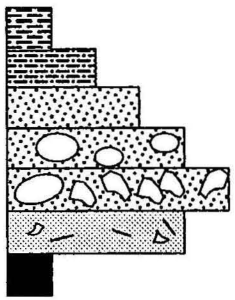


Figure 5. Graphic log of hole WSD001, Whim Creek deposit.

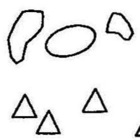
Legend for drill core logs

Lithology

r	Rhyolite
b	Basalt
d	Dolerite
q	Quartz vein
?	Unknown
bx	Breccia



Shale
Siltstone
Sandstone
Conglomeratic sandstone
Conglomerate
Ash-lapilli tuff
Massive sulphide



Clasts; shape indicates rounding
Angular clasts in breccia

Clast types

ARG	Argillite
GR	Granite
V	Volcanic
CH	Chert
CB	Carbonate
PM	Polymict; type not defined

Alteration

- Pervasive
- Patchy
- Disseminated
- Stringer

Mineralisation

- Massive
- Stringer
- Disseminated
- In quartz vein

Minerals

sl	Sphalerite
cp	Chalcopyrite
py	Pyrite
gn	Galena
Cu-ox	Copper oxides

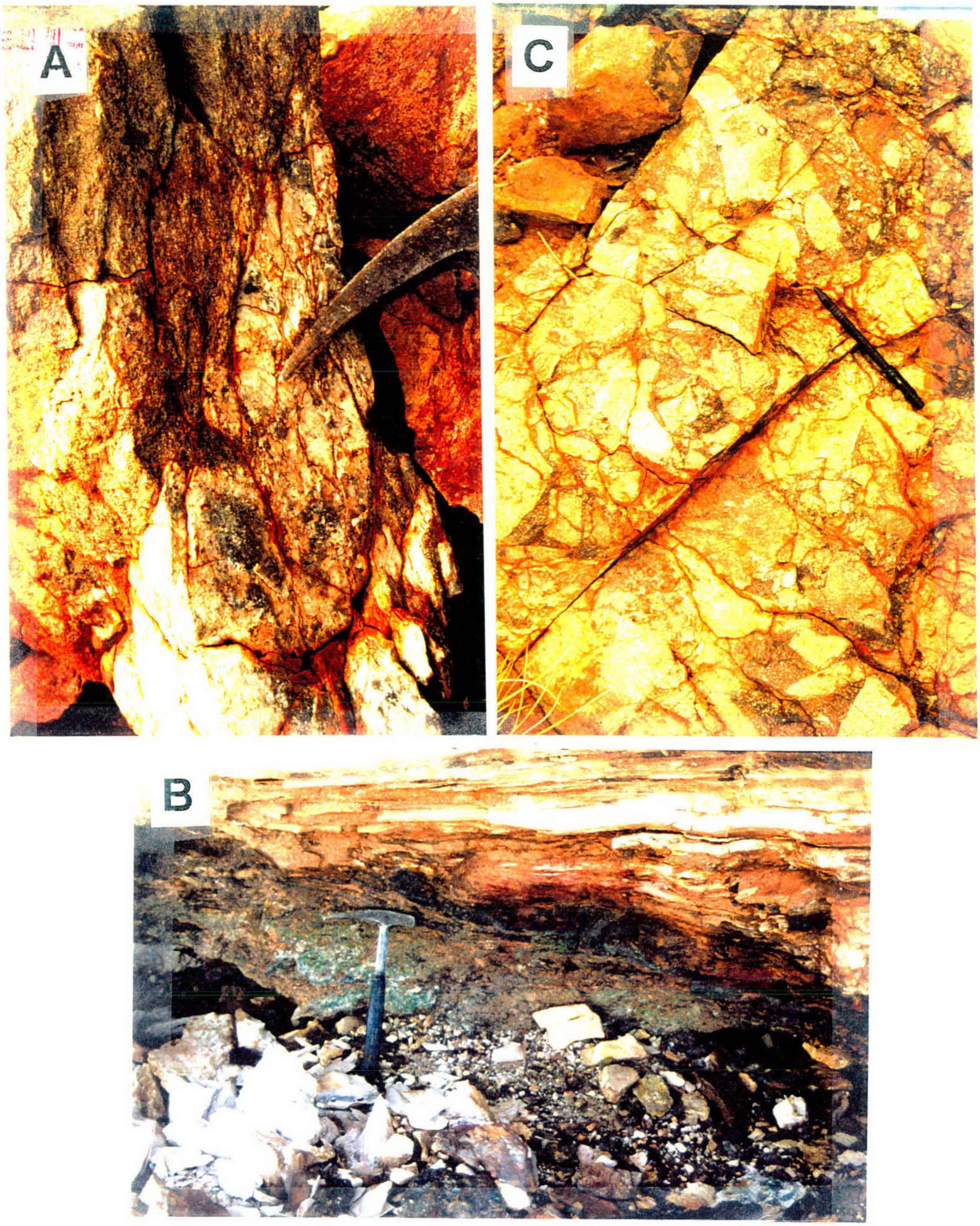


Figure 6. Photographs from the Whim Creek/Mons Cupri area showing : (a) complex inter-relationship between "felsite" and silicified sandstone, Whim Creek: (b) weakly discordant massive sulphide zone within Whim Creek host rocks; and (c) hyaloclastite (?) developed along the margin of the "Domal Rhyolite", Mons Cupri.

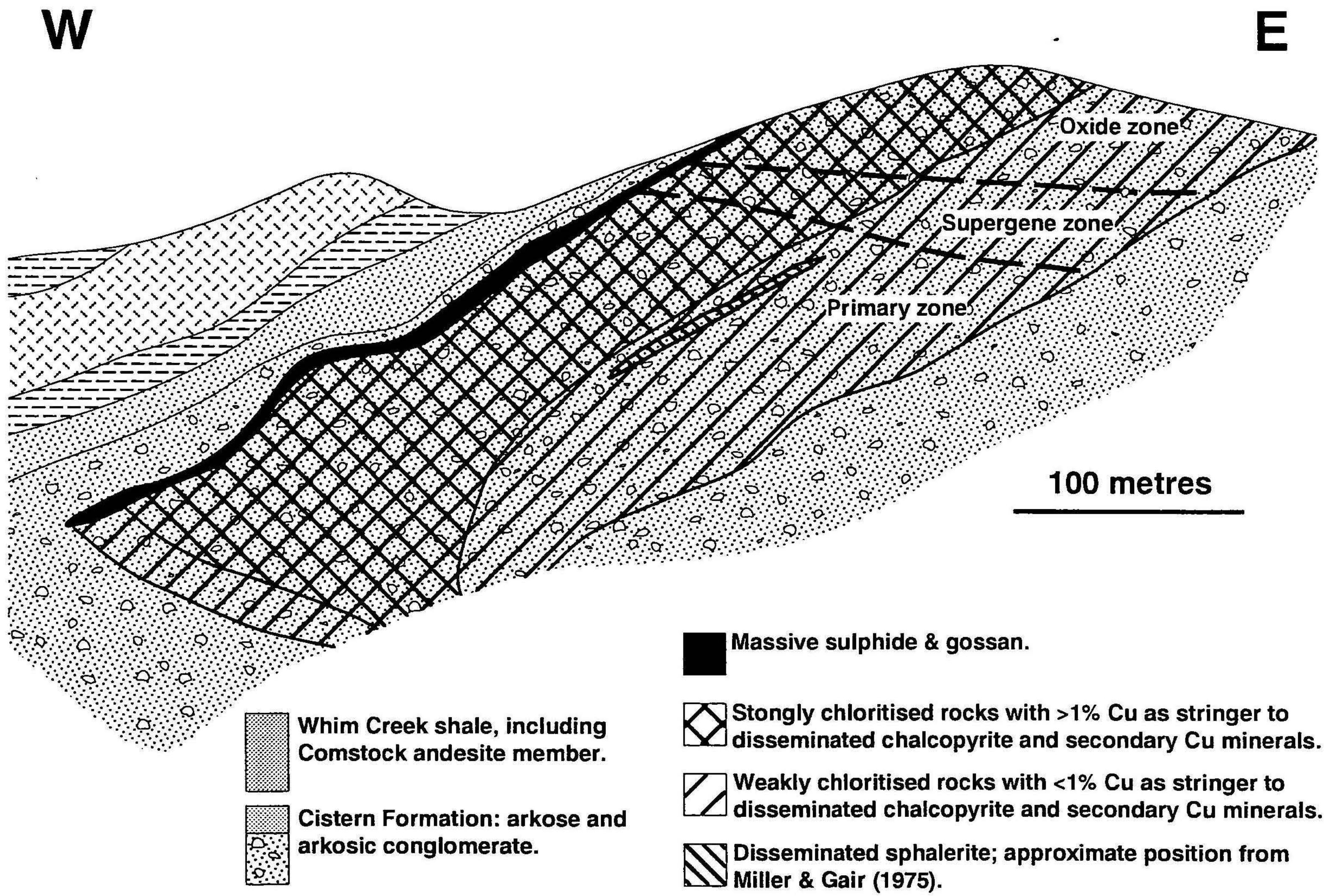


Figure 7. Cross section of the Mons Cupri (modified after Dominion Mining Anuual Report, 1996).

"Cap Shale". The Cap Shale is overlain by massive basalt termed the "Comstock Andesite", which, in turn, is overlain by the Rushall Slate proper. In the following descriptions, emphasis is placed on the units associated intimately with the Mons Cupri deposit.

The Cistern Formation

Smithies redefined the Cistern Formation to include coarse clastic sedimentary rocks that overlie and underlie the Mons Cupri deposit. This redefined unit includes the old Cistern Formation and the upper part of the Mons Cupri Volcanics of Miller & Gair (1975) and Smith (1975).

The Cistern Formation in the immediate vicinity of the Mons Cupri deposit (Fig. 3), consists of polymict conglomerate, conglomeratic sandstone and sandstone. This unit is generally poorly stratified, and the clasts, which are dominantly cobbles and pebbles, are mostly sub-rounded to sub-angular. The uppermost part of the unit, which corresponds to the old Cistern Formation of Miller & Gair (1975), consists of a bedded, tuffaceous arkose up to 20 m thick, with only minor pebbles and cobbles.

Figures 8 and 9 are graphical logs of drill holes MSD001 and MSD005, respectively, which show variations in grain size and clast type, alteration assemblages and mineralisation characteristics. Despite their close proximity (collared within 50 m of each other), lithological correlations are not apparent between these holes. Hole MSD001 is characterised by three 10-15 m thick sequences that fine upward from conglomerate to sandstone, and a relatively high abundance of sandstone. In contrast, hole MSD005 lacks fining upward sequences, and has a higher abundance of conglomeratic sandstone. The rounding of clasts increases uphole in both holes, although this is more apparent in hole MSD001. In both drill holes, finer-grained sediments such as "chert" and siltstone, although uncommon, occur in close proximity to the horizon containing the massive sulphide lens.

Granite, felsic volcanic, mafic volcanic and argillite clasts are present in both drill holes, and hole MSD005 contains carbonate "clasts". Volcanic clasts, which are similar to the Mt Brown Rhyolite and Warambie Basalt, are present through the entire length of both holes. However granite clasts, which are similar to the weakly foliated phase of the Caines Well Granite Complex, only occur beneath the Zn-bearing ore horizon, and argillite clasts occur mainly above this horizon. Weakly banded, colloform and massive angular "clasts" of siderite are present in siderite-altered sandy conglomerate within 5 m of the Zn-rich horizon in MSD005. However, many of these "clasts" have vaguely defined margins, which suggests that at least some formed by replacement.

The matrix to the conglomerate and sandy conglomerate is generally variably altered medium- to coarse-grained arkose. However, abundant 0.5-2 mm chlorite- and sericite-altered shards are present in the matrix toward the bottom of both holes: below 51.9 m in MSD001, and below 58.5 m in MSD005.

The lack of bedding and correlation of sub-units over short stratigraphic distances, the coarse clastic character of the unit, and the geographically restricted outcop suggest that the lower part of the Cistern Formation in the Mons Cupri area was deposited in a high energy, channelised environment, possibly at the base of a fault scarp. A likely candidate for a syn-sedimentary fault is the Miller Fault: the apparent change in the stratigraphic thickness of the Cistern Formation across this fault and the extension of this formation along the northwestern (downthrown?) block of this fault (Fig. 3) supports this interpretation.

The presence of shards within the sandy matrix toward the bottom of both drill hole suggests that nearby volcanic activity continued during the initial deposition of the Cistern Formation. The apparent change in clast populations at or about the Zn-mineralised horizon suggests a change of source provenance at or about the time of ore formation. As most of the

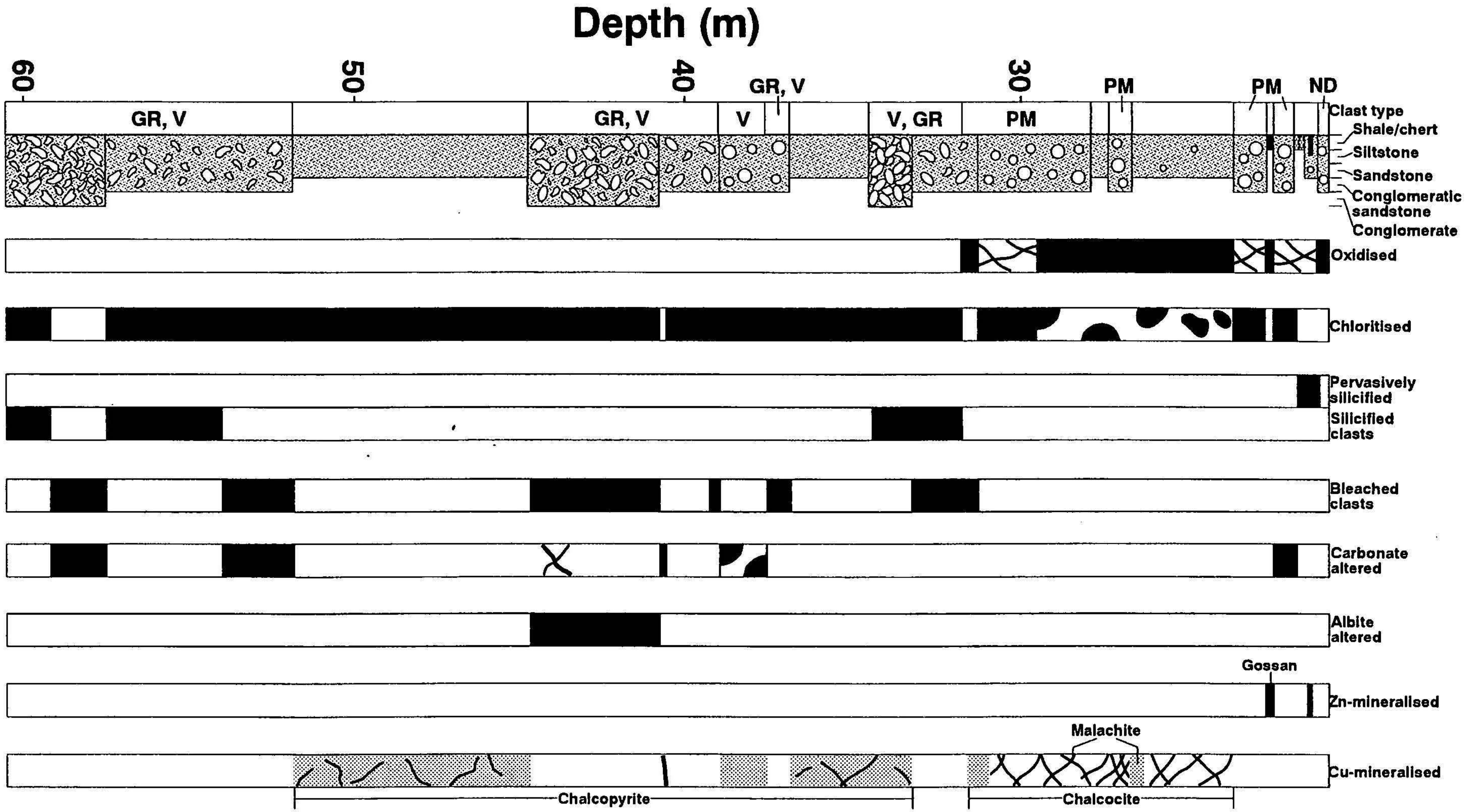


Figure 8. Graphic log of hole MSD001, Mons Cupri deposit.

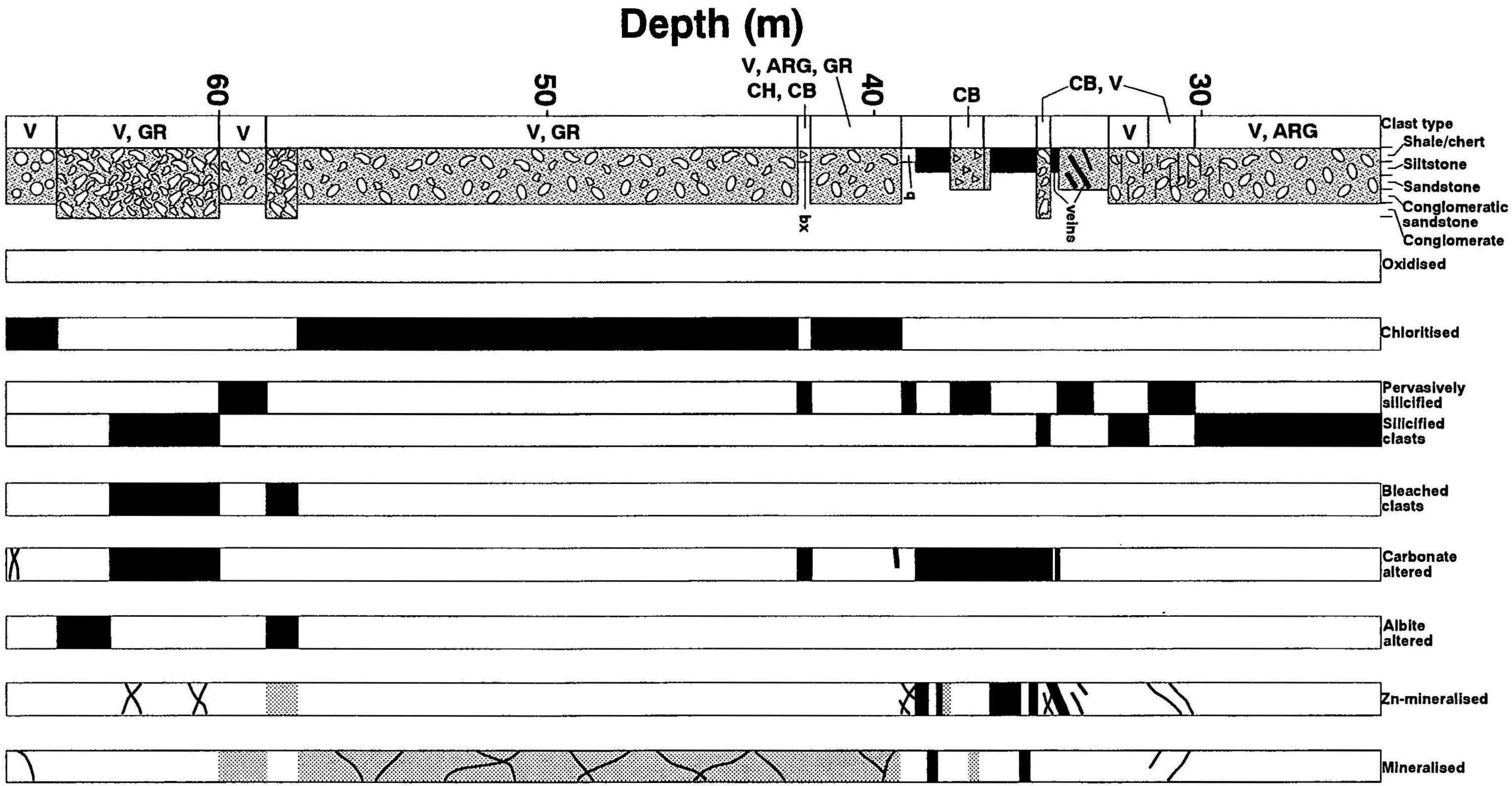


Figure 9. Graphic log of hole MSD005, Mons Cupri deposit.

finer grained rocks (shales, siltstone, chert and massive siderite) occur close to the mineralised horizon, a local quiescent period may have accompanied the change in source provenance and ore formation.

Igneous rocks hosted by the Cistern Formation

Exploration company mapping (c.f. Smith, 1975) identified an east-west trending, 100 m x 700 m body of feldspar-phyric rhyolite within the Cistern Formation approximately 300 m south of the Mons Cupri deposit (Fig. 3). This body, which has been informally termed the "domal rhyolite", consists of variably altered feldspar-phyric rhyolite similar to the Mt Brown Rhyolite. Although this body is generally massive and coherent, Smith (1975) reports that this body contains interbedded tuffs; observations by the author indicate brecciation in marginal locations. These zones consist of angular 5-25 cm clasts of rhyolite that occur in a fine-grained felsic matrix. The clasts commonly have a jigsaw fit and grade into massive coherent rhyolite (Fig. 6c), which may be consistent with a hyaloclastic origin.

The Cistern Formation also contains several small (<200 m) granitoid outcrops 700 m east-southeast and 1100 m east of the Mons Cupri deposit, respectively. These outcrops and a larger body 2.5 km to the east-northeast of the deposit resemble the weakly foliated leucocratic phase of the Caines Well Granite Complex, which supposedly unconformably underlies the Whim Creek Group. However, Smith (1975) infers these outcrops to be intrusive into the Cistern Formation, citing the following evidence: (1) the presence of veins that cut both the granite and volcanics, (2) the presence of volcanic inclusions in the granite (including a large inclusion of Warambie Basalt), and (3) a crosscutting relationship of the granite to the volcanics 500 m northeast of the Ant Hill workings. The author visited on the larger outcrop and one of the smaller outcrops. No definitive evidence of relative timing was observed; however, the smaller exposure of this granite is strongly weathered and clay altered, and it occurs within a highly silicified and sulfidic wall rocks. If the granite is intrusive, it could have acted as the heat and/or fluid source to the Mons Cupri deposit.

The Cap Shale and Comstock Andesite

The "Cap Shale" immediately overlies the upper Cistern Formation in the Mons Cupri area. This unit, which is generally less than 10 m thick, consists of fissile shale that is commonly strongly silicified. The Cap Shale is restricted to the immediate Mons Cupri environs and has been traced along strike for 5 km.

The "Comstock Andesite", which overlies the Cap Shale consists of massive to vesicular basalt up to 70 m thick (Miller & Gair, 1975). This unit, which is also limited to the immediate vicinity of Mons Cupri, has also been traced about 5 km along strike. The Comstock Andesite is directly overlain by Rushall Slate.

Mineralisation

The orebody at Mons Cupri is hosted by Cistern Formation, and two broad types of mineralisation are present: (1) Zn-Pb-Cu-rich, strataform, semi-massive to massive sulphide, and (2) stockwork to disseminated mineralisation that occurs in an underlying chloritic zone.

The strataform lens occurs < 5 m below the contact of the lower, conglomeratic facies with the upper arkosic facies of the Cistern Formation (Fig. 7; Miller & Gair, 1975). This lens, which is 3-15 m thick, 270 m wide and 400 m long (Miller & Gair, 1975), is associated with chert, minor shale and siderite (Fig. 8). Miller & Gair (1975) reported "typical" intersections within this lens of 2 m @ 16.2% Zn, 10.9% Pb, 0.5% Cu and 161 g/t Ag, and

18 m @ 6.5% Zn, 5.2% Pb, 1.2% Cu and 62 g/t Ag. The strataform sulphide lens contains the following ore and gangue minerals, in decreasing order of abundance: sphalerite, galena, quartz, siderite, chalcopyrite and pyrite. Tanner (1990) also reported the presence of tetrahedrite ($(Cu,Ag)_{10}(Fe,Zn)_2(Sb,As)_4S_{13}$), bournonite ($CuPbSbS_3$) and linnaeite ($Co_3S_4$) in the strataform zone.

The strataform lens overlies a zone of chloritic alteration with disseminated and stringer chalcopyrite and pyrite. Gangue minerals include quartz, chlorite and siderite. Other trace ore minerals include sphalerite, galena, magnetite and possibly a bismuth sulphosalt. Miller & Gair (1975) divided the underlying Cu-mineralised zone into two parts (Fig. 7): (1) a funnel-shaped zone having grades in excess of 1.0% Cu, and (2) a surrounding zone grading less than 1% Cu. A tabular zone containing significant Zn grades occurs near the contact between these two zones.

Moderately extensive pits, termed the Western Pits, occur in chloritised, fine-grained sandstone of the Cistern Formation approximately 500 m west-northwest of the Mons Cupri deposit. Dump samples are commonly malachite stained, with minor azurite, and are generally kaolinitised and limonitic. One dump sample consisted of vuggy, fine-grained cuprite with the vugs filled by goethite; this may suggest the presence of local massive sulphide zones in the primary ores. Sulphidic samples were not observed on the dumps, suggesting that the old workings did not extend into the supergene or hypogene zones. The Western Pits probably occur at or slightly above the Mons Cupri stratigraphic position.

Numerous pits and adits of the Comstock prospect are present along much of the ridge 600 m to the south of the Mons Cupri deposit. This ridge consists of variably chloritised Constock Andesite, and workings are associated with west trending quartz veins. Gossanous material containing malachite and cerrusite (?) was found in dumps along the western-most part of the ridge, almost due south from the Mons Cupri deposit.

Alteration

The main purpose of fieldwork at the Mons Cupri deposit was to determine the extent and characteristics of alteration as a tool to understand fluid flow within the hydrothermal system and to assess the efficacy of alteration mapping as an exploration tool in the Whim Creek belt. In addition to core logging, approximately four days were spent undertaking reconnaissance traverses and preliminary alteration mapping around Mons Cupri.

Alteration zonation in drill core. The most intensely altered rocks at the Mons Cupri deposit are strongly chlorite-altered conglomeratic sandstones that underlie the strataform lens and host chalcopyrite- pyrite stringers. This alteration zone, as mapped by exploration geologists, is confined to within 100 m of the Mons Cupri deposit. Although a chloritic alteration assemblage is the most prominant, core logging indicates that ore deposition was also closely associated with silification, siderite alteration, albite alteration and light coloured alteration of clasts, and that these alteration assemblages vary systematically through the orebody (Figs. 8 and 9).

In core, chloritic alteration is characterised by pervasive chlorite-quartz alteration, with associated chalcopyrite-pyrite-quartz stringers. The intensity varies from dark green chlorite-quartz rock in which primary textures are only vaguely apparent to a less strongly altered, paler green rock with primary textures still well preserved. The less intensely chlorite altered rock generally contains additional alteration minerals, such as albite or siderite.

Although chlorite-altered rocks are closely associated with Cu-rich stringers, these rocks have an antipathetic relationship to Zn-rich mineralised zones. In hole MSD005, chloritic alteration assemblages are not present in the strataform sulphide lens or in footwall

Zn-rich zone. Rather, these zones contain rocks with alteration assemblages characterised by silica, siderite and/or albite (Figs. 8 and 9).

Silica-altered rocks, which occurs mainly within and stratigraphically above the strataform sulfide lens, are characterised by fine-grained silicification that can be either pervasive or only affect clasts. Silica-altered rocks also occur within the footwall Zn-rich zone in the footwall. Carbonate-altered rocks, which are characterised by colloform siderite and disseminated, fine-grained siderite, occur mainly in the stratabound sulphide lens and the footwall Zn-rich zone. Siderite was not observed in rocks overlying the strataform sulphide lens.

Albite alteration is a distinctive, but minor alteration type, that is characterised by the presence of 0.5-5 mm, white to off-white subhedral albite grains that have overgrown pre-existing feldspar phenocrysts in volcanic clasts or nucleated within the arkosic matrix to the clasts. Albite-altered rocks also have been chloritically and sericitically altered in the matrix and may contain minor disseminated pyrite and sphalerite. In many albite-altered zones, pebbles and cobbles are commonly bleached along margins (Figs. 8 and 9). The mineralogical changes involved in bleaching have not be determined.

Alteration zonation at the surface. At surface, the major alteration assemblage observed is chlorite-quartz. Texasgulf Australia mapping has defined a lenticular zone of intensely chlorite altered rocks that are closely associated with the gossan at Mons Cupri (Fig. 3). This zone, which cuts stratigraphy, extends roughly 700 m east-west and has a width of 20-100 m. Reconnaissance traversing indicates that this chlorite-altered zone may be more extensive than previously mapped. This traversing also indicated that albite-altered rocks are also present along the periphery of the mapped chlorite alteration zone.

Preliminary alteration mapping was undertaken in the Cistern Formation (as defined by H. Smithies), the Cap Shale and the Comstock Andesite. Although this mapping is not far enough advanced to produce a map, comments can be made regarding alteration within the immediate vicinity (<1 km) of the deposit. For instance, the central part of the "domal" rhyolite is characterised by feldspar-destructive quartz-chlorite-sulphide alteration assemblages, whereas the eastern and western parts are characterised by silica-sericite assemblages and relic feldspar phenocrysts. Cistern Formation rocks that surround the "domal" rhyolite are generally chlorite-quartz-sulphide altered, as are the sandstones that host the Western Pits deposit.

Preliminary mapping in the Cap Shale and Comstock Andesite indicate that both these units are altered in the vicinity of the Mons Cupri and the Western Pits deposits. The Cap Shale is typically silicified, and in the hanging wall to the Western Pits, the Cap Shale has been extensively veined by bedding-parallel and stockwork quartz veins. Although the intensity of alteration varies, the overlying Comstock Andesite is generally chlorite altered. The most intense alteration in the Comstock Andesite occurs to the west of the Western Pits, where the rock has been intensely chlorite-silica altered with 0.5-1% disseminated pyrite, and amygdales are filled with quartz±pyrite. Elsewhere, the Comstock Andesite is variably chloritised, with more intense chlorite±pyrite alteration occuring in some places close to the contact with the underlying Cap Shale.

Implications and potential applications. Preliminary core logging, traverses and mapping have defined several different alteration assemblages within the vicinity of the Mons Cupri deposit. These studies suggests that silicification and chlorite-quartz-pyrite alteration continued during or after the deposition of the Comstock Andesite, particularly in the hanging wall of the Western Pits workings. These studies also suggest that systematic spatial and temporal zonation in alteration assemblages may exist around Mons Cupri; if such zonation can be established, it potentially could be used as an exploration guide in the Whim Creek Group.

Paragenesis of drill holes MSD001 and MSD005

Three types of mineralisation are recognised in MSD001 and MSD005: (1) Zn-rich stratiform semi-massive to massive sulphide, (2) Cu-rich stringer sulphide in chloritic alteration zones, and (3) Zn-rich stringer sulphide in carbonate- and albite-altered rock that corresponds to the footwall Zn-rich zone of Miller & Gair (1975). Based on these two holes, five preliminary paragenetic stages of mineralisation are recognised (Figure 10). All five stages are present in close proximity to the strataform sulphide lens, but only the latter two stages are present in the stringer zone.

Stage I. The earliest paragenetic stage consists of banded to collofom, semi-massive to massive, fine-grained siderite with associated quartz, pyrite and minor sphalerite that occurs as 0.5-10 cm clasts in a sandy matrix, or as veins. Some siderite "clasts" have sharp margins, which suggests that they formed by sedimentary or hydrothermal fragmentation. However, the margins of other "clasts" are diffuse, suggesting that they formed by preferential replacement. Siderite commonly is disseminated throughout the arkosic matrix to these "pseudo-clasts". Probable 1-2 cm clasts of semi-massive to massive, fine-grained sphalerite-galena occur with massive siderite clasts in sample MSD005-42.0. A few other samples also have probable clasts of fine grained massive sphalerite-galena with siderite and quartz gangue. The paragenetic relationships between early siderite and early massive sphalerite-galena is not clear.

Stages II and III. The second paragenetic stage is characterised by 2-20 mm veins of semi-massive to massive, fine- to medium-grained sphalerite-galena with siderite and quartz gangue. The third paragenetic stage consists of prevasive silicification to form chert or cherty quartz veining and brecciation. In sample MSD005-37.0, "cherty" silicified siltstone also contains disseminated sphalerite and galena, but in sample MSD005-37.8, a stage I massive sulphide nodule is replaced along its margin by silica flooding. Stages II and III are the least abundant paragenetic stages, and they are restricted to the immediate vicinity of the Zn-rich strataform sulphide lens.

Stage IV. Veins, stringers and replacement zones of chalcopyrite, pyrite and quartz cut the Zn-rich strataform sulphide lens. However, within the underlying chloritic alteration zone, these minerals occur as disseminated grains or in stringers, and form the earliest paragenetic stage. A possible Bi-sulphosalt occurs along the margins of some of these stringers. Stage IV is the only paragenetic stage that lacks significant siderite.

Stage V. Stage V, which is dominated by siderite, quartz and pyrite, is the only paragenetic stage present through both drill holes. In the Zn-rich, strataform sulphide zone and in the chloritic stringer zone, stage V occurs as colloform veins and open space filling, with two sub-stages: (a) collofom to "bladed" siderite-quartz-pyrite±magnetite, which occurs along vein margins, and (b) quartz±sphalerite±pyrite±galena, which occurs in vein centres. In the carbonate-altered and albite-altered, footwall Zn-rich zone, stage V is the only paragenetic stage present. In these rocks, disseminated siderite±pale sphalerite occurs in the arkosic matrix, and this assemblage is cut by dark sphalerite-galena-pyrite±chalcopyrite stringers.

Discussion. The above paragenetic relationships can be summarised as follows: siderite-sphalerite-pyrite-galena-quartz → silica → chalcopyrite-pyrite-chlorite-quartz → siderite-quartz±pyrite±sphalerite. This paragenetic sequence is consistent with that established for VHMS deposits in the Hokuroku district in Japan (Eldridge et al., 1983) and black smoker deposits (Campbell et al., 1984). Textural relationships at Mons Cupri suggest that most of the ores are epigenetic, and definitive evidence of syngenetic mineralisation is relatively sparse. This suggests that most, if not all, ore formed as sub-seafloor replacement.

	Stage I	Stage II	Stage III	Stage IV	Stage V
Strataform sulphide lens	Siderite±quartz±pyrite (Massive, colloform and banded; possibly syngenetic; also replaces sandy matrix) Sphalerite-galena-quartz±siderite (Massive to semi-massive; some may be syngenetic)	Sphalerite-galena± siderite (Veins)	Silica flooding± chlorite (Pervasive or forms matrix to breccia)	Chalcopyrite-pyrite± quartz±siderite (stringers, veins and replacement zones)	Siderite-quartz-pyrite± sphalerite±galena (Colloform; veins and open space filling)*
Chloritic alteration zone				Chalcopyrite-quartz± pyrite±chlorite (Veins, stringers and dissmenations)	Siderite-quartz-pyrite± magnetite±sphalerite± galena (Colloform; veins and open space filling; rarely in matrix)*
Footwall Zn-rich zone					Siderite±pyrite±sphalerite± galena±chalcopyrite (In matrix or stringers)#

*In the strataform sulphide lens and the chloritic alteration zone, stage V has two substages: (a) colloform siderite-quartz-pyrite±magnetite quatz±sphalerite±pyrite±galena.
#In the footwall Zn-rich zone, stage V is characterised by disseminated siderite±pale sphalerite in the matrix and by crosscutting dark sphalerite-galena-pyrite±chalcopyrite stringers.

Figure 10. Paragenetic sequence of mineralisation, Mons Cupri deposit.

A preliminary model for the formation of the Mons Cupri deposit

Figure 11 illustrates a geological model for the formation of the Mons Cupri deposit based on preliminary observations discussed in this report. Deposition of the Whim Creek Group began with the eruption of the Warambie Basalt and the Mount Brown Rhyolite on an erosional surface above the Caines Well Granite Complex. Reworking of the Mount Brown Rhyolite resulted in the deposition of the Mons Cupri Epiclastics (Fig. 11a). Syn-volcanic block faulting (e.g. Miller Fault) resulted in the formation of a narrow basin into which depositon of the basal conglomerates of the Cistern Formation began. Effusive rhyolitic volcanic activity continued during this period, as evidenced by the hyaloclastite textures along the margins of the "domal" rhyolite, and by the presence of glass shards within the basal Cistern Formation (Fig. 11b).

This volcanism eventually ceased, as evidenced by the lack of juvenile volcanic material in the upper part of the Cistern Formation. However, as juvenile volcanic material is present within the Cistern Formation elsewhere in the Whim Creek belt (H. Smithies, pers. comm., 1996), cessation of volcanism may have been localised at Mons Cupri. Mineralisation probably occurred at Mons Cupri during the cessation of volcanism. Textural relationships suggest that ore deposition occurred mainly as sub-seafloor replacement (Fig. 11c).

Following the deposition of the Cistern Formation, coarse clastic sedimentation ceased, and deposition of the Rushall Slate commenced. The Comstock Andesite was extruded near the base of this unit. As the Comstock Andesite pinches out just to the east of the Miller Fault, activity along this fault may have continued at the time of Comstock Andesite extrusion (Fig. 11d).

Geology of the Salt Creek and ACL prospects

The Salt Creek and nearby ACL prospects are are located along the northern margin of the Caines Well Granite Complex (Fig. 1), within a ENE-trending, steeply dipping sequence containing spherulitic rhyolite, felsic tuff, sandstone, siltstone and and basalt (Fig. 12). The prospects, although located within three kilometers of each other, are characterised by different styles of mineralisation and alteration.

Host rocks

Surface mapping and RAB chip logging has been used by Pilbara Mines and previous leaseholders to define four rock types, as follows: (1) "tuffaceous" sandstone and siltstone, (2) spherulitic rhyolite, (3) lapilli tuff, and (4) basalt. Sandstone hosts disseminated sulphide at ACL and siltstone hosts massive sulphide at Salt Creek. This sequence overlies the Caines Well Granite Complex to the south, and is intruded by gabbro/dolerite to the north.

ACL prospect. Three stratigraphic units are present in drill core from the ACL prospect (Figs. 13 to 15). The southernmost unit, which occurs at the base of holes ACLD16 and ACLD19, consists of massive vitric-crystal-lithic ash-lapilli tuff of probable felsic composition. Locally this unit contains up to 20%, 0.5-20 mm, sub-angular granite and/or "argillite" (field term; may be silicified felsite?) clasts (e.g. Fig. 15). This unit corresponds to the lapilli tuff at surface.

A unit consisting of massive to weakly bedded, fine- to medium-grained sandstone and massive to bedded siltstone is present in all holes. In holes ACLD16 and ACLD19, it occurs immediately above intervals of ash-lapilli tuff. In core, the relative proportion between sandstone and siltstone is quite variable, and sub-units cannot be correlated between

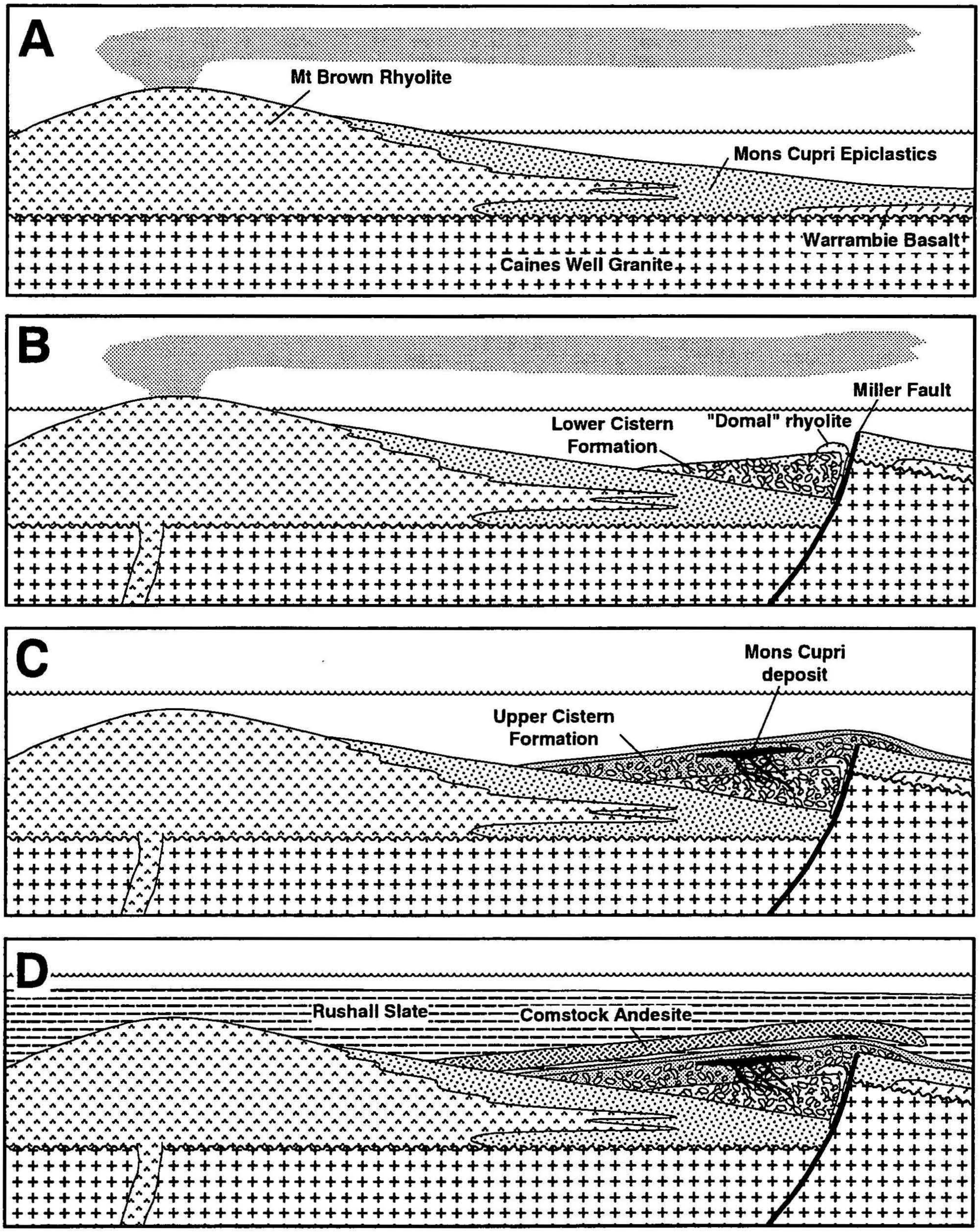


Figure 11. Reconstruction of geologic events important in the formation of the Mons Cupri deposit.

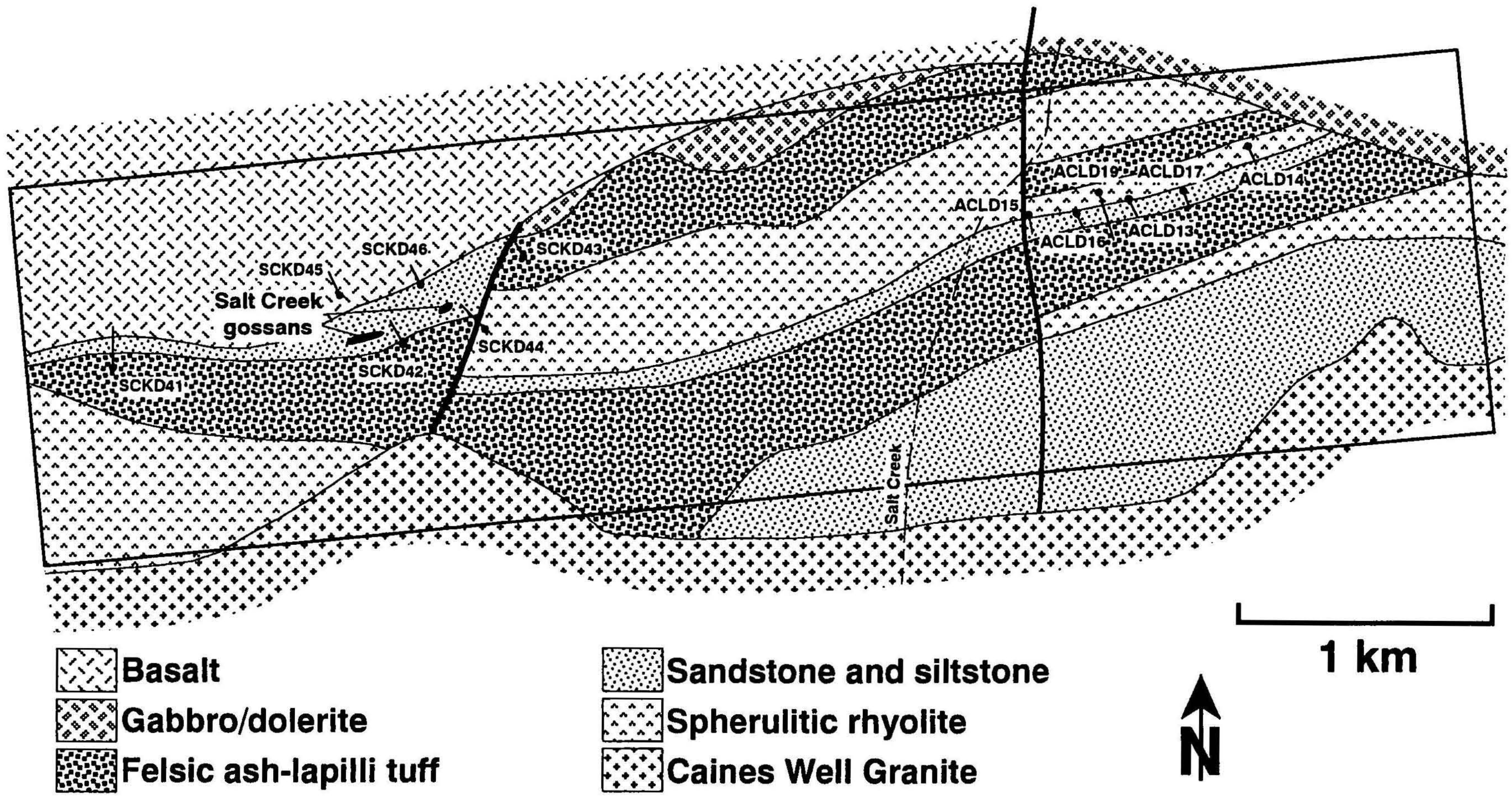


Figure 12. Geology of the Salt Creek and ACL prospects (modified from 1995 Pilbara Mines Annual report using additional data of A. McKeesick).

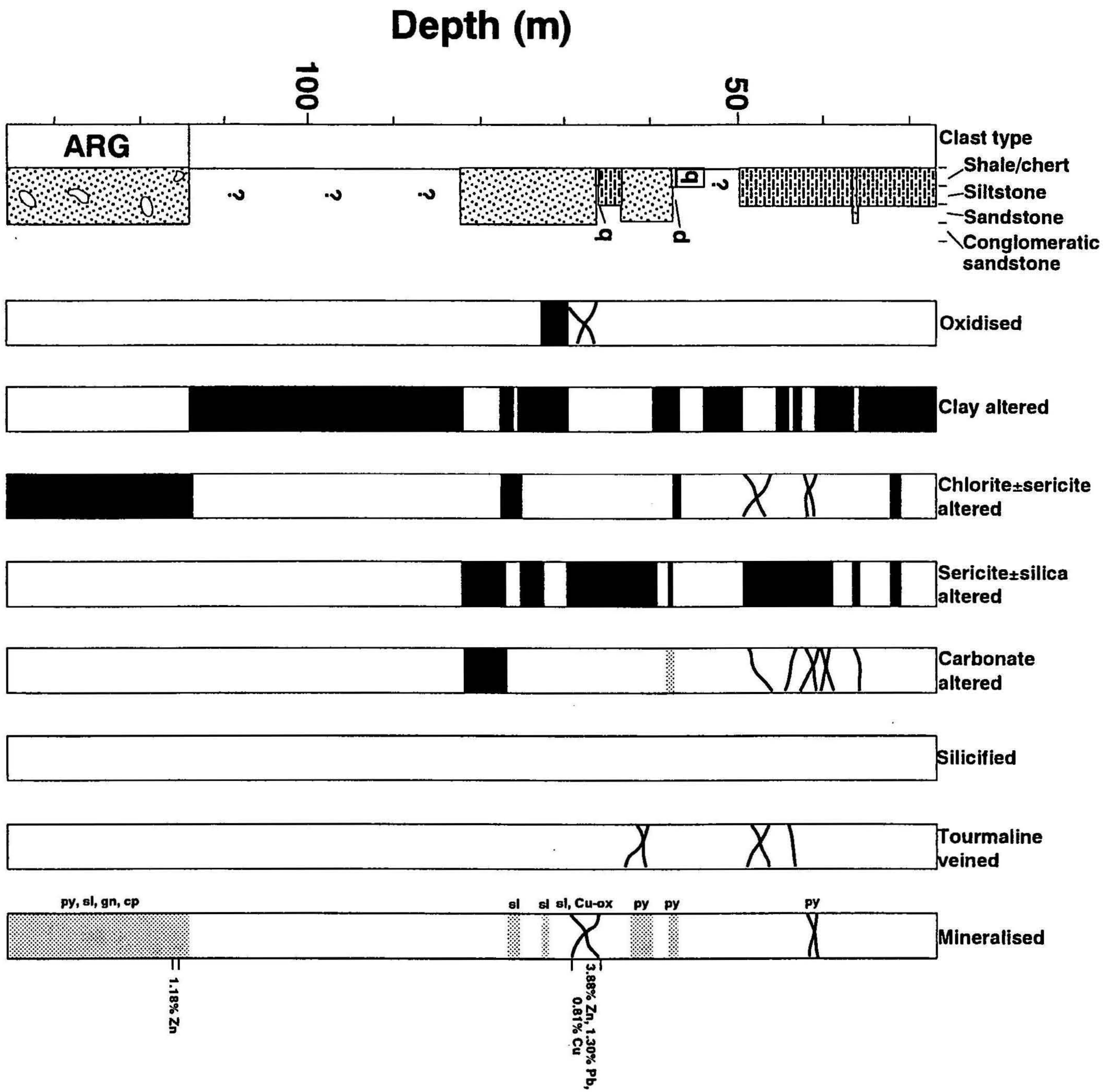


Figure 13. Graphic log of hole ACLD13, ACL prospect.

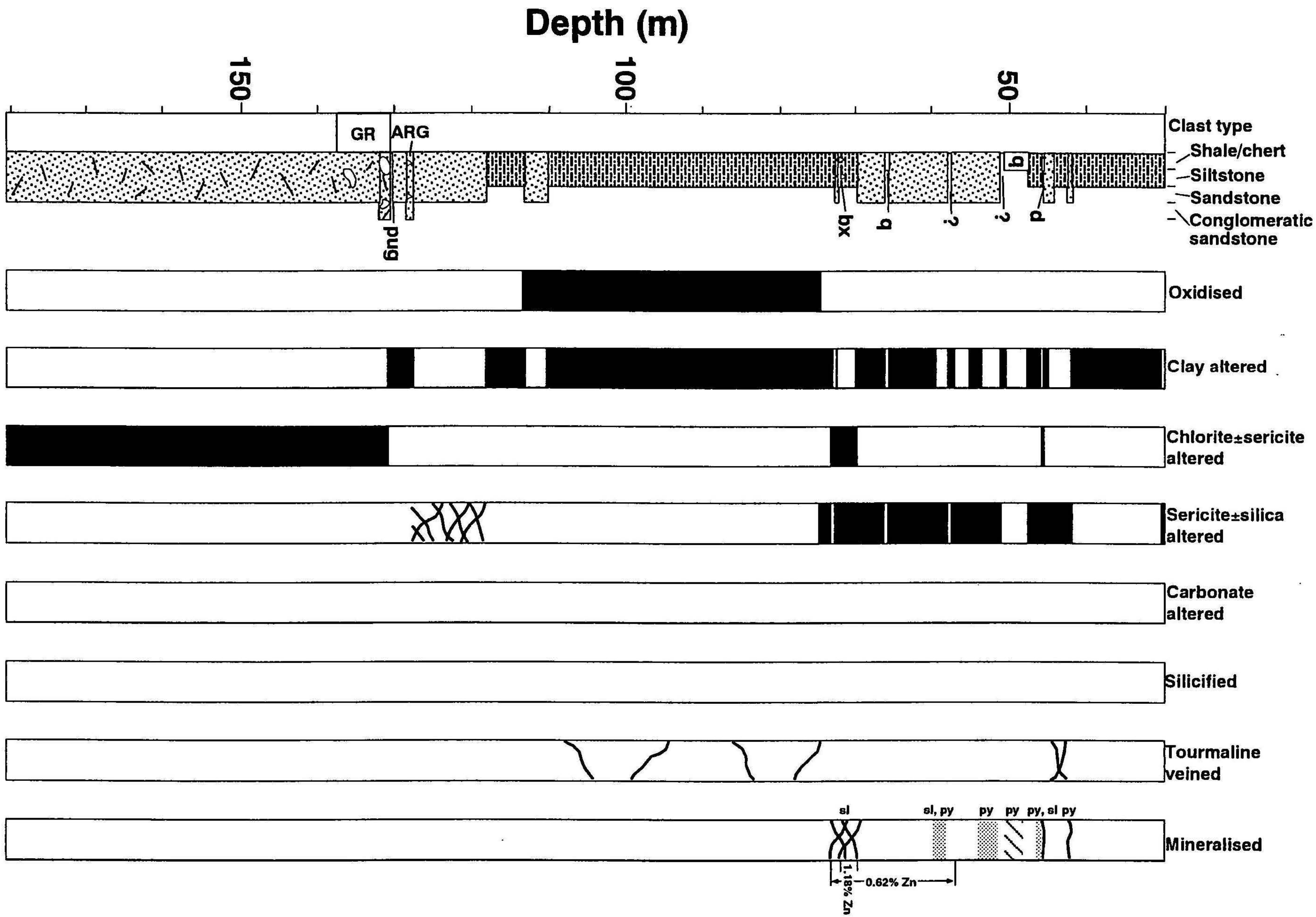


Figure 14. Graphic log of hole ACLD16, ACL prospect.

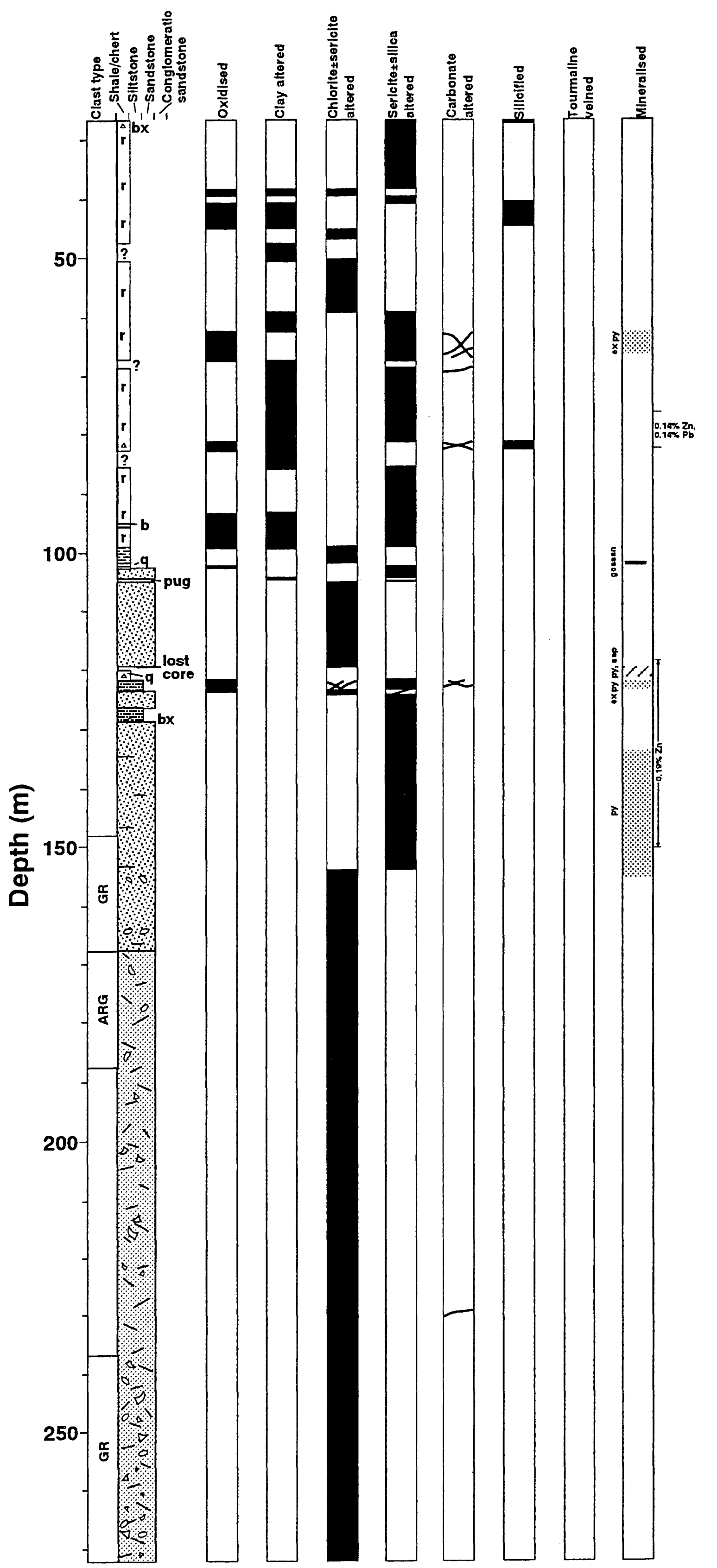


Figure 15. Graphic log of hole ACLD19, ACL prospect.

holes. Although sandstone and siltstone is generally featureless, in hole ACLD16, possible graded bedding at a depth of 45 m suggests an up hole (north) facing. Granite clasts are present toward the base of this unit in hole ACLD19, and argillite clasts are present in parts of this unit in holes ACLD13 and ACLD16. This unit corresponds to the "tuffaceous" sandstone at surface, and it hosts disseminated sphalerite, pyrite and Cu-oxide minerals.

In hole ACLD19, the sandstones and siltstones are overlain by spherulitic rhyolite. This unit is characterised by up to 50% 1-3 mm spherulites, but generally lacks phenocrysts.

Salt Creek deposit. Based on an existing cross section (Fig. 16) and on limited inspection of recent drilling (Fig. 17), the Salt Creek deposit is hosted by a 200 m thick sequence of pyritic sandstones and shales (Fig. 16; Barley, 1995). These rocks overlie deformed felsic ash-lapilli tuff, and underlie basaltic rocks of the Louden Volcanics.

In hole SCKD44 (Fig. 17), the unit that hosts the deposit consists of monotonous, massive to weakly bedded fine-grained sandstone and siltstone. Previous drilling indicates that the uppermost part of this unit is an argillite that may be up to 10 m thick (Fig. 16). The thickness of the host unit increases from less than 100 m some 400 m west to more than 200 m in the vicinity of the Salt Creek deposit. The thickness continues to increase to a fault 100-200 m to the east of the deposit.

A unit of felsic ash-lapilli tuff underlies the host sandstones. This unit is only ~100 m wide 1.2 km to the west of the deposit, but increases in apparent thickness ~300 m immediately south of the Salt Creek deposit (Fig. 12). Although this unit is broadly similar to the felsic ash-lapilli tuff to the south of the ACL prospect, it has a very strong cleavage and lacks argillite and granite clasts.

Hole SCKD44 (Fig. 17) did not intersect the basaltic rocks that overlie the deposit (Fig. 16), but a basaltic dike was intersected along the fault to the east of the deposit. The basalt is strongly fractured and intensely chlorite altered, with abundant 1-10 mm carbonate±quartz veinlets along fractures. It may be a feeder dike to the overlying basaltic rocks. To the east of the fault, hole SCKD44 intersected variably oxidised, foliated rhyolite that is only locally spherulitic.

Facing. Although regional relationships (Fig. 1) suggest a north facing sequence for the Salt Creek area, B. Eisenlohr (pers. comm., 1996; also Pilbara Mines NL Annual Report, 1995) has suggested that the ACL sequence faces south. However, the only facing evidence observed by the author in the ACL sequence suggests a north facing. More detailed studies are required to resolve this dilemma.

Correlation. Because of a lack of distinctive units, direct correlation of units is difficult, even between the Salt Creek and ACL deposits. However, correlation of the mineralised sandstone units is most likely. Barley (1995) has correlated the rocks that host the Salt Creek deposit with the Mons Cupri Volcanics as previously defined. Using the stratigraphy of H. Smithies (Fig. 2), the regional correlation would be with the lower part of the Cistern Formation. The ash-lapilli tuffs in the Salt Creek-ACL area have a similar composition to the matrix of conglomerates from the base of the Cistern Formation at Mons Cupri. Although not nearly as abundant as at Mons Cupri, these tuffs also contain granite and "argillite" clasts.

Mineralisation

The Salt Creek deposit contains an estimated resource of 0.65 Mt of 1.18% Cu, 3.53% Pb and 9.1% Zn (R. Butler, pers. comm., 1996) that is contained within two moderately east plunging lenses of massive sulphide (Fig. 18). Inspection the sulphide intersection in hole NUD11 indicates that the ore mineral assemblage is dominated by chalcopyrite, sphalerite, pyrite, galena and pyrrhotite. Significant quantities of magnetite are

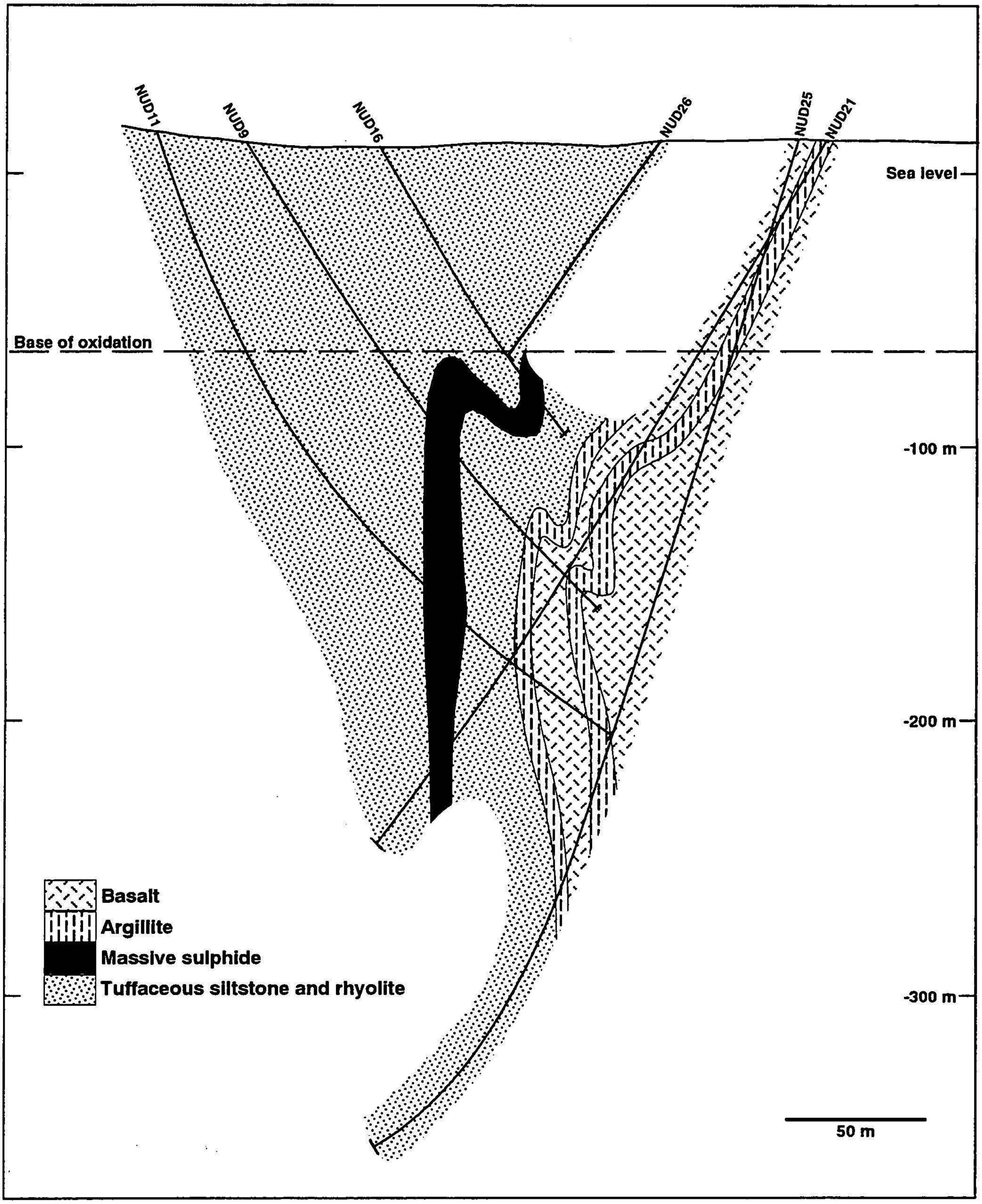


Figure 16. Cross section of the Salt Creek deposit (modified from an unpublished Texasgulf diagram).

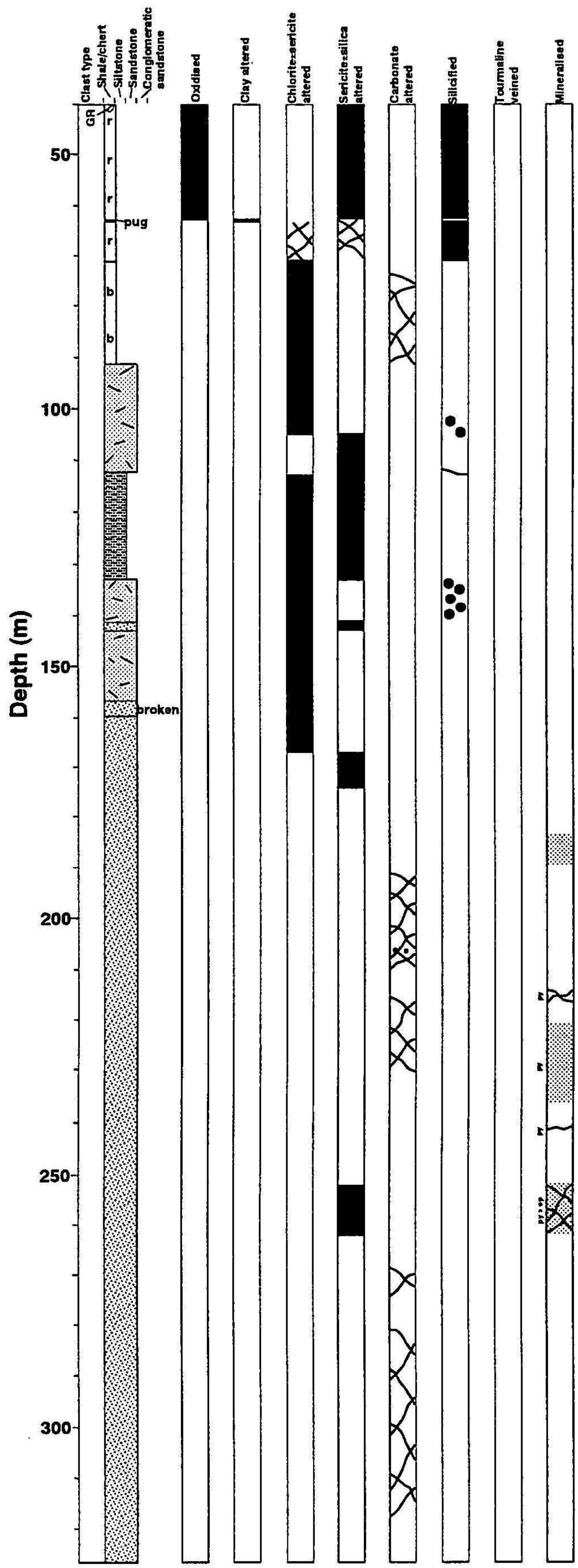


Figure 17. Graphic log of hole SCKD44, Salt Creek deposit.

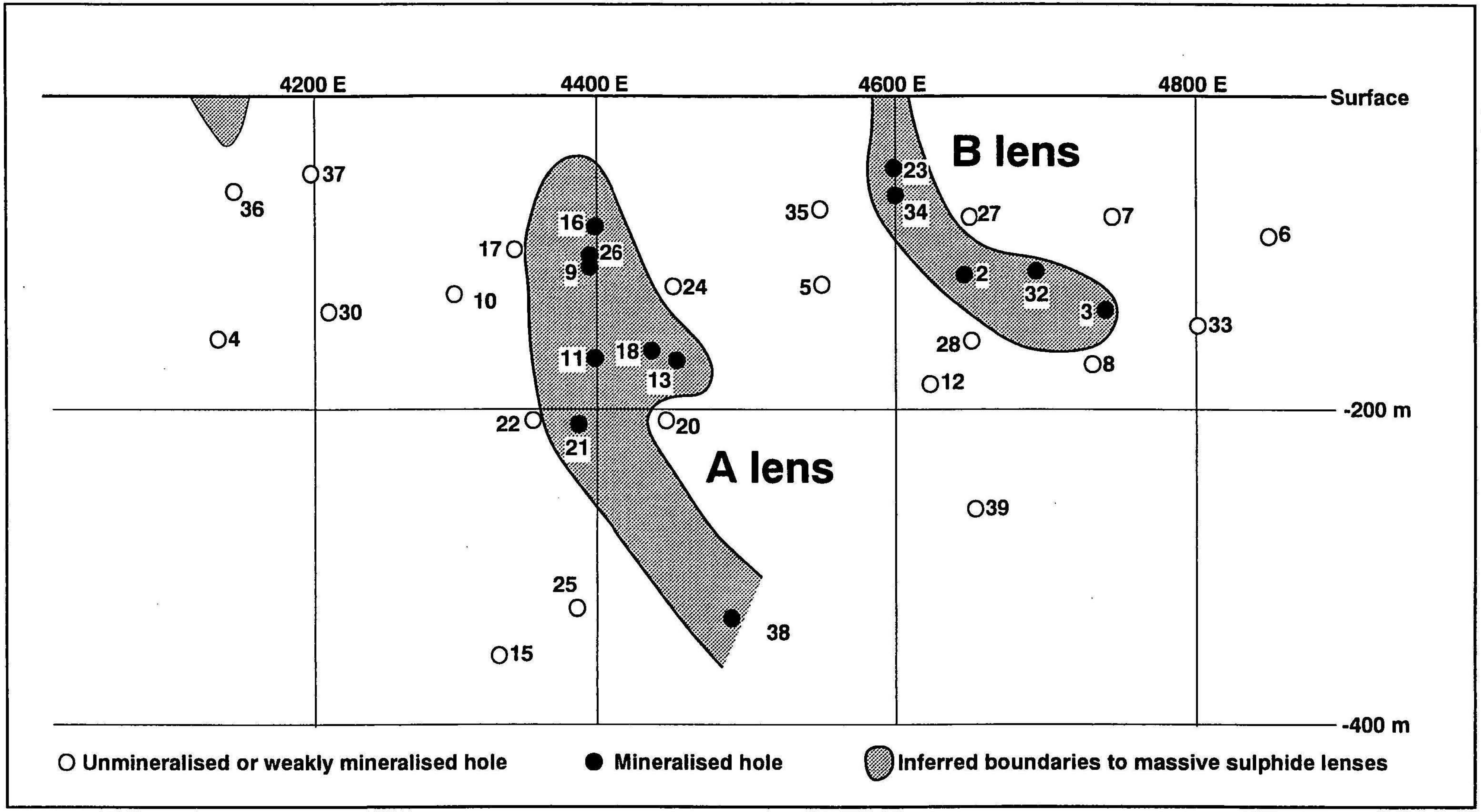


Figure 18. Long section of the Salt Creek deposit (courtesy Ray Butler).

also present in this intersection, but this may not be typical of the sulphide lenses as a whole. Chlorite, brown siderite and a second, white, carbonate mineral (calcite?) are the dominant gangue minerals. Minor quartz and feldspar also occur in late fibre veins. The ore and gangue minerals are generally fine-grained, with complex relationships between minerals. Sphalerite from this intersection is commonly reddish brown to purple in colour, which indicates a high iron content.

Mineralisation at the ACL prospect consists of disseminated and stringer-hosted yellow to honey sphalerite with lesser quantities of pyrite, galena, chalcopyrite and secondary copper oxides within sericite-altered sandstone. As a consequence, grades at ACL are much lower, with the best intersection being 2.7 m at 0.81% Cu, 1.30% Pb and 3.88% Zn. Some of the sphalerite is nodular and botryoidal. The mineralisation at ACL is not syngenetic, but probably formed below the seafloor as the consequence of fluids passing through a sandy aquifer.

Alteration

Rocks at both the Salt Creek deposit and the ACL prospect have been extensively chlorite±quartz and sericite±quartz altered. At Salt Creek, mineralisation is associated with chlorite- and carbonate-rich alteration assemblages (e.g. NUD11), whereas at ACL, mineralisation is associated with sericitic alteration assemblages (Figs. 13 to 15). In both areas, ash-lapilli tuff is generally weakly to moderaly chloritised, with shards being most susceptible to alteration. In contrast, the sandstone at ACL is generally sericitically altered, although some zones have been chloritised. Sericite-altered zones at ACL also contain carbonate veinlets.

Silicified zones are not common at ACL, but are developed in the rhyolite and ash-lapilli tuff in hole SCKD44 (Fig. 17). Rocks at the ACL prospect have also been tourmaline-altered and clay-"altered". Tourmaline at ACL invariably occurs in thin, <2 mm veinlets, some of which may be associated with sphalerite introduction (e.g. ACLD13-43.9 m). These tourmaline veinlets may be related to tourmaline veining in the Caines Well Granite Complex or to a late, tourmaline-bearing leucogranite that intrudes the Whim Creek Group (H. Smithies, pers. comm., 1997).

Clay "altered" zones at ACL consist mainly of intervals of core that have totally decomposed to white, clay powder. These intervals occur within both the spherulitic rhyolite and the sandstone unit, but are restricted to the upper 130 m of drill core (i.e. within 100 m of the surface). These intervals may be up to 30 m in length, with only scatterd, small (<10 cm) pieces of intact (commonly unoxidised) core remaining. These intervals are best interpreted as the result of extensive, recent leaching possibly related to the influx of seawater.

Controls on mineralisation in the Whim Creek group

The unit which hosts the Mons Cupri, Salt Creek and ACL prospects is the lower to central part of the Cistern Formation (using definition of H. Smithies). This stratigraphy, which corresponds to the Mons Cupri Volcanics of previous workers (e.g. Miller & Gair, 1975; Barley, 1987, 1995), is characterised a significant proportion of cuspate vitric ash and lapilli in a tuffaceous rock or as the matrix to a conglomeratic rock. These rocks also contain pebbles and cobbles of granite, volcanic rock and argillite, particularly at the Mons Cupri deposit. The Whim Creek deposit occurs in the overlying Rushall Slates.

The more significant mineral occurrences in the Whim Creek belt appear to be localised along syn-sedimentary structures. The Mons Cupri deposit is localised along the down thrown block of the Miller Fault. Changes in the thickness of the Cistern Formation across this fault suggest that it was a syn-volcanic fault. The Whim Creek deposit occurs in a graben between the Martin and Jaffrey Faults in a small inlier of Rushall Slate. The third significant deposit in the region, the Salt Creek deposit, occurs within a thickened zone of sandstone that could be interpreted as the down thrown block of a syn-sedimentary growth fault. The ACL prospect, which is the smallest VHMS prospect in the Whim Creek belt, is the only deposit that does not appear to be associated with syn-sedimentary faulting.

The above observations and inferences suggests that the most prospective unit of the Whim Creek belt is the lower to central Cistern Formation, particularly along zones of active syn-sedimentary faulting. Active, syn-volcanic faults have been recognised over the past two decades as important controls localising VHMS deposits in many districts (e.g. Noranda, Kerr & Gibson, 1993; Mount Windsor, Berry et al., 1992). These faults localise the mineralising fluids into local basins where VHMS deposits form.

An introduction to the geology of the Panorama VHMS district

Volcanic-hosted massive sulphide deposits of the Panorama district were initially discovered in volcanic rocks intruded by the Strelley granite in the central Pilbara 45 km west of Marble Bar (Fig. 19) by H. Wilhelmij in 1984. Since then significant resources have been defined at the Sulphur Springs deposit, Kangaroo Caves and Bernts prospects, and sulphide-bearing zones have been intersected at several smaller prospects in the belt (Morant, 1995). The author was introduced to this district by C. Brauhart, who is presently conducting a Ph.D. study on regional alteration in rocks underlying the VHMS deposits, and M. Doepel, who is the Managing Director of Sipa Resources Limited. The following summarises rock relationships described by Brauhart and Doepel, supplemented by observations of the author.

Stratigraphy

Figure 20 illustrates the general stratigraphic and intrusive relationships in the northern part of the Strelley domain as described by Carl Brauhart. The basal unit in this succession, which youngs from west to east, consists of turbiditic sandstones and shales. The Strelley Granite has intruded the contact between this unit and a volcanic sequence consisting largely of andesite and dacite in the north, and rhyolite and andesite to the south. Morant (1995) estimates the thickness of volcanic sequence to be up to 1.5 km.

In the northern part of the Strelley domain, the volcanic sequence consists of andesite overlain by dacite and rhyodacite. Brauhart has subdivided the andesite into two geochemical types: "felsic" andesite, which occurs at the contact with the intrusive Strelley Granite, and "normal" andesite, which comprises most of the volcanic sequence in the north. "Normal" andesite has a stratigraphic thickness of approximately 1 km, is massive to pillowed and is characterised by abundant, fine leucoxene in hand sample when moderately to strongly altered. Less altered samples can contain magnetite.

Approximately 500 m of dacite, which is characterised in the field by strong weathering, sparse, coarse leucoxene and coarser, elongate amygdales, overlies the andesite. J. McPhie (University of Tasmania) has observed peperitic textures along the upper contact of the dacite and interprets this unit as a sill intruded into wet, unconsolidated sediment. With the exception of Bernts, VHMS deposits in northern part of the Strelley domain occur near the top of the dacite; this may not be consistent with the dacite being a shallow intrusion.

The dacite is overlain by a sequence of silicified shales, siltstones and local sandstone that has been termed the "marker chert". Although generally less than 10 m in thickness, the marker chert is up to 100 m thick immediately above the Sulphur Springs deposit. Vearncombe (1995) has documented the existance of an olistostrome overlying the Sulphur

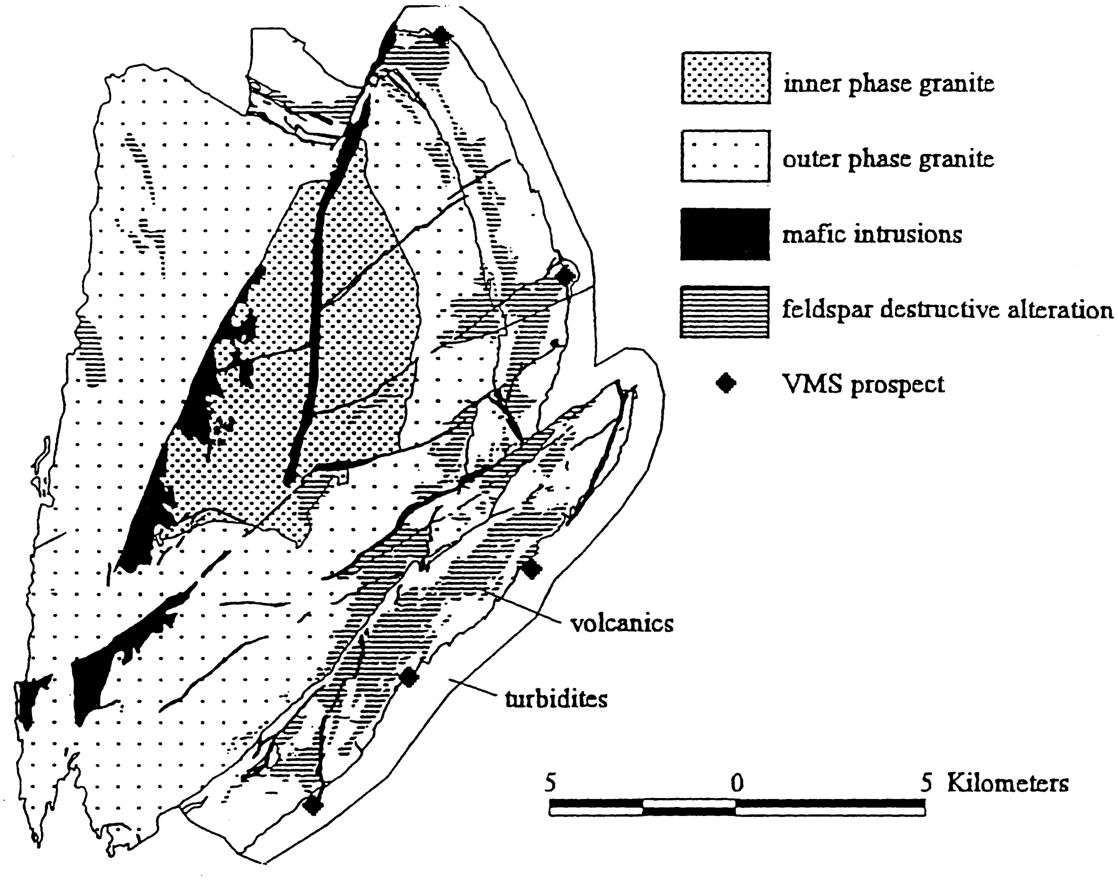


Figure 19. Geologic map of the Strelley Belt, central Pilbara (after Bruahart, 1997).

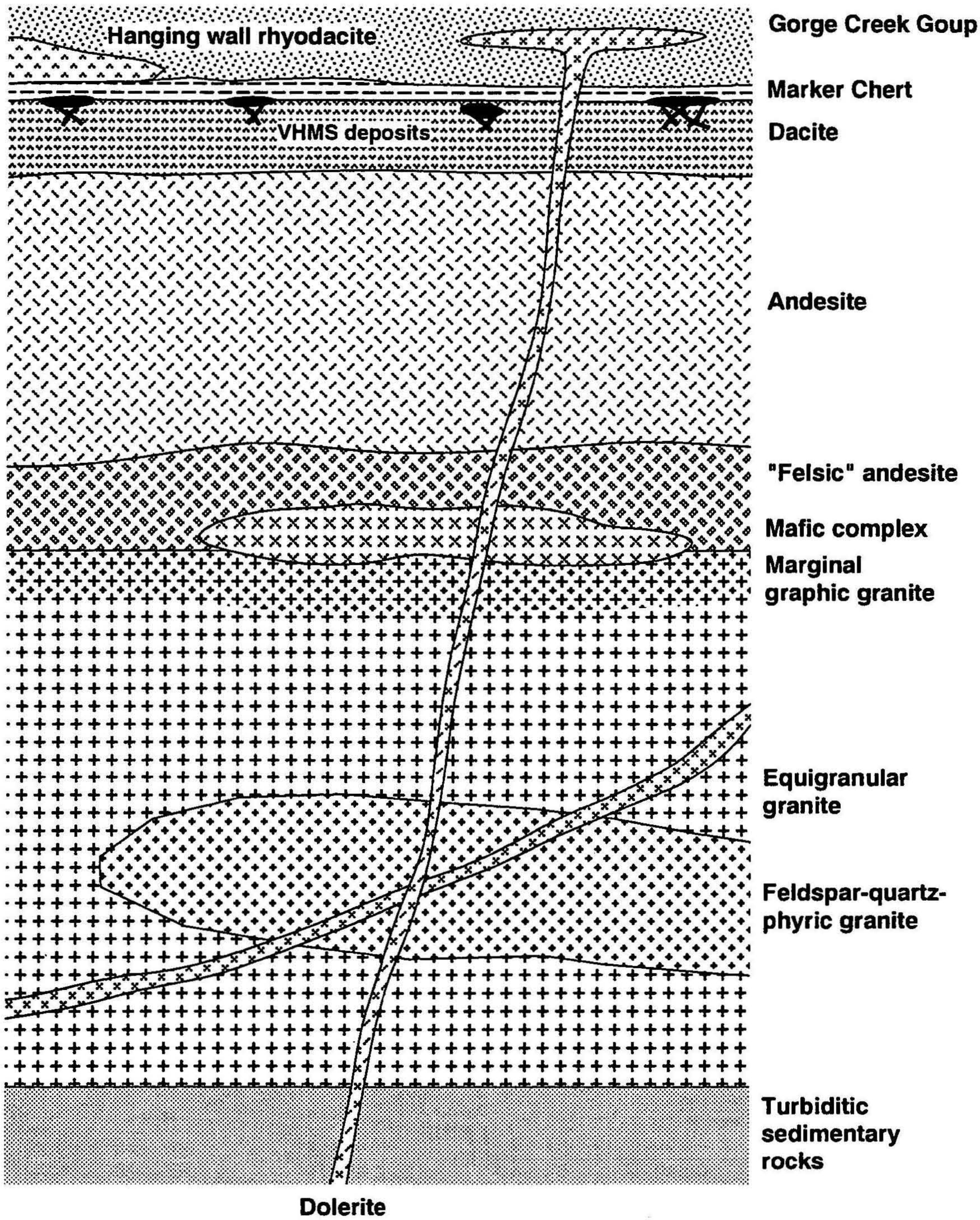


Figure 20. Stratigraphic and intrusive relationships between rock units in the Strelley Belt, central Pilbara (summarised from descriptions by C. Brauhart).

Springs deposit. A body of massive, domal feldspar-phyric rhyolite occurs in the hanging wall to the Kangaroo Caves deposit. This body, which is restricted to Kangaroo Caves, is calc-alkaline in composition, whereas the rest of the volcanics in the Strelley domain are tholeiitic in composition (Vearncombe & Kerrich, 1995).

The Strelley domain is overlain by shales, siltstones, sandstones and banded iron formation of the Gorge Creek Group. These rocks are extensively intruded by dolerite dikes, and are locally silicified.

Intrusive rocks

The Strelley Granite is a polyphase sill that intrudes the Strelley domain along the contact between the basal turbiditic sediments and the "felsic" andesite. In plan the Strelley Granite complex is 20 km long and up to 10 km wide (Fig. 19). As the Strelley domain dips moderately to the east, the true thickness of the Strelley Granite is probably of the order of 5 km.

Figure 20 shows schematically the relationship between different phases of this granite complex and the enclosing rocks. The Strelley Granite complex is comprised mainly of the early equigranular phase, which is generally medium- to coarse-grained, but becomes finer-grained and graphic toward the contact with the "felsic" andesite. The equigranular phase is intruded by a 5 km wide by 10 km long, slightly cross-cutting sill of quartz-feldspar-phyric leucogranite (Fig. 19). Both early granite phases are intruded by leucocratic microgranite. Microgranite is best developed as sills up to a few hundred metres wide in the outer phase, but occurs as dykes in both phases.

The contact between the early granite phase and the "felsic" andesite is commonly intruded by 100-200 m wide, discontinuous body of dolerite and diorite. Mafic dykes up to several hundred metres wide occupy faults within the Strelley Granite. These rocks also intrude the Gorge Creek Group as sills. A major composite dyke, which contains dolerite and dunite, occupies a fault that trends NNE through the granite complex.

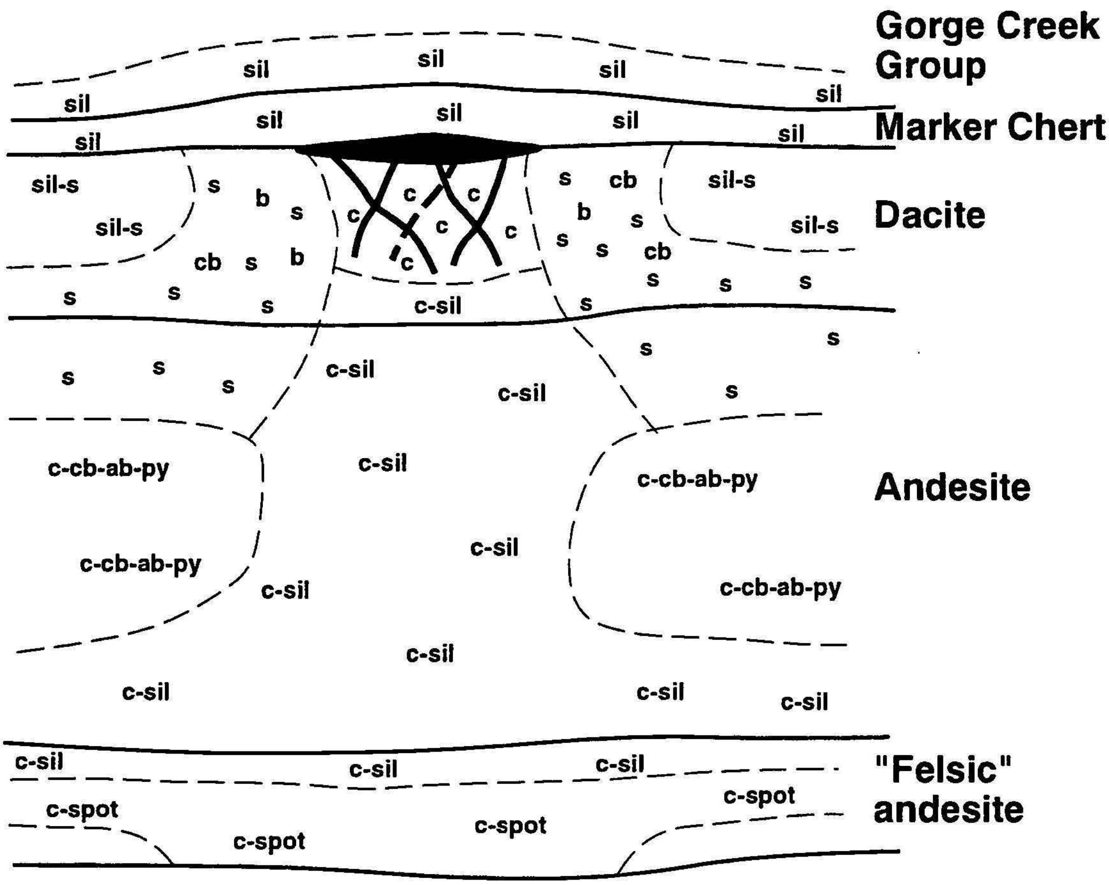
Regional alteration

The major aim of C. Brauhart's Ph.D study is to document the distribution and geochemistry of altered rocks in the Strelley granite and volcanic belt. At the time of the author's visit, Brauhart had mapped altered zones within the granite and the northern part of the volcanic belt. Figures 21 and 22 summarise Brauhart's observations of alteration in the volcanic rocks and granite, respectively.

Brauhart has recognised nine broad alteration assemblages. Two alteration assemblages, greissen and albite, are only present in the granite. The greissen assemblage, which contains fluorite and topaz, is present deep within the interior part of the equigranular granite, whereas albite-altered rocks only occur in graphic granite adjacent to the intrusive mafic complex (Fig. 22).

Both the marginal phase of the granite and the overlying volcanic rocks are altered to chlorite-carbonate-albite-pyrite, chlorite-silica and sericite-quartz±feldspar assemblages. The chlorite-carbonate-albite-pyrite assemblage, which Brauhart defines as the "background" alteration assemblage, occurs in the central part of the andesite away from vent zones (see below), and in the upper part of the granite.

The chlorite-silica alteration assemblage, which is characterised by albite destruction, occurs in broad, crosscutting, zones underlying VHMS deposits. This alteration facies may also be developed at the top of the equigranular phase of the granite, again underlying VHMS deposits. Brauhart has demonstrated that below the two major VHMS deposits in the district,



Assemblages in volcanic rocks

sil	**Silicifica flooding**
sil-s	**Silica-sericite**
c	**Chlorite**
c-spot	**Chlorite-spotting**

Assemblages in granites

ab	**Albite**
gr	**Greissen**

Assemblages in both volcanic rocks and granite

c-sil	**Chlorite-silica**
c-cb-ab-py	**Chlorite-carbonate-albite-pyrite**
s	**Sericite±feldspar**

Other alteration minerals

b	**Barite**
cb	**Carbonate**

Figure 21. Generalised relationships between alteration zones in the Strelley volcanic sequence (summarised from descriptions by C. Brauhart).

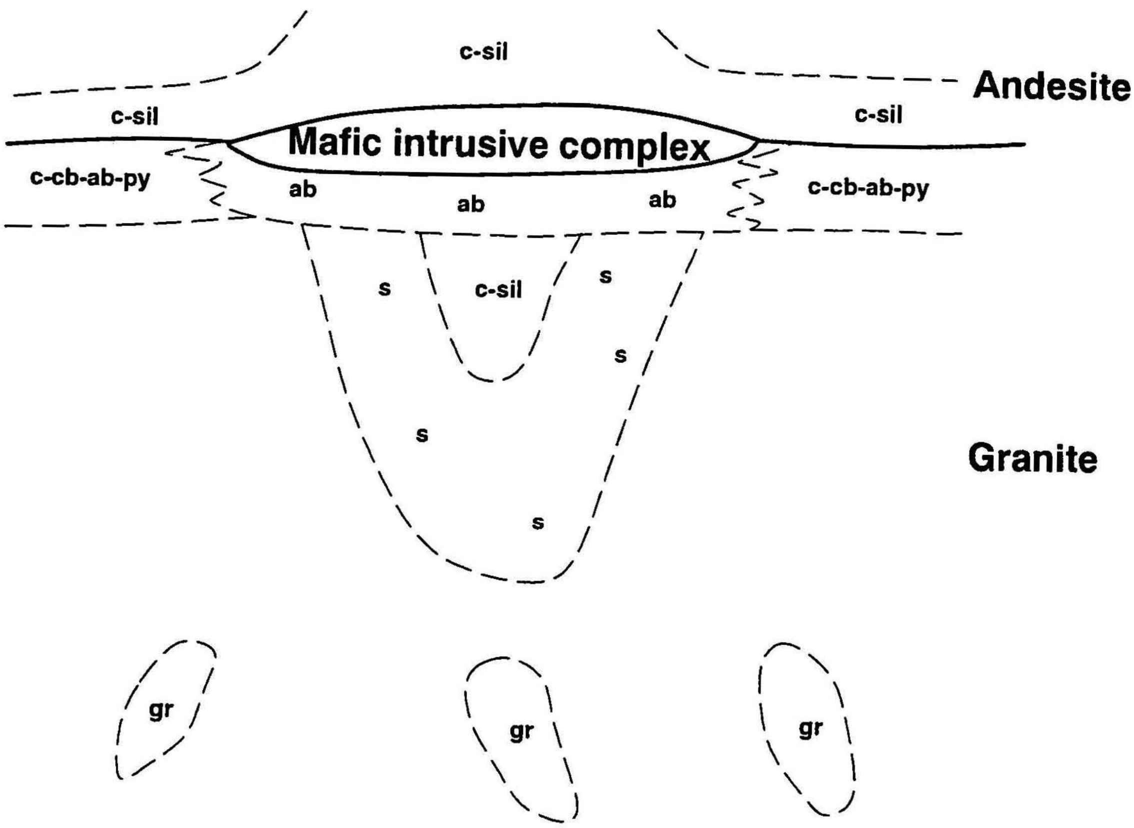


Figure 22. Generalised relationships between alteration zones in the Strelley Granite (summarised from descriptions by C. Brauhart).

chlorite-silica alteration zones extend from the base to the top of the andesite, and suggests that this characteristic can be used directly as an exploration guide. Within the granite, chlorite-silica alteration assemblages can form "carrot-shaped" zones that are surrounded by an outer sericite±feldspar alteration assemblage (Fig. 22).

Sericite-quartz±feldspar alteration zones occur not only in the granite, but also in the dacite and the andesite. Within the dacite, the sericite±feldspar zone occurs lateral to stringer zones associated with VHMS deposits. These zones also commonly contain barite and carbonate veins close to the deposits. The sericite±feldspar assemblage also occurs along the upper margin of the andesite (Fig. 21), and the selvedges to Cu-bearing veins in the granite are also characterised by a sericite±feldspar alteration assemblage.

Brauhart has recognised four alteration assemblages that are restricted to the volcanics and the overlying sediments: chlorite-dominant, chlorite spotting, feldspar-silica-sericite and silica flooding. Chlorite-dominant alteration is restricted to stringer zones in the immediate footwall of the VHMS deposits. Silica flooding affects the marker chert and hanging wall sediments above VHMS deposits. Chlorite spotting is restricted to the central part of the "felsic" andesite. This alteration type is characterised by 1-5 mm chlorite spots. Finally, feldspar-sericite-silica alteration assemblages, which are considered to be "least altered" by Brauhart, form a zone in the dacite lateral to the sericite±feldspar zone.

Mineralisation

To date three significant VHMS deposits and a number of other minor occurrences have been discovered in the Panorama district. Sulphur Springs, which is the most significant deposit, has resources of 5.3 Mt at 6.2% Zn, 0.3% Pb, 2.2% Cu and 26 g/t Ag. The Kangaroo Caves deposit has a resource of 1.7 Mt at 9.8% Zn, 0.6% Pb, 0.6% Cu and 18 g/t Ag, whereas the Bernts prospect has a resource of 0.6 Mt at 7.8% Zn, 1.7% Pb, 0.3% Cu and 69 g/t Ag (Sipa Resources Limited anouncement to ASX, March 1997). Other minor prospects include Breakers,, Man O'War, Anomaly 45, Jamesons and Roadmaster (Morant, 1995).

The Sulphur Springs deposit crops out at surface as a well developed gossan. The gossan consists of a ferruginous gossan that is developed stratigraphically below and lateral to siliceous gossan with anomalous Pb, Ag, Sn and Bi. The ferruginous gossan is after Fe-rich massive sulphide, whereas the siliceous gossan is after Zn-rich massive sulphide (M. Doepel, pers. comm., 1996). At depth, two stratigraphically distinct lenses are present (Fig. 23). The lower lens occurs along the contact between the dacite and the Marker Chert, whereas the upper lens, which is less extensive, occurs within the Marker Chert (Morant, 1995). Examination of drill core indicates that most of the ore formed by replacement, however other textures such as graded bedding and hydrothermal banding may indicate the presence of exhalative mineralisation. The ores are characterised by low-iron sphalerite, and barite is present. Vearncombe (1995) has described ore textures in detail and has compared them to modern black smokers. The textures in the Sulphur Springs and Kangaro Caves deposits are among the best preserved in Australian VHMS deposits.

The gossan at Kangaroo Caves is poorly developed relative to Sulphur Springs. At depth, massive sulphide mineralisation occurs mainly within the Marker Chert (Fig. 24). Sediments onlap onto this surface, suggesting that the ore lens dipped at a shallow angle when the sediments were laid down.

During the 1995 field season, Brauhart discovered a number of narrow (<1 m) cupriferous veins in the upper part of the Strelley Granite. At surface these veins, which are oriented roughly orthogonal to the upper granite contact, consist of secondary copper carbonates and quartz. Sipa-Outokumpu drilled a hole below one of these veins at depth and intersected a narrow (<1 m wide) vein containing chalcopyrite, sphalerite, pyrite, and quartz,

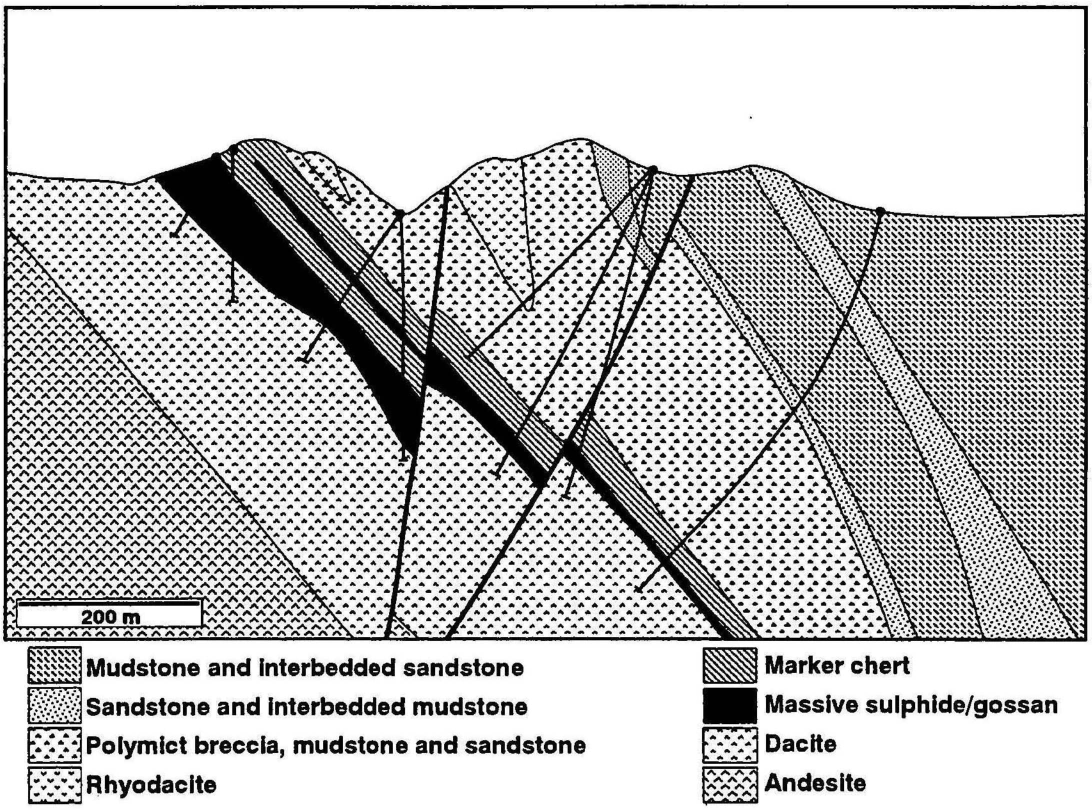


Figure 23. Geological cross section of Sulphur Springs (modified after Morant, 1995).

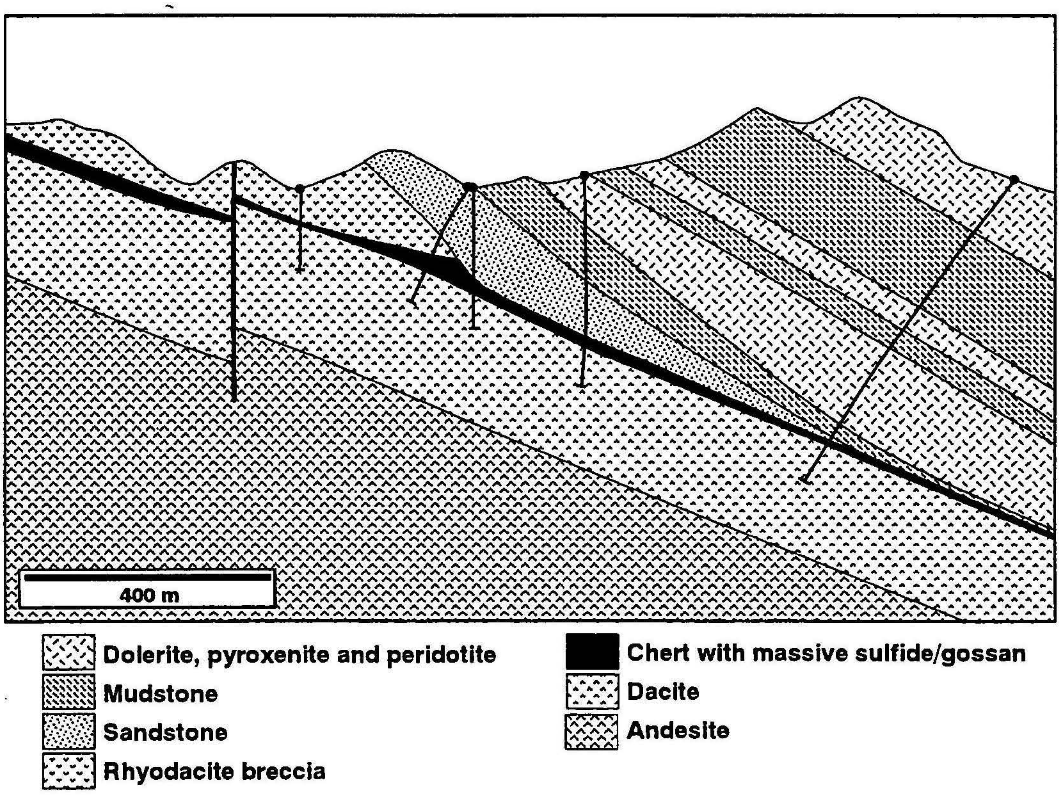


Figure 24. Geological cross section of Kangaroo Caves (modified after Morant, 1995).

with minor to trace galena, arsenopyrite, native bismuth, tetrahedrite and cassiterite (C. Brauhart, pers. comm., 1996). These veins are surrounded by interior sericite-dominant and an exterior chlorite-dominant alteration zones.

Questions on the genesis of VHMS deposits in the Strelley district

Because of excellent exposure, low intensity deformation and metamorphism, and the detail of existing geological information, the Panorama district is one of the best places in the world to test hypotheses of VHMS ore genesis. The Panorama district is one of the very few VHMS districts in the world where a temporal and genetic link has been established between ore formation and a subvolcanic granite complex (Brauhart, 1997).

Like many other subvolcanic intrusions in VHMS districts (e.g. Flavrian Complex, Noranda district, Goldie, 1979; Beidelmen Bay Complex, Mattabi district, Franklin et al., 1981; Sneath Lake Complex, Snow Lake district, Galley et al., 1990), the Strelley Granite is grossly sill-like and polyphase. The equigranular phase of Strelley granite is chloritically altered along its graphic margin and sericitically and chloritically altered internally. In contrast, the younger feldspar-quartz-phyric phase is virtually unaltered. This relationship suggests that the equigranular phase underwent significant hydrothermal alteration after intrusion, whereas the feldspar-quartz-phyric phase did not. Consequently, fluids responsible for altering the equigranular phase and possibly the overlying volcanic rocks. were probably driven by heat generated by the intrusion of the feldspar-quartz-phyric phase of the Strelley Granite.

Arching of the Strelley domain and intrustion of the Strelley Granite. The overlying volcanic rocks form an arch above the Strelley Granite. As the rocks that underlie the granite do not show a similar broad folding pattern (Fig. 19), the arching of the volcanic rocks may have resulted from granite intrusion. Arching associated with granite intrusion would result in the development of tensional faults and fractures, and possibly the development of local graben structures. These structures would facilitate the passage of ore fluids and allow the focussing fluids along faults into upflow zones beneath VHMS deposits. Intrusion of multiple granite phases would have enhanced the development of tensional structures. The olistostrome that overlies the Sulphur Springs deposit (Vearncombe, in press) may have been triggered by slope instability associated with this arching, and the onlapping of sedimentary rocks onto the Kangaroo Caves deposit (Fig. 24) may be associated with the inferred arching.

Constraints on metal budgets. An aspect of mineral systems that is generally neglected in economic geology studies is the metal budget. The total metal content of a mineral deposit is critically dependent on the amount of metal that can be extracted from country rocks and/or magmas. For zinc, which is probably leached from country rock (Franklin et al., 1981; Ohmoto et al., 1983; Huston et al., 1995), the amount of metal available to form a mineral deposit depends on: (1) the concentration of zinc in the country rock, (2) the efficiency with which zinc is leached, and (3) the size of the hydrothermal cell. Deposition of the ~0.4 Mt of zinc present in the Sulphur Springs deposit requires approximately 3 km^3 of country rock if 50 ppm is leached from the rock. C. Brauhart's alteration mapping and geochemical studies will be provide constraints on metal budgets in the Panorama district that could have universal implications not only to VHMS deposits, but other classes of base metal deposits.

The possibility of magmatic-hydrothermal copper introduction. Although ore metals in VHMS deposits have traditionally been thought to be derived by leaching of wall rocks (e.g. Franklin et al., 1981; Ohmoto et al., 1983), recent geological and geochemical arguments (Huston et al., 1995; Large et al., 1996) have supported the alternative hypothesis (e.g. Urabe & Sato, 1978) that copper in some deposits is derived from magmatic-hydrothermal fluids. The excellent preservation and exposure of the Panorama district allow for critical evaluation of this hypothesis.

Mapping by Brauhart (1997) suggests that the copper-rich Sulphur Springs deposit occurs at the closest approach of the feldspar-quartz-phyric phase of the Strelley granite to the Panorama ore horizon. Greissen zones and copper-bearing veins occur within the equigranular phase of the granite. These observations suggest that magmatic-hydrothermal fluids may have been part of VHMS hydrothermal systems in the Panorama district. Studies by Brauhart of fluid inclusions, stable isotopes and S/Se ratios in alteration zones within the Strelley Granite and Strelley domain volcanics potentially could determine the importance of magmatic-hydrothermal fluids in copper-bearing VHMS deposits.

The Lynas Find deposits

The Lynas Find district, which occurs in the Pilgangoora Syncline some 75 km west of Marble Bar, contains six small gold deposits (Main Hill, Breccia Hill, Iron Stirrup, Old Faithful, McPhees and Zakanakas) and several prospects (Fig. 25). Historic production from this district totals 37.9 kg (Hickman, 1983). In March 1995, Lynas Gold NL commenced open cut mining operations at the Breccia Hill deposit; since then mining has commenced at the Main Hill and Iron Stirrup deposits. When the author visited the operations, operations at the Iron Stirrup deposit were well advanced, and reserves at the Breccia Hill and Main Hill deposits had been exhausted. Up to June 1996, 52,200 ounces (1.68 tonnes) had been produced, and a total resource of 3.652 Mt at 2.03 g/t (7.41 t) had been established (Lynas Gold NL Annual Report, 1996). Total production and resources total approximately 0.29 million ounces.

Two types of ore lenses occur in the Lynas Find district: (1) BIF-hosted lenses (e.g. Breccia Hill and Main Hill), and (2) ultramafic/basalt-hosted lenses (e.g. Iron Stirrup, Old Faithful, McPhees and Zakanakas). The banded iron formation-hosted deposits were the subject of a doctoral study by Neumayr (1993), who found that gold mineralisation at Breccia Hill and Main Hill is controlled by competency contrasts between the host BIF and enclosing quartzite. The gold occurs in quartz breccias with a sulphide matrix or in the wallrock adjacent to quartz-biotite±amphibole±diopside veins. Other ore minerals include pyrrhotite, arsenopyrite, löllingite ($FeAs_2$) and minor chalcopyrite (Neumayr, 1993; Neumayr et al., 1993).

The largest ultramafic/basalt-hosted lens is the Iron Stirrup deposit, which had a pre-mining resource of 1.758 Mt at 2.07 g/t Au (Lynas Gold NL Annual Report, 1996). The author was shown this deposit by Adrian Barnett; the following description is based on that trip and brief descriptions in Lynas Gold NL annual reports. The Iron Stirrup deposit occurs within a shear zone that dips 70° to the west. The structural hanging wall to this shear consists of massive to jointed serpentinite, which is interpreted as altered basalt. The ore lens occurs within the shear zone; it is 5-25 m thick and carbonate-rich. In addition to gold, ore minerals include pyrite, pyrrhotite, pentlandite and other nickel sulphide minerals. The footwall to the shear consists of biotite-talc±carbonate schist that contain more pyrite, but less nickel sulphide than the ore. Head grades from the Iron Stirrup deposit are 2.0-2.5 g/t; and 93-94% of the gold is recovered. Sulphidic ore must be oxidised for gold extraction.

The Old Faithful deposit, which was shown to the author by Gerry Brennan, occurs along the same structure as the Iron Stirrup deposit, also within talc-carbonate rocks. Two ore zones are present: zone A, which has low grade but a larger tonnage, and zone B, which has higher grade but low tonnage. A total resource of 0.933 Mt at 1.6 g/t Au has been estimated for the Old Faithful deposit (Lynas Gold NL Annual Report, 1996).

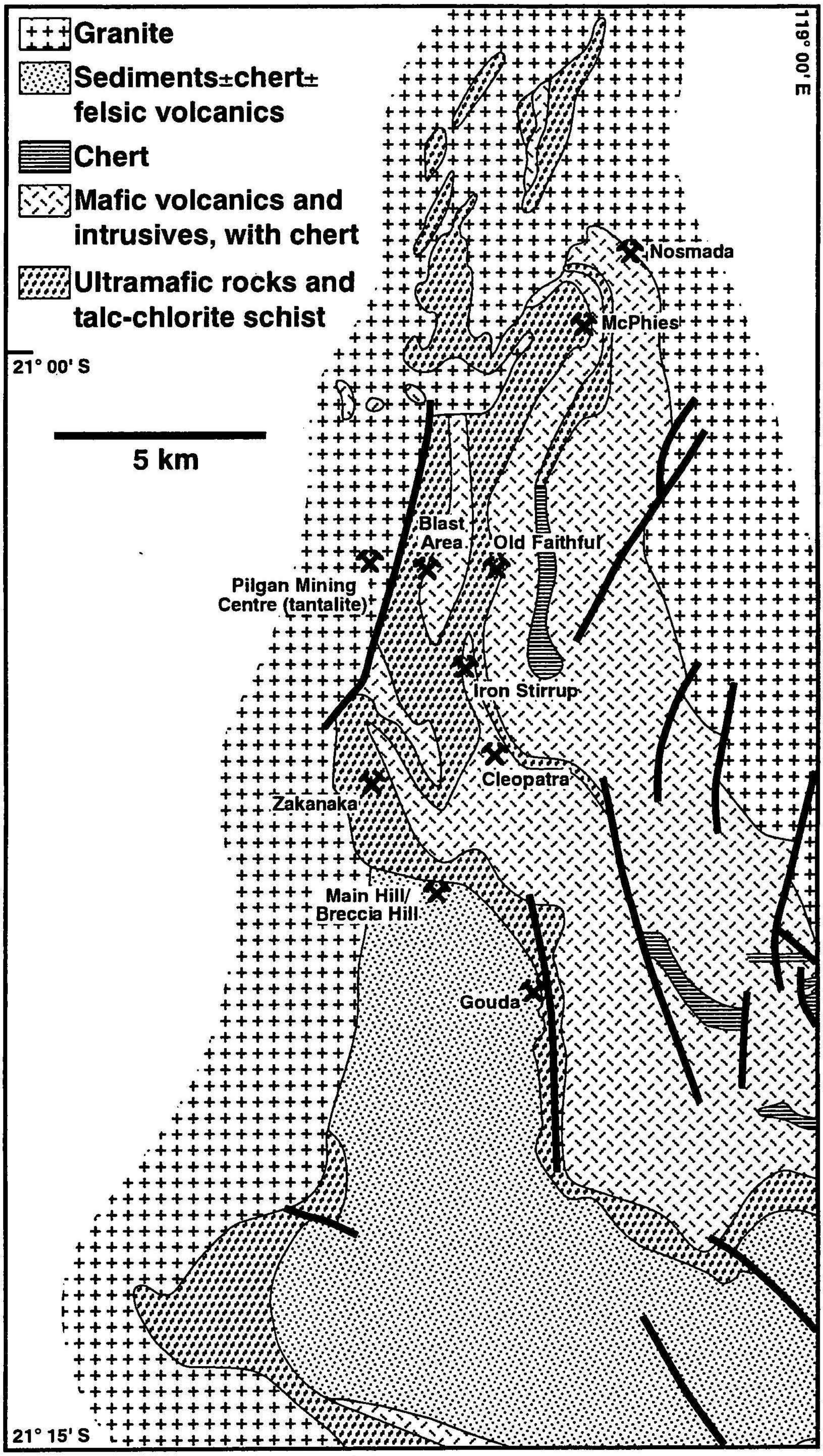


Figure 25. Geology of the Pilgangoora syncline showing the location of gold deposits and prospects in the Lynas Find district (modified after Lynas Gold NL Annual Report, 1996).

Proposed field program for 1997

The purpose of 1996 field work was to aquaint the author with the geology of the North Pilbara and to define potential economic geology projects for the 1997 field season.

The primary aim of the 1997 field program is to largely complete studies of VHMS deposits in the west and central Pilbara. In combination with the results from ongoing UWA studies of the Panorama district, this research program is intended to resolve the following questions relavant to VHMS deposits in the North Pilbara:

- Did the orebodies form from subseafloor replacement or exhalation?
- How extensive is regional alteration, what are the most efficient means for recognising alteration, and can alteration assemblages be used as a guide to exploration?
- What is the role of sub-volcanic intrusions in ore formation?
- Are the various geochemical indicators of prospectivity (e.g. trace element signatures, Lesher et al., 1986; quartz phenocryst $\delta^{18}O$, Huston et al., 1996) valid in the North Pilbara?
- Can mass balance considerations be used to assess the prospectivity of VHMS districts? and
- Are there craton-scale metallgenic controls (e.g. age, tectonic setting, etc) on VHMS mineralisation in the North Pilbara?

Table 1 indicates university research programmes in the Pilbara to which AGSO is providing supervision, chemical analyses, isotopic analyses and/or PIMA analyses. Detailed programs for 1997 UWA Honours research projects are appended.

It is essential that this economic geology research program be supported by specialist volcanic architecture and structural studies over the next two field seasons. Volcanic architecture studies are essential in understanding VHMS districts as they can define syn-volcanic faults which localise ore, determine the location of volcanic centres and water depths, and determine favourable stratigraphic positions.

Structural studies are essential to establish controls on shear-hosted gold deposits, both on a cratonic scale and on the local scale. Structures that host gold mineralisation in the North Pilbara Craton appear to be different to those in the Yilgarn Craton. In the Yilgarn, gold mineralisation is localised on second or third order structures related to crustal-scale shear zones (Groves et al., 1995). In the Pilbara, gold deposits are not associated with crustal-scale shears, but with arcuate shear zones in greenstone belts near the margins of diapiric granitoid intrusions.

Acknowledgments

Dominion Mining, Straits Resources, Ray Butler, Pilbara Mines, Sipa Resources, CRA Exploration and Lynas Gold are thanked for allowing access to confidential data, drill core and exploration properties. The author was shown around the various deposits by C. Brauhart, M. Doepel, B. Davis and A. Barnett and G. Brennan. Many of the descriptions herein summarise observations made to the author by these individuals. Hugh Smithies is thanked for an excellent introduction to the geology of the Whim Creek Group which placed much of the core logging and alteration mapping by the author in context. A. Glikson, H. Smithies, C. Brauhart and P. Morant made numerous comments which substantially inproved the observations and discussions presented herein.

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Appendix—Research proposals for B. Sc. Honours theses

PROPOSED FOOTWALL HONOURS THESIS

STUDY: Geochemical variations in the Sulphur Springs footwall dacite and their potential as vectors to ore in fresh and weathered rock.

STUDENT: Carl Young

AIMS: 1. To document alteration facies in the Sulphur Springs footwall dacite using fresh exposure from drill core.
2. Relate petrological variations to variations in lithogeochemistry in an attempt to develop local vectors to ore.
3. Identify any elements that are mobile in the alteration environment but immobile in the weathering environment in an attempt to document silicate alteration in weathered rock.

METHODS: 1. Review of the current geochemical database in conjunction with logging relevant drill core at Sulphur Springs.
2. Surface sampling in conjunction with a review of the footwall mapping to date. There is only limited scope for additional footwall alteration mapping of the dacite but a map to place the samples in context should be produced.
3. Petrological studies including microprobe work
4. Additional geochemistry to refine local vectors to ore in fresh rock and apply the relevant vectors to weathered surface samples

RELEVANCE TO EXPLORATION: The successful completion of this study will greatly improve our understanding of which elements are mobile in the local alteration environment and provide geochemical "local vectors to ore". Silicate altertion halos are likely to be larger and more robust than base metal halos and as such a better appreciation of their expression in the local environment will go a long way to targeting drill holes within discharge zones. Its possible application to weathered rocks would provide a cheap means of targeting drill holes based on surface sampling.

PROPOSED HANGING WALL HONOURS THESIS

STUDY: Paleosea-floor conditions during and immediately after VMS mineralisation at Sulphur Springs and associated hanging wall alteration.

STUDENT: Richard Hill

AIMS: 1. Document the sedimentology, syn-sedimentary structures and associated alteration in the hanging wall of the Sulphur Springs resource.
2. Reconstruct the paleosea-floor conditions at, and immediately after the time of mineralisation.
3. Isolate those parameters which have potential as local vectors to ore.

METHODS: 1. Detailed mapping of the marker chert, sedimentary breccia, and other hanging wall units above and beyond the limits of the Sulphur Springs Discharge Zone.
2. Logging relevant drill core
3. Petrology , geochemistry and possible oxygen isotope work
4. Review of work by Vearncombe, Archibald and others.

RELEVANCE TO EXPLORATION: The study outlined above has the potential to improve our understanding of the environment of VMS mineralisation at Sulphur Springs and place hanging wall alteration in the context of this environment. If this can be achieved, hanging wall vectors to ore applicable to Sulphur Springs and other prospects, can be developed. Variations in the petrology and geochemistry of the Marker Chert, iron-manganese formations and siltstones provide potential vectors to ore. Documenting faults that were active at the time of mineralisation may also help locate the ore forming environment. A thorough review of the previous work on the Sulphur Springs hanging wall will be a useful starting point for the project and will make these results easily accessible for other workers on the project.

. July 1996

Professor David Groves
Department of Geology and Geophysics
University of Western Australia
Nedlands, WA 6009

Dear David,

Following our discussions about a potential Honours project on the Lynas Find deposits, I have had more discussions with Taff Davies, who indicates that they are mainly interested in defining a suite of "gold-related" elements (e.g. Se, Tl, Ga, Cu, Pb, Zn, Ni) that could be used during exploration of adjacent ground. Using this as a basis, I would like to see a thesis covering the following topics:

(1) Alteration, lithological and structural mapping of the McPhies and/or Old Faithful prospects at a scale of 1:1000 or 1:2000. This would then be comparable to Peter Neumayr's mapping at Mount York.

(2) Collection of surface and RAB samples for thin section (both transmitted and reflected) and chemical analysis to define any gold pathfinder elements.

(3) PIMA analysis of powdered samples to determine zonation in alteration mineralogy and to test the applicability of the PIMA to exploration.

(4) Dating of the mineralization using galena and/or hydrothermal zircon.

AGSO could offer the following logistical support to the student: (1) analysis of up to 100 samples for "gold related" elements (these analyses must be released to the public as part of AGSO data bases, but a moratorium on their release can be arranged), and (2) access to the PIMA (in Canberra) for the analysis of powders. In addition, I can offer assistance in directing the student's research, but probably not as a main supervisor. My discussion with Taff indicate that Lynas Gold may be able to provide logistical support (airfares and accomadation), but this has to be confirmed. This project has the potential of being quite a nice honours thesis for the right student.

Regards,

David Huston
Pilbara Project