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ALAN E MARSHALL[1]

[1]*Qestore, 21 Viewway, Nedlands, Western Australia 6009*
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Department of Industry, Science & Resources

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SUMMARY

A variety of siliceous vein deposits with the characteristics of low temperature-low pressure hydrothermal deposits ('epithermal veins' of Lindgren, 1933) occur across the Palaeo- to Mesoarcheaen granite-greenstone terranes of the North Pilbara Craton and flanking volcanics and sediments of the overlying Neoarchaean to Palaeoproterozoic Hamersley Basin. These deposits are, by and large, poorly documented, and this record provides an overview of occurrences, distribution and mineral potential drawn largely from Department of Minerals and Energy of Western Australia WAMEX Open File statutory company exploration reports and from proprietary files of various companies.

Although epithermal vein deposits with economically significant mineral resources of Au, Ag and base metals are mostly of Cainozoic age, they have been found recently in Precambrian rocks where prospective high-level and largely sub-aerial volcanic terranes have been preserved. In this context, the Pilbara region, with a combination of well exposed bedrock and substantial areas of 'greenstones' at low metamorphic grade is an appropriate starting point for investigating the mineral potential of these deposits in Australian Precambrian sequences.

In the West Pilbara granite-greenstone terrane, the only two documented occurrences of low temperature-low pressure vein deposits, Elizabeth Hill Ag and Sullam Ni, are very different. Elizabeth Hill, a small, very high-grade Ag deposit, is within a quartz carbonate vein system which cross-cuts the base of the ca 2.93 Ga layered mafic ultramafic Munni Munni intrusion, which also hosts sub-economic PGE and Cu-Ni deposits). Structures, textures and alteration assemblages of the Elizabeth Hill vein system are consistent with an epithermal deposit. The mineral assemblage at Elizabeth Hill is quite unusual: native metals (Ag and PGEs) and exotic sulphides and sulphosalts (including Ni-, Co-, Cu-, Pb-, Zn-, As- and Sb-bearing minerals) are associated with pyrite, chalcopyrite, galena and sphalerite. At the Sullam deposit a pyritic chalcedonic vein system in ca 3.12 Ga basalt with sub-economic Ni in bravoite and millerite, has textures, structure and alteration assemblages typical of vein mineralisation of the Buchanan (1981) low sulphidation model for epithermal deposits.

Both Sullam and Elizabeth Hill are on prominent northerly trending faults and district geological relationships indicate the faulting probably occurred during the earliest stage of rifting of the North Pilbara granite-greenstone terrane and deposition of the oldest parts of the Hamersley Basin between 2.9 and 2.7 Ga.

Further to the east, on the margin of the Mallina Basin, and within 25 km of the historic Whim Creek and Mons Cupri Cu deposits, there are three well defined Au base metal epithermal prospects, Sams Ridge, Morning After South, and Stone Well East, and at least fifteen other small but similar prospects. Although the siliceous deposits may reflect several episodes of Au-base metal mineralisation, there are common themes: a simple base metal sulphide suite (Pb, Zn, Cu and Sb), and textures, structures and alteration characteristics of different levels of low sulphidation epithermal vein systems. Exploration as reported is inconclusive as very few programs reach the drilling stage.

The East Pilbara granite-greenstone terrane, some 50% of the area considered here, has only two well documented high level-low temperature vein deposits, Miralga Creek Au-Ag-Zn-Pb-Cu (Groves, 1987) and Meentheena fluorite (Hickman, 1974). This imbalance may be an artifact of 1970s/1980s company exploration focus rather than geology.

The Miralga Creek prospect is hosted in a high level felsic intrusive system consisting of a porphyry stock and dyke swarm that were emplaced into ca 3.5-3.4 Ga Warrawoona Group basalts and sediments on the eastern flank of the North Pole Dome. The sub-economic Au and base metal mineralisation has been interpreted (Groves, 1987, Goellnicht et al. 1988) as a poorly mineralised felsic porphyry overprinted by later, near surface, vein and breccia epithermal mineralisation.

In three areas of well exposed greenstones around Marble Bar, the North Pole Dome, the McPhee Dome and the Kelly Belt, there are Au and base metal deposits where descriptions, although ambiguous, are suggestive of a high level low temperature hydrothermal origin. Several of the Cu deposits have been interpreted (Marston 1979, Barley 1982, Witt et al. 1998) as primitive Archaean porphyry Cu systems with similarities with Miralga Creek. While the epithermal veins of Miralga Creek are products of a low sulphidation system, elsewhere in the other Warrawoona Group calc-alkaline centres, geology is permissive for high sulphidation deposits. Occurrences of cinnabar and rocks with anomalous Hg in both the ca 3.4-3.5 Ga Warrawoona Group rocks and younger occurrences in Fortescue Group volcanics are further indication that deposits of high level volcanic/sub-volcanic systems are preserved in areas of the East Pilbara granite-greenstone terrane.

The Meentheena fluorite deposits, which also contain quartz and minor Cu and Pb minerals, occurs in a large (4 km^2) conjugate vein set in basalts of the lowermost Fortescue Group. The fluorite deposits are most likely related to regional north trending faults.

Along the eastern margin of the Pilbara Craton, the Gregory Range Inlier has the most extensive low temperature-low pressure vein systems in the Pilbara region. The Gregory Range Inlier is a highly faulted complex of Neoarchaean basalt, sediment, felsic volcanics, high level felsic intrusives, and granitoids (Gregory Granitoid Complex) between the Paterson Orogen and the East Pilbara granite-greenstone terrane. Major contacts within the inlier are NNW trending faults, and the boundaries of these tectonic slices, as recognised by Trendall (1991), are also the boundaries of three distinct low temperature vein systems.

An extensive vein system, which includes Ag-base metal vein deposits of the Braeside lead field, is present on the western flank of the Gregory Range Inler, between the Antiform and Barramine Faults. Host rocks to the veins include basalt and sediments of the lower Fortescue Group, and the deposits are localised within short sections of regional NNW trending faults. Vein mineralogy, textures and structures are consistent with the lower base metal zone of the Buchanan (1981) model.

East of Barramine Fault and west of Camel Hump Fault, the Koongaling vein system, which is hosted in felsic volcanics and granophyres of the Gregory Granitoid Complex, are similar to the Fortescue veins. The veins contain chalcedony, cryptocrystalline quartz, amethyst and carbonate only, but no significant precious or base metal mineralisation has been found in the Koongaling veins. Mineralogy, alteration and vein textures suggest Koongaling is similar to the Braeside veins but may represent a higher level in the Buchanan (1981) low sulphidation model.

The third regional vein system, which is present east of the Camel Hump Fault, has no obvious affinities with the other two except emplacement along generally north trending structures. These veins are siliceous hematitic (martite) veins which in several localities appear to follow older faults, shears and mylonites. Away from the veins and localised argillic and silicic alteration, hematitisation of the host granitoids and rafts/xenoliths of metasediments and amphibolites, is common. Hematitisation is also prominent in younger Proterozoic systems which overlie the Gregory Granitoid

Complex and probably also the Gregory vein system. No significant base metals or Au prospects have been found in the Gregory vein system to date.

From this study it appears that most of the high level siliceous hydrothermal deposits of the granite-greenstone terranes of the North Pilbara and the overlying lower part of the Hamersley Basin are related to either to an event during deposition of the Warrawoona Group or a second event during deposition of the basal part of the Fortescue Group.

The youngest (2.8 – 2.7 Ga) and most widespread episode of low temperature-high level hydrothermal activity is associated with the initial rifting of the granite greenstone terranes, the deposition of basal Fortescue Group volcanics and sediments, and intrusion of granitoids. The deposits of the West Pilbara granite-greenstone terrane (Karratha district), Mallina Basin (Whim Creek district) and the Gregory Range Inlier have a common metal suite, Au-Ag-Pb-Cu-Zn±Sb±As, and most variations in the styles of mineralisation can be explained in terms of different levels of the Buchanan (1981) low sulphidation model. As the early-Fortescue rifts have received little attention from exploration companies, the precious and base metal potential of this geological setting has not been evaluated. However, positive results from Elizabeth Hill and various prospects around Whim Creek justify more focussed and systematic exploration.

Epithermal mineralisation related to calc-alkaline centres of the lower Warrawoona Group (ca 3.5-3.4 Ga) in the Marble Bar and Nullagine areas is the oldest known in the North Pilbara, and the Miralga Creek prospect (Groves 1987) is possibly one of the oldest epithermal systems in the world. As targets of 1970s/1980s mineral explorers in these areas were base metals, these centres remain largely unexplored for precious metals. In the light of current continuum models for precious and base metal hydrothermal deposits, results of these programs and the setting of the various structural and stratabound base metal hydrothermal deposits of this area should be reconsidered.

INTRODUCTION

Scattered across the granite-greenstone terranes of the North Pilbara and parts of the Hamersley Basin are a variety of siliceous vein deposits with features typical of veins formed in low temperature-low pressure hydrothermal regimes. Such deposits are more generally referred to as 'epithermal deposits'. Since the late 1870s, base metal and precious metal veins have provided a focus for prospecting, mineral exploration and small scale mining in the Pilbara. Very few of the epithermal deposits are documented and there is no regional overview of occurrences, their distribution, or review of mineral potential. This paper addresses these matters.

Worldwide epithermal veins, particularly those deposits with economically important mineral resources, are mostly of Cainozoic age. However, they are not restricted exclusively to younger terranes. In Australia there are economically important auriferous epithermal vein deposits in Palaeozoic rocks, including Pajingo, Queensland (Middle Carboniferous; Richards et al. 1998) and Temora, New South Wales (Middle Silurian; Thompson et al 1986). To date no economic epithermal precious metal deposits have been found in Australian Precambrian rocks. However, recent discoveries, such as the Proterozoic Hope Brook Au-Cu mine in Newfoundland (Dube et al. 1998), highlight the potential of Australian Precambrian rocks. For a study of the potential of epithermal veins in older rocks, the Archaean Pilbara Craton has merit: outcrop of granites and greenstone rocks are better than in the other Australian

Archaean cratons, and there are substantial areas of greenstone where high level geological features are preserved at low metamorphic grades.

LOW TEMPERATURE - LOW PRESSURE SILICEOUS VEIN DEPOSITS

Characteristics

Lindgren (1933) classified hydrothermal metalliferous deposits into epithermal, mesothermal, and hypothermal groups based on interpretation of deposit features including form, ore and gangue minerals, textures, and geological setting. According to Lindgren (1933), epithermal veins formed at slight depth and moderate pressure, perhaps 50°-150°C and ≤100 bars. Modern research, particularly fluid inclusion studies, have shown that the pressure-temperature conditions for epithermal deposits are somewhat higher, with temperatures up to 300°C and pressures about 0.5 Kb (1-2 km depth). However, the features recognised by Lindgren (1933) as supporting classification as epithermal remain essentially unchanged today. As very few detailed academic studies have been undertaken, identification and classification of the various Pilbara vein deposits is dependent largely on mesoscopic and megascopic characteristics in company exploration reports, including: (1) the geometry of veins and vein systems; (2) ore and gangue mineralogy; (3) geochemistry; (4) mineral textures; and (5) alteration and zoning. As a descriptive term, "epithermal" is widely used and understood by field geologists and is used here in preference to the non-genetic descriptor "low temperature-low pressure".

Over the last fifty years, there has been substantial research on epithermal deposits, particularly precious metal deposits of the Western USA and, more recently, those around the Circum Pacific rim. From these studies, consensus has emerged recognising two basic subdivisions of epithermal deposits which are primarily controlled by fluid geochemistry. They are high sulphidation (acid-sulphate deposits which formed from acidic, oxidised fluids), and low sulphidation (adularia-sericite deposits, which formed from neutral, reduced fluids). The characteristics of these two deposit types are summarised in Table 1 and shown schematically in Figure 1. The low sulphidation model shown in Figure 1 was originally proposed by Buchanan (1981) and it is referred to in this review as the Buchanan (1981) model.

Two other important classes of hydrothermal Au deposits are sometimes linked with epithermal deposits: Carlin, or sediment-hosted micron Au deposits (e.g. Poulsen 1996, Pirajno 1992), and epizonal Archaean lode Au (Gebre-Mariam et al. 1995). Although both classes of Au deposits are interpreted to form within the same temperature envelope as epithermal deposits, pressures are interpreted to exceed 0.5 Kb, so they have not been considered in this review.

High sulphidation deposits occur within or adjacent to areas of active volcanism with significant direct input of magmatic fluids. They are often modelled as the distal part of porphyry Cu systems. Low sulphidation deposits form in active geothermal systems with fluids dominated by ground waters. Here the connection with magmatism is less direct and intrusives may only be important in supplying the heat to drive the fluid circulation. While epithermal systems, particularly low sulphidation, can develop in a wide variety of geological settings, the economically significant Au or Au-Ag deposits are largely restricted to convergent plate margins. The direct application of such models, which were derived from features of Cainozoic deposits, to Archaean terranes and the Pilbara in particular raises obvious questions.

Table 1. Characteristics and examples of epithermal deposits based on White and Hedenquist 1995).

	Low sulphidation (adularia-sericite deposits)	High sulphidation (acid-sulphate) deposits
Form	Open-space veins are dominant. Disseminated and replacement ore is mostly minor. Stockwork ore is common.	Veins are generally subordinate, although locally dominant. Disseminated ore is generally dominant. Replacement ore is common. Stockwork ore is minor.
Ore mineralogy*		
Pyrite	Ubiquitous (abundant)	Ubiquitous (abundant)
Sphalerite	Common (variable)	Common (very minor)
Galena	Common (variable)	Common (very minor)
Chalcopyrite	Common (very minor)	Common (minor)
Enargite-Luzonite	Rare (very minor)	Ubiquitous (variable)
Tennantite – Tetrahedrite	Common (very minor)	Common (variable)
Covellite	Uncommon (very minor)	Common (minor)
Stibnite	Uncommon (very minor)	Rare (very minor)
Orpiment	Rare (very minor)	Rare (very minor)
Realgar	Rare (very minor)	Rare (very minor)
Arsenophyrite	Common (minor)	Rare (very minor)
Cinnabar	Uncommon (minor)	Rare (very minor)
Electrum	Common (variable)	Uncommon (very minor)
Native Gold	Common (very minor)	Common (minor)
Tellurides-Selenides	Common (very minor)	Uncommon (variable)
Gangue mineralogy*		
Quartz	Ubiquitous (abundant)	Ubiquitous (abundant)
Chalcedony	Common (variable)	Uncommon (minor)
Calcite	Common (variable)	Absent (except as overprint)
Adularia	Common (variable)	Absent
Illite	Common (abundant)	Uncommon (minor)
Kaolinite	Rare (except as overprint)	Common (minor)
Pyrophyllite-Diaspore	Absent (except as overprint)	Common (variable)
Alunite	Absent (except as overprint)	Common (minor)
Barite	Common (very minor)	Common (minor)
Geochemical associations		
Anomalously High	Au, Ag, As, Sb, Hg, Zn, Pb, Se, K and Ag/Au	Au, Ag, As, Cu, Sb, Bi, Hg, Te, Sn, Pb, Mo and Te/Se
Anomalously Low	Cu and Te/Se	K, Zn and Ag/Au
Vein and Ore Textures	Banded, crustiform quartz and chalcedony veins; druse-lined cavities. Multiple veined breccias, episodes of mineral deposition and hydraulic fracturing. Lattice textured bladed calcite replaced by quartz as system cools. Silica sinters often rhythmically banded with vertical growth structures and may contain plant fragments - deposited at paleosurface by neutral-pH hot-spring waters	Relatively little variety, most characteristic massive bodies of vuggy quartz local veins and breccias as hosts to higher grade ore. Vuggy quartz caused by acid leaching at pH <2 which leaves open spaces and residual silica; residue recrystallises to quartz, with additional quartz and pyrite deposited from solution. Massive to banded sulphide veins consisting of pyrite and enargite may also cut the vuggy quartz bodies.
Alteration Mineralogy	Sericitic replaces argillic facies (adularia ± sericite ± kaolinite); Fe-chlorite, Mn-minerals, selenides present; carbonate (calcite and/or rhodochrosite) may be abundant, lamellar if boiling occurred; quartz-kaolinite-alunite-subtype minerals possible in steam-heated zone.	Advanced argillic + alunite, kaolinite, pyrophyllite (deeper) ± sericite (illite); adularia, carbonate absent; chlorite and Mn-minerals rare; no selenides; barite with Au; *steam-heated:* vertical zoning.
Examples	McLaughlin, California; Hishikari, Japan; Emperor, Fiji; Golden Cross and Waihi, New Zealand; Kelian, Indonesia; Porgera Zone VII, Papua New Guinea; Pajingo, Australia.	Goldfield, Nevada; Iwato, Kasuga and Akeshi, Japan; La Coipa and El Indio, Chile; Pueblo Viejo, Dominican Republic; Lepanto, Philippines; Temora, Australia.

*Shown as frequency of occurrence (abundance)

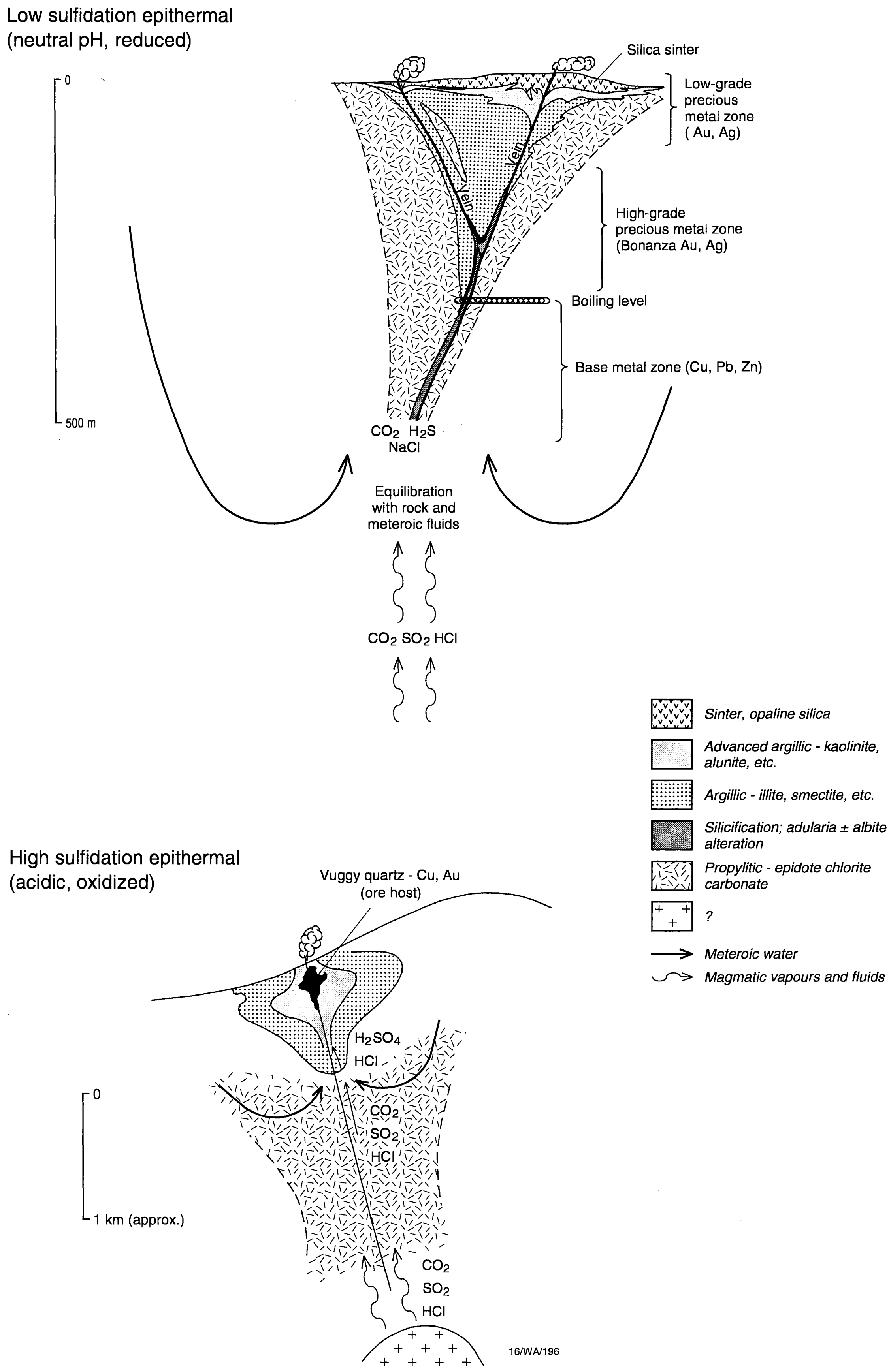

Figure 1. Epithermal deposits, low and high sulphidation models (modified after Buchanon (1981) and White and Hedenquist (1995)).

The dominance of Cainozoic epithermal deposits and scarcity of Precambrian epithermal deposits is largely a function of preservation. Deposition in sub-aerial conditions or very shallow water, favours erosion rather than preservation. Recognition, or lack of recognition, of epithermal deposits in older rocks is obviously hampered by diagenesis metamorphism and deformation and in the Pilbara also by weathering.

Distinction of acid alteration due to low temperature hydrothermal fluids or acidic meteoric waters (weathering) is difficult in field studies, particularly if no drill hole data are available to establish the weathering profile. In Precambrian greenstones there is also the obvious problem of distinguishing, at a local scale, low greenschist facies metamorphic effects from propylitic alteration.

Currently, economic interest in epithermal deposits is due almost entirely to the potential for precious metal, particularly 'Bonanza' Au or Au-Ag deposits. However, historically they have been an important source of base metals. Exploitation of precious metals and base metals from separate bodies and at different times within the same vein system is part of the history of many mining camps of the Circum-Pacific region.

Data Base

Regional background data for this study, where possible and/or appropriate, uses 1:100 000 scale maps, explanatory notes and geochronology from the current National Geoscience Mapping Accord (NGMA) North Pilbara project and the Geological Survey of Western Australia (GSWA) Archaean mineral prospectivity enhancement program. The granite-greenstone terranes of the North Pilbara, with the advantages of good exposure of some of the oldest Archaean rocks and preservation of a wide variety of tectonic and stratigraphic terranes are rightly considered as the best field geological laboratories for the study of older rocks and geological processes in Australia. As results of 1:100 000 mapping become available there has been published or there is awaiting publication a considerable number of research papers on Pilbara regional geology. The most recent published paper by Hickman (1999) provides an efficient introduction to this literature.

Very few of the vein deposits as such are recognised in 1:100 000 scale mapping. Published data on details of deposits are drawn mostly from earlier Aerial Geological and Geophysical Survey of Northern Australia (AGGSNA) and GSWA bulletins records and notes.

A computer WAMEX search was carried out at Western Australia's Department of Minerals and Energy for references to reports on the Pilbara with the following keywords: gold, silver, mercury, lead, amethyst, fluorite, antimony, calcite, cinnabar, galena, quartz, stibnite, and tetrahedrite. In addition, a text search of annotations was done using the words epithermal, chalcedonic, and crustiform. Publications were searched for references to epithermal vein deposits in Western Australia by AESIS (at DME) and by GEOREF (at UWA). Both searches found a thesis on Miralga Creek by Groves (1987) but did not indicate any other research papers on epithermal vein mineralisation in the Pilbara. Unfortunately most company exploration reports provide insufficient detail to classify deposits. The Honours Thesis study of the Miralga Creek precious-base metal prospect (Groves 1987) provides the only research quality data on a Pilbara epithermal deposit. Most of the descriptions and tables presented here are from company exploration reports held in the GSWA

WAMEX Open File, and are referred to by WAMEX Open File Numbers (see Appendix 1).

In the Pilbara, the early prospectors and miners explored vein deposits primarily for Pb, Cu and Ag. Records of exploration for Au and Au/Ag date largely from the 1980s. Across the Pilbara, very few company programs on epithermal precious metal prospects advanced to a drilling stage. By and large, observations on characteristics follow from surface mapping and exploration geochemistry. Interpretation of the nature of most individual deposits is from personal observations of various company geologists, including the author.

In this review the epithermal deposits of the Pilbara Craton are grouped under headings as west Pilbara, east Pilbara and Gregory Range. While these subdivisions are geographic rather than geological, they correspond more or less with Krapez and Barleys' (1987) tectonostratigraphic domains. The west Pilbara equates to domains 4 and 5, whereas the east Pilbara equates to domains 1, 2 and 3. The most recent subdivision of the North Pilbara granite-greenstone terranes by Hickman's (1999), which reflects 1:100 000 mapping between 1995 and 1999, is into western and eastern terranes separated by the Mallina Basin. Oldest rocks of the West Pilbara granite-greenstone terrane are ca 3.27 Ga, while in the East Pilbara granite-greenstone terrane there are ca 3.66 Ga gneiss and 3.51 Ga greenstones (Hickman, 1999). The Mallina Basin is less than 3 Ga in age.

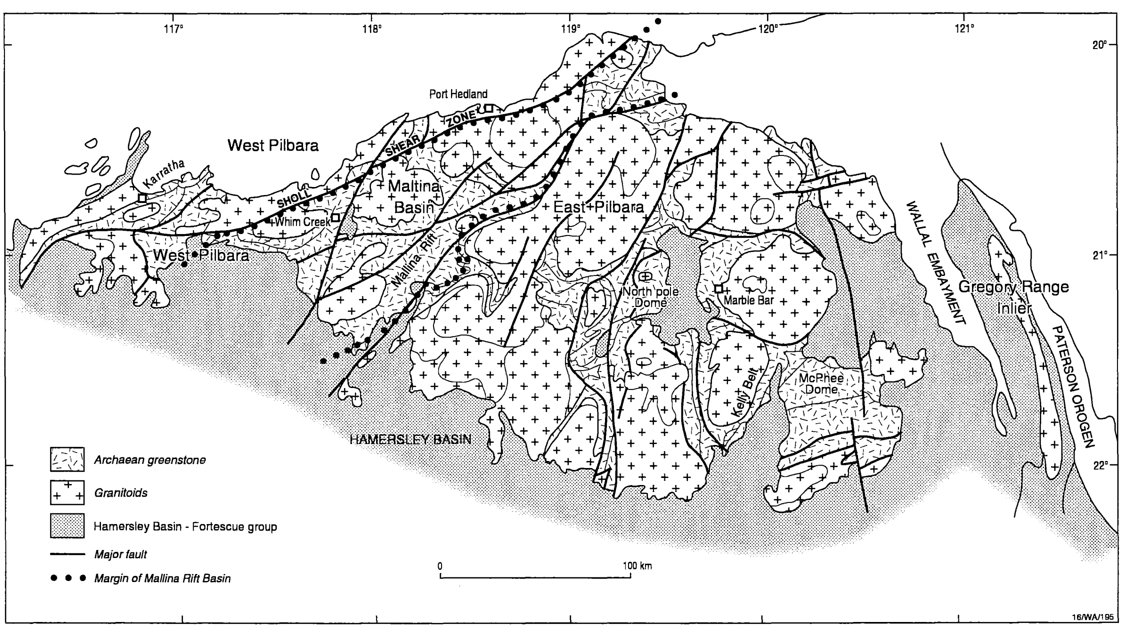

Figure 2. Regional geology of the North Pilbara Craton (modified after Hickman (1999)).

Deposits of the Karratha District, West Pilbara

The two documented occurrences of low temperature-low pressure siliceous vein deposits in the Karratha district, the Elizabeth Hill Ag and Sullam Ni deposits, are both south of the Sholl Shear Zone (Figure 3). The deposits are dissimilar in most, if not all of their characteristics. Sullam is by any criteria an epithermal deposit. The structures, textures and other features of Elizabeth Hill are consistent with epithermal conditions for deposition of the quartz carbonate vein system but the sulphide assemblage is unusual for epithermal deposits.

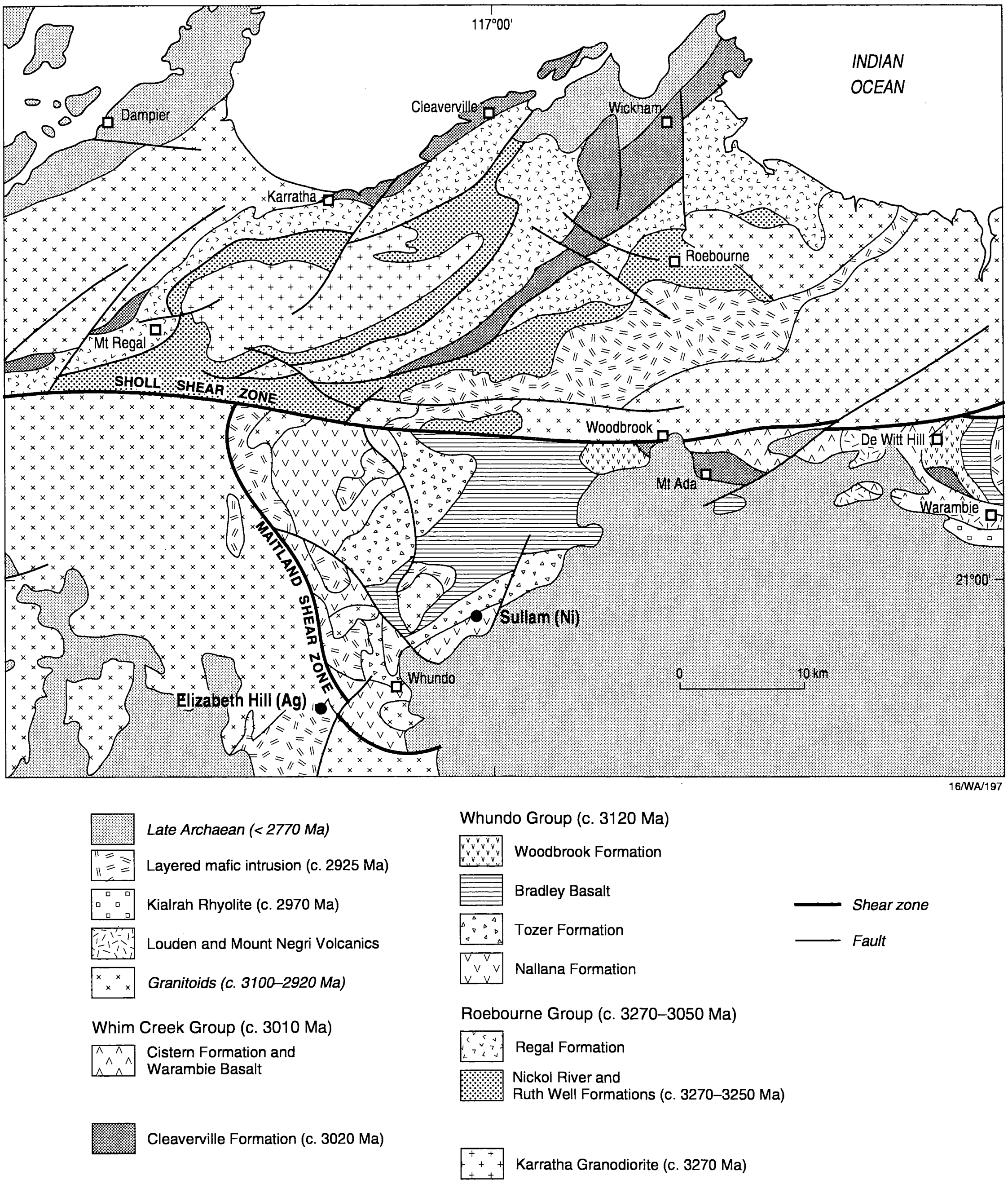

Figure 3. Distribution of epithermal deposits in the Karratha district of the West Pilbara granite-greenstone terrane (modified after Hickman, 1997b).

Although Elizabeth Hill and Sullam are outside the boundaries of the recently published 1:100 000 Dampier (2256) geological sheet, Hickman's (1997a,b) mapping and interpretation of the Dampier Sheet is easily extrapolated to the area of the Sullam prospect. Elizabeth Hill is on the northern contact of Munni Munni complex and within the area of Hoatson et al (1992) 1:20 000 mapping. Both of the Karratha district deposits are younger than Whundo Group rocks (ca 3.12 Ga, Hickman 1997b) and the West Pilbara layered mafic-ultramafic intrusive complexes (ca 2.93 Ga, Arndt et al., 1991), and may have formed during the earliest stage of rifting of the Pilbara Craton and the deposition of the Fortescue Group.

Since the mid-1960s, there has been considerable company exploration in the Karratha district for Cu-Zn volcanogenic massive sulphide (VMS) deposits and for komatiite and layered ultramafic-mafic intrusion hosted Cu-Ni sulphides and PGEs.

Since the mid-1980s, there has also been exploration for Au. Historic prospecting and more recent company exploration has located a large number of sub-economic quartz vein deposits with variable components of Pb, Cu and Zn sulphides and Au and Ag. However, all of the documented vein deposits other than Sullam and Elizabeth Hill are typically mesothermal in their characteristics.

Elizabeth Hill Ag (Pinderi Hills (2255) 486900mE, 7667800mN)

Elizabeth Hill is an unusual, very high-grade Ag vein deposit located about 35 km south of Karratha on the northern basal contact of the layered mafic-ultramafic Munni Munni complex. The indicated resource for Elizabeth Hill is 28,000 t averaging about 1% Ag for about 9 M oz contained Ag (Flint et al. 1998). The outcrop of the deposit was discovered by AGIP in 1987 (I 5997) during an investigation of major Karratha district lineaments for hydrothermal mineralisation (de Angelis et al. 1988).

The vertical, north-trending Munni Munni Fault and the basalt contact of the Munni Munni Complex, which dips 15-45° to the south, are the major controls on the the geometry of the vein system. Within the 10-15 m wide, near vertical vein system, drilling and exploratory mining to about 100 m vertical depth have delineated four ore pods or shoots. These shoots plunge shallowly to the south, and are 20-80 m in length and 5–15 m in width. Stratiform concentrations of Cu-Ni sulphides with variable PGE content have been recognised at several levels in the Munni Munni Complex, including the basal websterite and a second horizon (J reef) 20–30 m above the basal contact (Barnes 1995). Both of these Cu-Ni-PGE horizons are intersected and modified by the vein system. The 82 m level west drive exposes the core of the vein system as a 1.5 m wide body of carbonate quartz breccia with about 25% clasts predominantly of pyroxenite with lesser granite (Figure 4). The selvedges of the shoot show anastomosing quartz carbonate and sulphide veins and stringers in silicified, carbonatised and chloritised country rock. A 100t bulk sample from this level averaged about 1% Ag, 20% of which occurred as native silver and the rest in as complex of Ag sulphides and sulphosalts and base metal sulphides. Petrographic and mineragraphic studies including SEM/EDS and XRF (Townend 1996-1998) have identified a very diverse assemblage of over 60 ore minerals, including native metals, alloys and sulphides. Gangue minerals are predominantly quartz, calcite, calcian siderite and chlorite.

Within the vein system and country rock, there are suites of sulphides and native metals typical of layered mafic-ultramafic intrusions (e.g. pyrrhotite, chalcopyrite, pentlandite, and native PGEs), hydrothermal Cu-Zn-Pb minerals (e.g. chalcopyrite, sphalerite, and galena) and an exotic suite of Ag sulphides and other minerals containing Ni, Co, Cu, Pb, Zn, As and Sb (e.g. argentopentlandite). The very high Ag content of the Elizabeth Hill vein system was originally interpreted as the result of supergene enrichment (de Angelis et al. 1988). However, the Ag mineralisation exposed at the 82 m level is dominantly a primary assemblage, although mineragraphic studies show that supergene sulphides (e.g. marcasite, violerite, millerite and mckinstryite) and oxidised products (goethite) extend to around 100 m depth. The paragenesis from polished sections shows much of the Ag minerals are very late. The complexity of the sulphide assemblage may reflect primary magmatic sulphides overprinted by Ag-base metal rich, hydrothermal solutions with subsequent supergene sulphide deposition and partial oxidisation of the entire assemblage. Native silver occurs as veins, sheets, wire, crystals, globules and dendrites. Polished sections show that while many of Ag-bearing minerals are late, acanthite is widespread in earlier siderite silicates and quartz assemblages. There are no geochemical scans of the deposit, but the mineralogy indicates that there would be anomalous Ag, Cu, Ni, Pb and Zn with elevated and/or anomalous levels of PGEs, As and Sb. Nearly all assays for Au are below detection and although there are erratic high values in assays, it would appear that the system does not contain significant Au.

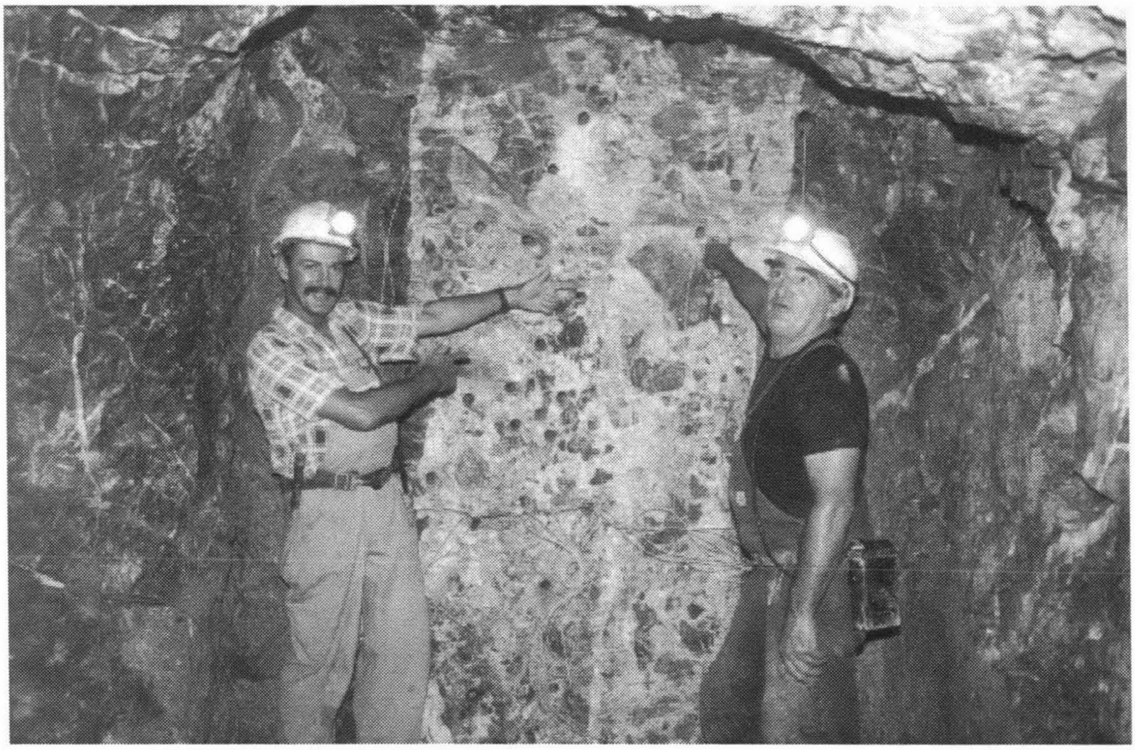

Figure 4. Calcite-quartz breccia vein with 'wire silver' from the 82 level, Elizabeth Hill deposit. Clasts (100-350 mm) in the breccia are mostly pyroxenite/peridotite.

The vein system is clearly younger thant the Munni Munni Complex and is probably older than the base of the Fortescue Group. The Munni Munni Fault is part of a set of north trending faults that offset the Munni Munni Complex but not the Fortescue unconformity.

Barnes (1995) considers three possible origins for the mineralisation: (1) supergene enrichment, (2) hydrothermal vein deposit along Munni Munni Fault or (3) derivation from the Munni Munni Complex at a late stage of emplacement. He argues for the latter possibility, inferring a Ag-rich phase differentiated from the intrusion following assimilation of country rock. Barnes (1995) also infers a close connection with the stratabound Cu-Ni-PGE horizons, particularly the upper horizon (J reef), which he reports contains anomalous Ag. From the geometry of the vein structure and textures there seems little doubt that Elizabeth Hill is primarily a hydrothermal carbonate-quartz vein system typical of deposition in a low-pressure and low to moderate temperature regime. Juxtaposition of magmatic and hydrothermal sulphides and the exotic suite of Ag and base metal sulphides seems best explained as an overprint of magmatic sulphides by the hydrothermal event. The vein system is clearly younger than the Munni Munni Intrusion (2925±16 Ma; Arndt et al., 1991).

As noted by Barnes (1995), there are some obvious gross similarities between Elizabeth Hill and somewhat exotic Ag vein deposits referred to by Ruzicka and Thorpe (1996) as arsenide vein Ag-Co, and arsenide vein Ag-U deposits (e.g. Cobalt, Ontario; Bou Azzer, Morocco and Jachymov, Czech Republic). However, in Elizabeth Hill arsenides are uncommon, and mineragraphic studies have not identified significant As-bearing minerals nor any U or Ra minerals.

Sullam Ni (Cooya Pooya (2355), 500160E, 7675480N)

The Sullam prospect, which is located about 35 km SSE of Karratha, is a pyritic chalcedonic silica deposit with anomalous Ni hosted in mafic volcanics of the Whundo Group. Sullam was found by Westfield Minerals (WA) NL geologists in 1969 (I 6066, I 9424) during follow-up of Ni geochemical anomalies in stream sediments.

The deposit is a composite of flat lying lenses and sub-vertical veins extending across a width of 50 m and over about 250 m on a NNE strike trend. It is localised within a prominent fault which shows 1 km sinistral displacement of the Fortescue-Whundo Group unconformity. Host rocks of the deposit are basalts of the 3.125 Ga Nallana Formation (Hickman 1997b). The southwest limit of the deposit is the unconformity and here there are boulders of gossan and chalcedony in sandstones and conglomerates of the Hardey Formation, which is locally at the base of the Fortescue Group as the Mt Roe basalt is missing.

At surface, the deposit is characterised by grey-green chalcedony with very fine disseminated pyrite, which highlights colliform textures, along with vuggy and cellular ferruginous gossans. The vein system is delineated at surface by a strong Ni (>300 ppm) and Co (>60 ppm), and moderate Pb (>30 ppm) and As (>20 ppm) soil anomalies and by notable Cu depletion in the soil. Drilling of the Ni soil anomaly returned a best intercept of 6 ft of 1.2% Ni in sulphides. Rock chip samples of the pyritic and gossanous chert show anomalous Ni (to 1100 ppm), Co (to 400 ppm), Au (to 50 ppb), Sb (to 100 ppm), As (to 295 ppm) and Zn (to 240 ppm), but very low Cu, Pb and Ag values.

In drill core massive iron sulphides and carbonate-chlorite altered basalts are interleaved with fine-grained siliceous vein material. Below 60 m the chloritised basalt passes into a coarser chlorite carbonate rock after gabbro. Polished sections identified the ore minerals as pyrite, bravoite and millerite. The vein system has strong geochemical signature and corresponds with a magnetic low and a strong IP anomaly.

The Sullam veins are interpreted to have formed near the palaeosurface and my in part be a sinter deposit. Anomalous Ni and Co in the epithermal vein deposits may have a local source, such as komatiites in the Nallana Formation, or a large differentiated gabbro intrusive that crops out about 500 m to the west of the Sullam veins. The age of the mineralisation is younger than 3125 ± 4 Ma (Hickman 1997b) but probably not much older than the Mt Roe Basalt about 2765 Ma.

DEPOSITS OF THE WHIM CREEK DISTRICT, WEST PILBARA

The Whim Creek district near the northwest margin of the Mallina Basin, is notable for a variety of Cu-Zn-Pb-Ag and Ti-V deposits. Since discovery of the Whim Creek and Mons Cupri Cu deposits in the late 1890s, there have been several cycles of company exploration, mostly focused on the Whim Creek Group volcanic and sedimentary rocks for massive sulphide Cu-Zn deposits. The district has no significant historic Au production. During the 1980s several companies explored for Au and found Au–base metal vein prospects which have the distinctive characteristics of epithermal deposits (Figure 5).

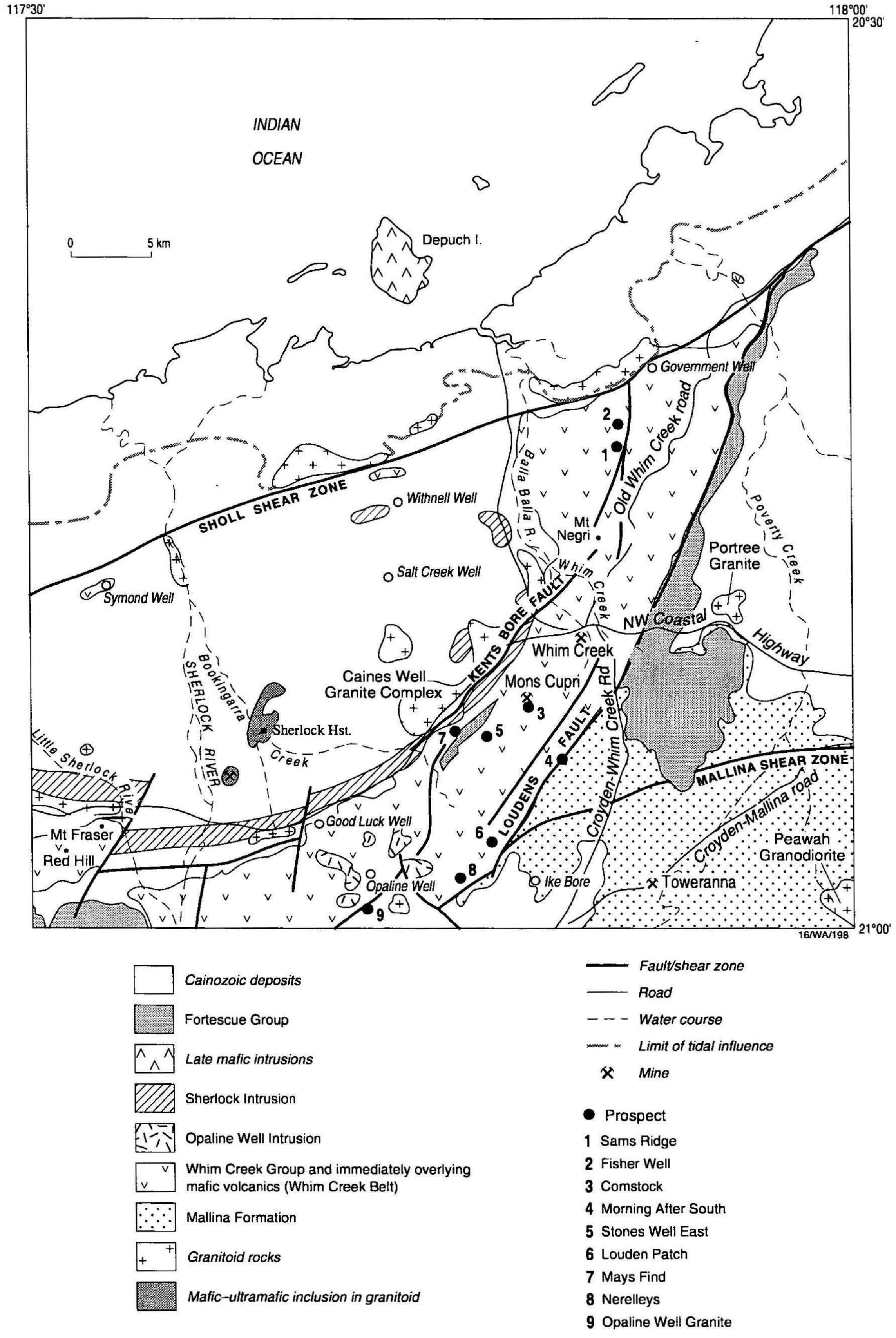

Figure 5. Epithermal deposits of the Whim Creek district West Pilbara granite-greenstone terrane (modified after Smithies (1997b)).

The presence and preservation of such mineralisation follows from several regionally anomalous features of the district geology. The sedimentary and bimodal volcanic rocks of the ca 3.0 Ga Whim Creek Group and associated high level intrusives are moderately well exposed and exceptionally well preserved for a Mesoarchaean volcanic terrane. A NNE to northeast trending structure corridor about 5-10 km wide cuts across the Whim Creek belt. This corridor, which is interpreted to be of late Archaean age, has been the locus of repeated periods of faulting, volanism and intrusion during the early deposition of the Fortescue Group.

The following compilation and summaries of the high level siliceous vein deposits of the district are derived mostly from the reports of three companies, Texasgulf (1968-1985), Duval Mining Australia Ltd (1982-1984, Alston 1984) and Whim Creek Consolidated NL (later Dominion Mining, 1987-1993; I 6934, I 7562). The principal source of regional geological data is from the current North Pilbara NGMA mapping project, in particular, the Sherlock (2456) 1:100 000 sheet and explanatory notes (Smithies 1997a, 1998). Where possible Smithies terminology and interpretations have been adopted except where this conflicts with more detailed company geological mapping and aeromagnetic survey data over specific prospects.

Within the Whim Creek district there are three well-defined Au-base metal, epithermal prospects, Sams Ridge, Morning After South and Stones Well East, and at least another 15 small prospects and occurrences of similar style (Figure 5). From company reports, it appears that exploration of the major prospects have been inconclusive; there has been no drilling reported on Sams Ridge, Morning After South or Stones Well East.

While the epithermal vein systems around Whim Creek almost certainly reflect several separate episodes of high level Au – base metal hydrothermal mineralisation, there are common themes. The suite of base metals is relatively simple, Pb, Cu and Zn, and they typically contain anomalous Sb. There are no recorded Ag minerals and it appears that most Ag occurs in argentiferous galena. The deposits are typical of low sulphidation systems and the various prospects represent a range of levels from surface or very near surface to depths at the lower levels of epithermal systems.

Sams Ridge Au-Cu-Sb (Sherlock (2456) 590100mE, 7704700mN)

Sams Ridge, a prominent ridge capped by chalcedonic quartz was identified as a possible epithermal vein deposit by a Whim Creek Consolidated geologist in 1988 (I 7562). There are no historic workings, which is surprising as there are exposures of secondary Cu minerals and the ridge is only a few hundred metres west of the old Northwest Coastal Highway.

The prospect, which is marked by massive and poddy chalcedonic quartz flanked by chloritised basic volcanics (Louden Volcanics; Smithies 1997a), extends over some 3 km. The zone of quartz veining and alteration is up to 150 m wide and strikes generally north. The mineralised zone is about 200-300 m west and parallel to the 'Negri Shear' which is expressed at surface only as a topographic low. Company aeromagnetics indicate up to 2.5 km of dextral displacement on the Negri Shear. Individual bodies of quartz and chalcedony are present as near vertical vein and flat lying lenses within the Sams Ridge zone, with the veins striking NNE. The chalcedonic quartz shows typical epithermal vein features, including colloform banding and crack-seal breccias, and rare outcrops show platey calcite replaced by quartz. Gossanous zones, some with oxide Cu minerals, occurs on the selvedges of some of the chalcedonic veins.

Rock chip geochemical prospecting gave some positive results. Fifteen of the 19 samples contained low order Au (0.01-0.07 ppm) with the majority of samples containing various combinations of anomalous Cu, Pb, Zn, As, Ag and Sb. A grab sample from a 1-2 m wide quartz chalcedonic vein with minor Cu oxide minerals returned values of 0.44 ppm Au, 90 ppm As, 14.5 ppm Ag, 8100 ppm Sb, 9800 ppm Cu, 70 ppm Pb and 255 ppm Zn.

Although results of initial prospecting of the Sams Ridge epithermal veins system were encouraging the follow-up reconnaissance soil geochemical survey failed to indicate any discrete drill target. Overall soil Au and base metal values were unexpectedly low with no distinctly anomalous patterns for Au, Cu, Pb, Zn, As or Sb, even including 10 x 50 m sampling over malachite quartz veins. There remain questions as to the effectiveness of surface soil geochemistry in this environment. The –80 mesh (silt fraction) may be dominated by quartz debris from the veins and/or aeolian and reworked aeolian deposits. Effective geochemical prospecting of Sams Ridge requires bedrock drilling.

Fisher Well Pb Cu-Au (Sherlock (2456) 590600mE, 7709400mN)

Three shallow pits immediately north of Fisher Well expose 0.1-0.5 m wide quartz veins with galena, stibnite and minor secondary Cu minerals (I 7562). The host rocks are highly chloritised basalts, probably of the Louden Volcanics. The veins have been sampled by at least four companies (Texasgulf, Homestake, Goldstream and Dominion) with Au analyses to 6.7 ppm. A selected grab collected by the author assayed 0.62 ppm Au, 2180 ppm Cu, 7,000 ppm Zn, 23% Pb, 245 ppm Ag, 40 ppm As, 74 ppm Sb. The veins, which trend about 350° are probably on the northern strike extension of the Sams Ridge prospect.

About 3 km east of Fishers Well there are two other Au-Sb prospects, sometimes referred to as Fishers Well in exploration reports. The northern (Pit E or Star Antimony Mine, late M 187, Hickman 1983, Finucane and Telford 1939) and southern (Pit D or Deep Well) prospects are both sheeted quartz veins hosted in strongly deformed metapelites and meta psammites. They are typical mesothermal veins with mineralisation similar to the Mallina Au-Sb deposits and quite unlike Sams Ridge or Fisher Well prospects. Although the host rocks are mapped by Smithies (1997a) as Louden Volcanics, which, within this region, contain metasedimentary rocks, the author interprets these rocks as Mallina Formation.

Comstock Lode (Colorado) Pb-Ag (Sherlock (2456) 583900mE, 7690100mN)

The Comstock Pb-Ag mine is 500 m due south of the cairn on Mons Cupri Hill. The deposit, which was discovered in the late 1890s, has produced 78 t of Pb amd 28.8 kg of Ag (Blockley 1971). Blockley (1971) describes Comstock deposit as a group of branching and intersecting quartz veins extending WNW over about 350 m. Where the veins coalesce the system is about 90 m wide and within this area there is a complex of veins 12 m across and 45 m in strike length which have been the focus of the most extensive mining activity. The veins are mostly steep dipping. Larger veins are within a 100 m thick shallow south dipping unit of basalts within the Rushall Slate (Comstock Member of Smithies 1997b) and probably have limited depth extent. The quartz veins contain, in addition to galena, angelsite, cerrusite and pyromorphite with lesser malachite and azurite. They exhibit textures characteristic of open space filling such as crustiform and banded veins.

About 2.6 km WNW of Comstock there are pits on another Pb-Ag vein deposit, which was referred to by Texasgulf as the Western Hill workings (581600mE, 7691200mN). The vein is in an area mapped by Texasgulf as Rushall Slate, close to the overlying Negri Volcanics. This contact is interpreted by the author as an unconfomity.

A grab sample of mineralised vein analysed 0.5% Cu, 0.17% Zn, 17% Pb, 260 ppm Ag, 230 ppb Au, 430 ppm As, 200 ppm Sb. The Texasgulf map (HS Gair, written communication, 1973) shows another Pb-Ag gossan about 250 m due south hosted within the basalt above the uncomformity.

The Comstock and Western Hill workings clearly postdate the Rushall Slate and may postdate the Mons Cupri and Whim Creek base metal deposits.

Loudens Patch Au (Sherlock (2456) 585200mE, 7686900mN)

Published maps of the Whim Creek district give a number of different locations for the Loudens Patch Au prospects although all are about 3km southeast to SSE of Mons Cupri and close to the Loudens Fault. A 1984 DME tenement plan shows the location as 586000mE, 7689000mN, but Smithies (1997a) shows it at 586200mE, 7688000mN. The location given in given in the title of this section is from Whim Creek Consolidated aerial photographs. It is quite likely that there are Au workings in all three locations and the same name has been applied at different times to different workings. The Loudens Patch working or workings are of interest in locating Au mineralisation close to this major NNE structure. At the most southerly locality referred to above, there are small pits and dry blowings in conglomerates and agglomerates that Smithies (1997a) mapped as undifferentiated Mt Roe Basalt. These workings are directly on the Louden Fault zone.

Morning After South Au (Sherlock (2456) 580400mE, 7688500mN)

Duval's 1984 stream sediment geochemistry survey (Alston 1984), which was based on analysis of heavy mineral concentrates, defined an area about 2 km^2 with strongly anomalous Au about 2.5 km southwest of Mons Cupri (I 6934). Concentrates from this area, which was named the Morning After prospect, contained up to 387 ppm Au with visible gold grains. The anomalous streams drain basalt ferruginous chert and shale of the Negri Volcanics. Duval drilled the ferruginous chert shale and also sampled localised quartz filled tensional gash veins in the volcanics without finding any significant Au mineralisation (highest vein value 0.22 ppm Au). Later (1988) stream and rock chip geochemical prospecting by Whim Creek Consolidated NL (I 6934) confirmed the broad Duval target area but indicated that the Au source was at least several 100 m south of Duval's prospect and probably sourced from an ENE striking ridge of strongly silicified and chloritised basalt with distinctive chalcedonic veins. Mapping and geochemical prospecting showed the ridge defined the northern margin of a broad ENE trending zone, 0.6 x 3.0 km in area, which was called Morning After South. This zone is notable for silicified and argillically altered basalt with widespread chalcedonic veining. Follow-up rock, soil and stream sampling showed elevated to weakly anomalous Au, Sb and Cu but failed to locate the source of the strongly Au anomalous stream sediments.

To the west, the Morning After South system is terminated at an uncomformity where the Negri Volcanics are overlain by unusual well laminated carbonate-silica chemical sediments. This unit was mapped by Smithies (1997a) as Mt Roe Basalt. The eastern limit of the system, where it terminates against the major NNE trending Miller Fault, is the Texasgulf Chert Ridge prospect (583500E, 7689300N). Rock chip sampling from various company prospecting programs here have shown high Pb (to 26%) and anomalous Au (to 140 ppb), Ag (to 74 ppm), As (to 1550 ppm), Sb (to 200 ppm) and Zn (to 1360 ppm).

Morning After South is a large well preserved high level hydrothermal system. If the unusual chemical sediments immediately overlying the prospect are sinters it is an epithermal system which remains largely undissected.

Stones Well East Au-Zn-Pb (Sherlock (2456) 582000mE, 7683000mN)

The Stones Well East Au prospect (I 6934) is defined by strongly Au anomalous stream sediment and soil values in a 400 x 1800 m zone over amydaloidal basalt of the Louden Volcanics. Aerial photographs indicate there is considerable quartz scree and relatively limited outcrop of the basalts. Stones Well East is located between two major NNE trending faults, the Louden Fault and the southern extension of the Miller-Gair Fault.

In following up Au anomalous stream sediment samples about 1.5 km east of Stones Well, Whim Creek Consolidated found obvious epithermal siliceous veins, but initially sampling found only very low Au values. However more detailed prospecting found gossanous veins within a 200 m strike section of the prospect where the quartz carbonate veins had strongly anomalous precious and base metal values (to 60 ppm Au, to 185 ppm Ag, to 1.55% Pb, to 4.1% Zn and to 155 ppm As). The veins contained primary and secondary Pb and Cu minerals including galena, chalcopyrite malachite and chyrsocolla. Descriptions of rock chip samples (I 6934) note chloritic and siliceous alteration within and adjacent to the veins. A follow-up soil geochemical survey, samples analysed for Au, Cu, Pb, Zn, Ag, As, Bi and Sb showed a well defined +100 ppb Au anomaly within an area of about 200 x 400 m which generally coincides with the location of the more anomalous rock chip samples. There are no matching patterns between the Au and other elements which may follow from the very fine fraction sub-samples used for the base metal analyses. The Stones Well East Au anomaly is open both northeast and southwest. There are no reports of drill follow-up of the anomalies.

Mays Find Pb-Cu-Sb (Sherlock (2456) 577800mE, 7687500mN)

Duval's Mays Find 1, 2 and 3 VMS prospects are along a narrow sliver of Mons Cupri Volcanics within the Kents Bore fault zone, immediately east of the Northwest Coastal Highway near Maree Bore. These targets consisted of gossans that were considered as indications of stratabound VMS mineralisation similar to Whim Creek and Mons Cupri. While exploration failed to find any stratabound based metal mineralisation it located structurally controlled base metal mineralisation which Alston (1984) noted was in epithermal quartz veins within the Negri Volcanics. Alston notes that the element associations averages 2800 ppm Cu, 8600 ppm Pb, 724 ppm Zn, 8.9 ppm Ag, 470 ppm As, 1050 ppm Bi, 1050 ppm Sb, and 7.6 ppm Hg. The Mays Find 1 prospect is close to the western end of the Morning After South vein system.

Nerelleys Au (Sherlock (2456) 578000mE, 7681000mN)

This Duval Au-base metal prospect (Alston 1984) covers an area about 500 x 3000 m as indicated by anomalous Au in heavy mineral concentrates from stream sediments. It is of interest as it is directly on trend southwest of the Stones Well East prospect. At Nerelleys, Duval investigated pyritic gossans along a shear contact between sediments (? Rushall Slate) and basalts (Louden Volcanics) but did not follow-up the stream Au anomalies as such. The gossans were described by Alston (1984) as pyritic arkose, and he notes base metal values as low, with maximum values of 320 ppm Cu, 330ppm Pb, 420 ppm Zn, 0.4 ppm Ag, and 64 ppb Au.

Opaline Well Granite Prospects (Sherlock (2456) 575400mE, 7679200mN)

Within a small exposure of the ca 2765 Ma tourmaline-bearing Opaline Well leucogranite (Smithies 1997a) about 1.5 km southeast of Opaline Well, there are several prominent northwest striking veins of very fine-grained quartz and chalcedony. The textures of the veins are typical of epithermal deposits, including colliform and crustiform banding, and silica replacement of platey calcite textures. Rock chip sampling of the veins of the Opaline Well granite prospect showed no significant Au or base metal values other than a single sample with 780 ppm Cu.

About 1.5 km southwest of the Opaline Well Granite prospect there are anomalous Au, Sb and Cu values in the stream sediments draining the Opaline Well Granite-Mallina Formation contact. At this Opaline Well South granite prospect (573400mE, 7678300mN) there are felsic dykes in the sheared contact zone. The leucogranite is tourmaline-bearing and is significantly younger that either the Whim Creek of Mallina Formation. Based on geological relationships, this mineralisation is the youngest present in the Whim Creek district.

DEPOSITS OF THE EAST PILBARA

The East Pilbara granite-greenstone terrane between the Mallina Basin and the Wallal Embayment, covers about 50% of the area considered in this review, but includes only two well-documented high level low temperature vein deposits, the Miralga Creek Au-Zn-Pb-Cu and Meentheena fluorite deposits (Figure 6). This imbalance may reflect the focus of company exploration during the 1970s and 1980s rather than geology.

The WAMEX open file data for the east Pilbara is dominated by 1970s/early 1980s reports of exploration programs targetted on VMS Cu-Zn and porphyry Cu-Mo mineralisation in the felsic volcanics and high level silicic intrusives of the oldest Pilbara greenstones. While during this period there were some discoveries of VMS and porphyry-style base metal deposits, no new mines were developed on these prospects.

All of the larger Au mines of the Pilbara Craton (e.g. Bamboo Creek, Comet, Blue Spec and Lynas Find) and most of the ~30 historic Au mining centres reviewed by Hickman (1983) are within the East Pilbara granite-greenstone terrane. These Au mines and prospects, which are usually considered as Archaean mesothermal lode or vein deposits, are the subject of a separate AGSO study and have not been reviewed for this paper. In the major revival of Au exploration on mining in Western Australia since the mid-1980s, the North Pilbara Craton overall has remained a backwater. In the Pilbara there are only a few grass roots discoveries, (e.g. Lynas Find and Indee) and only modest production from new Au mines (eg. Bamboo Creek and Lynas Find).

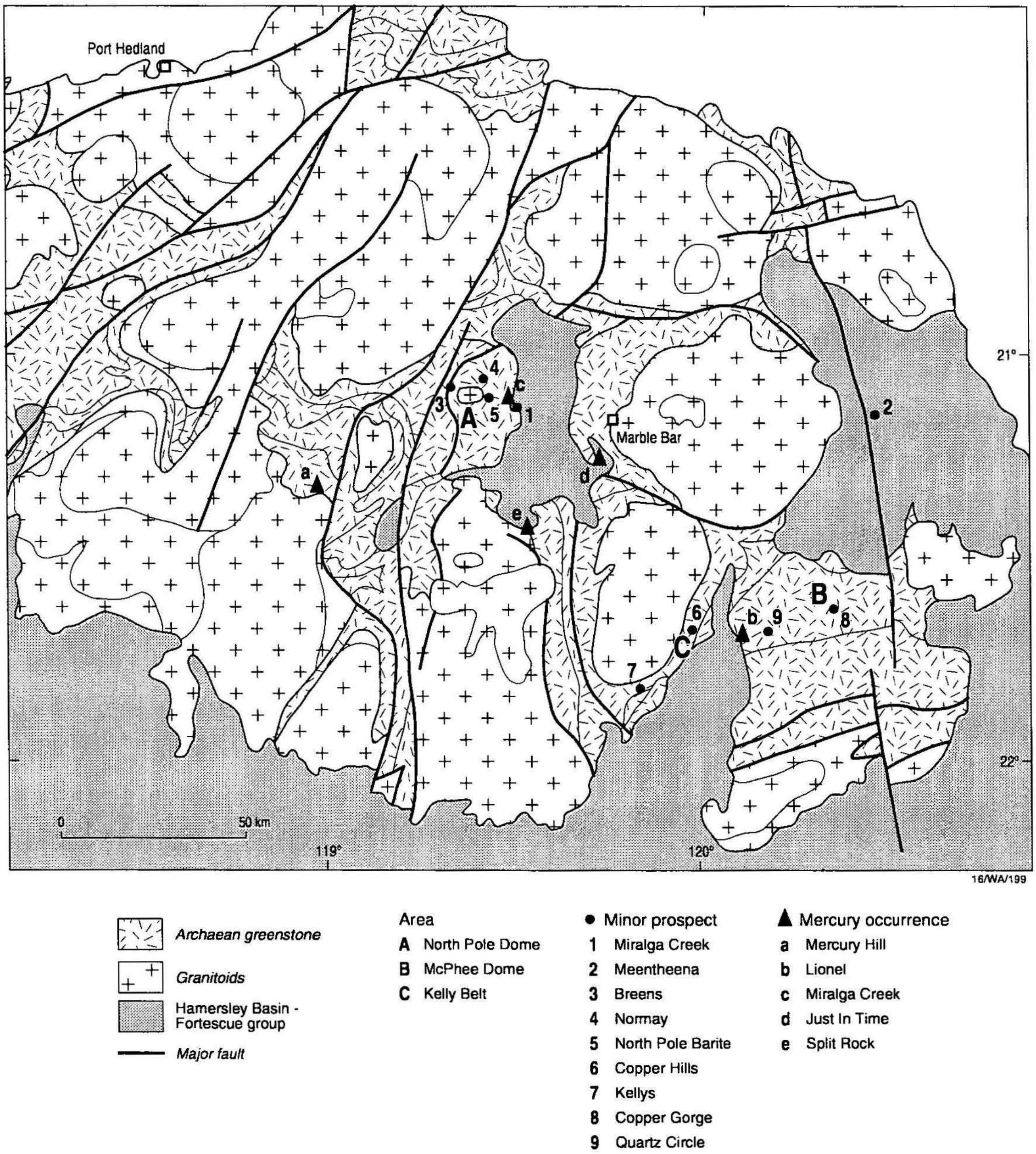

Figure 6. Epithermal deposits of the East Pilbara granite-greenstone terrane (modified after Hickman, 1999).

GSWA 1:250 000 mapping of the early 1970s and, in particular, Hickman's (1983) synthesis of the Pilbara Craton geology remain the principal source of regional geological data for the East Pilbara granite-greenstone terrane.

The 1:100 000 mapping of the current Pilbara Craton Project is well advanced but at the time of writing this review there is little published data other than papers by Van Kranendonk (1998) and Van Kranendonk and Morant (1998) which substantially revises Hickman's synthesis for the Marble Bar (Hickman and Lipple 1975) and Nullagine (Hickman 1978) 1:250 000 sheets. Where appropriate the newer definitions terminology and interpretations which reflect results of recent geochronology are adopted in this section of the review. Van Kranendonk and Morant (1998) recognised two volcanic sequences, the Sulphur Springs and Coonterunah Groups, which were previously included in Hickman's (1983) Warrawoona Group. However, as the newly published 1:100 000 geological mapping covers only a small part of Marble Bar and Nullagine 1:250 000 sheets, Hickman's (1983) Warrawoona Group is retained here.

At the broadest scale there are notable differences between the geology of the western and eastern granite-greenstone terranes of the North Pilbara which may be relevant to recognition and distribution of high level, low temperature vein deposits. In the east, the combination of deformation style and moderate erosion has preserved substantial areas of felsic and mafic volcanics and related high-level intrusives at low to very low metamorphic grades. Within the greenstone sequences around Marble Bar, several calc-alkaline volcanic centres have been recognised with rocks deposited in sub-aerial or shallow subaqueous conditions (Griffin 1990). Moreover, the proportion of outcrop of Archaean greenstones within the Marble Bar and Nullagine 1:250 000 sheets is exceptionally high.

Groves' (1987) study of the Miralga Creek precious and base metal deposit provides convincing evidence that epithermal vein deposits have formed, been preserved and can be recognised in the oldest greenstones of the North Pilbara Craton. No other deposits with similar characteristics are described in company reports for the Marble Bar and Nullagine 1:250 000 sheets.

Considering factors such as recognition and the bias of company exploration models, this section of the review considers, in addition to the well documented deposits at Miralga and Meentheena, other Au and base metal prospects in areas of permissible geology where descriptions are ambiguous but suggestive of high level-low temperature hydrothermal origin. Most of these prospects are in three areas of well-exposed greenstones: the North Pole Dome, the McPhee Dome and the Kelly Belt (Figure 6; Table 2).

Widely scattered occurrences of cinnabar and/or rocks with anomalous levels of Hg are further evidence of the preservation of high-level hydrothermal systems. Cinnabar was first recognised in Western Australia near Marble Bar in 1912 (Simpson 1951) and company exploration has since found other occurrences of cinnabar or rocks with anomalous Hg, in the Marble Bar and Nullagine 1:250 000 sheets. The occurrences (Figure 6; Table 3) are compiled here as a guide to areas where low temperature-low pressure hydrothermal mineralisation may be preserved.

Finally this section documents a number of siliceous vein deposits, mostly containing base metals, which crop out within several of the large granitoid complexes (Figure 6). Quartz and chalcedony veins and vein swarms are scattered through nearly all of the large granitoid complexes of the North Pilbara Craton. While of limited direct economic interest, some of these deposits may also provide evidence of previously unrecognised epithermal systems.

North Pole Dome (North Shaw (2755) and Marble Bar (2855))

Within the North Pole Dome there is a large area of well exposed tholeiitic and high-Mg basalts, felsic volcanics, volcanoclastics and chemical sediments of the Warrawoona Group generally at low to very low metamorphic grades.

The greenstones of the North Pole Dome host a variety of base metal, precious metal and barite deposits, most of which appear to have formed at low temperatures and near the palaeosurface. Most of the North Pole mineral deposits are in the lower most Talga Talga Subgroup and within a few km of the 3.46 Ga North Pole monzogranite (Thorpe et al. 1992a). This intrusion forms the core of the domal structure and is interpreted by Van Kranendonk (1998) as a synvolcanic laccolith. The more important small mines and prospects within North Pole Dome include The Normay Au, Breens Cu, North Pole barite and Miralga Creek Au-Ag-Zn-Pb-Cu deposits.

At the Normay Au deposit (749600mE, 7664900mN), production to 1989 is estimated from published and unpublished records at about 475 kg Au, and resources 1998 totalled 162,000 t at 16.0 g/t Au (Louthean 1999). The host rocks of the Normay deposit are tholeiitic basalt, dolerite and pyroxenite sills immediately overlying the moderately north dipping northern contact of the North Pole monzogranite. The Au deposit occurs within an east striking, steeply dipping shear as a lode of parallel 0.2-2.0 m quartz veins that are commonly banded. At depth Au mineralisation is intimately associated with pyrite, galena, some chalcopyrite and rare sphalerite. The mineralised structure has been traced over 1000 m with most production from shallow open pits and underground workings to 138m over about 400 m strike. Sipa geologists (I 9109) note that the Au is very fine-grained and possibly epithermal. Hickman (1983) relates Normay to the ca 3460 Ma North Pole monzogranite.

At the Breens Cu deposit (746000mE, 7664800mN), production to 1979 was 41.5 t of Cu from a complex of stratabound mineralisation, stockworks and strongly silicified breccia zones within a northeast striking, 500 m wide belt of bleached, silicified and brecciated mafic to felsic volcanic and volcanoclastic rocks of the Duffer Formation (Hickman 1983). Within the belt, the most prominent features are two strongly silicified breccia zones with fractured amorphous chert and fine-grained quartz, which, in places, are up to several tens of metres thick. Drilling of an east dipping breccia zone intersected massive sulphides containing pyrite, chalcopyrite, chalcocite, minor covellite, neodigenite, and native copper. Marston (1979) notes that the silicified breccia zones post-date the stockwork mineralisation and stratabound mineralisation. From Marston's description of alteration and mineralisation style, it is possible that Breens contains both early volcanogenic sulphides and later low temperature, high level breccia hydrothermal mineralisation. Breens is noted by Witt et al (1998) as epithermal style Cu mineralisation associated with sub-volcanic silicic intrusives.

The Breens deposit is noted by Maitland (1919) as 'a gold deposit of a type somewhat unusual in the North West' and he shows the lodes as saddle reef 'of country rock impregnated with gold contents from circulating solutions in which silica etc has been absent'.

The North Pole barite occurence (753800mE, 7665000mN) consists of the stratabound barite lenses in an 8km long stratigraphic zone immediately below the lower most unit of the Towers Formation (Griffin 1990, Ferguson 1999). Although the North Pole barite deposits were originally interpreted as of sedimentary (sabkha) origin (Dunlop 1978, Hickman 1973), later investigations, including company drilling programs show the barite to be associated with fine grained galena and sphalerite and led to an alternative model that the stratabound barite was probably of exhalative origin with an associated vein stockwork (Hickman 1990, I2760). Of note, the Big Stubby VMS Cu-Pb-Zn sulphide deposit near Marble Bar has abundant barite gangue (Reynolds et al 1975).

Miralga Creek Au-Zn-Pb-Cu (Marble Bar (2855) 764100mE, 7658900mN)

The Miralga Creek Au-Ag-Zn-Pb-Cu deposit is the most studied and best documented epithermal deposit in the Pilbara. Most of the following comments are based directly on Groves (1987) and Goellnicht et al (1988).

The prospect was discovered by conventional prospecting in 1983 and was explored by several companies, including Miralga Mining NL, Homestake Australia, and the Sipa-Ashling Joint Venture during the mid 1980s and 1990s. Goellnicht et al. (1988) indicated a resource of less than 1 t of Au from mineralised rock grading less than 2 g/t Au.

The geological focus of the Miralga Creek prospect is a high level felsic porphyritic stock and associated dyke swarms associated with a 1 km wide alteration zone of potassic/carbonate alteration around the intrusion. The intrusive rocks were emplaced in the basalts, dolerites and minor cherts of the Warrawoona Group and are geochemically similar to Duffer Formation felsic volcanics. Outcrop of the intrusive and mineralised system to the east is covered by the younger Mt Roe Basalt.

Disseminated stringer and hydrothermal breccia hosted mineralisation occurs within marginal breccias to the stock and dykes. At least two phases of mineralisation are recognised: early high temperature with high salinity fluids and later low-temperature with low to moderate salinity fluids.

Studies of fluid inclusions indicate that the early mineralising event formed from high temperature (> 600°C), high salinity (30–70 eq wt % NaCl) fluids that are interpreted as magmatic fluids from the porphyry stock. Inclusions representative of the later fluids homogenised below 250°C, with most homogenising around 160°C. These fluids are of low to moderate salinity (3-12 eq wt % NaCl).

The alteration around the stock also shows two distinct phases: an early quartz-muscovite-pyrophyllite±pyrite±rutile±phlogopite assemblage and a later ankerite-siderite-quartz assemblage. Carbon and oxygen isotopes are interpreted to identify the late stage fluid as mainly heated seawater.

Coxcomb, comb and crustiform textures, the mineral assemblage sphalerite-galena-tetrahedrite-Ag minerals and the metallogenic association, Pb-Zn-Cu-Ag-Au-As-Sb±Hg±Bi±Ti±Se, are typical of low sulphidation epithermal systems. There is vertical zonation of the metals with Au, Pb, Zn and Cu concentrated at different levels. The Miralga Creek deposit is interpreted by Groves (1987) and Goellnicht et al (1988) as a poorly mineralised felsic porphyry hydrothermal system overprinted by a later vein, stringer and breccia hosted epithermal mineralisation. Isotope data from Miralga Creek galena mineralisation shows a model age of ca 3.45 Ga (Thorpe et al. 1992b), which is consistent with more recent zircon U-Pb data of ca 3.45 Ga for the porphyry host rock and related Duffer Formation volcanism (Thorpe et al. 1992a).

Miralga Creek mineralisation has obvious similarities with several other Cu deposits in the felsic volcanics and high-level felsic intrusives exposed in the McPhee Dome and Kelly Belt. Groves (1987), in discussing economic significance, notes that 'the Au content of the Pilbara porphyry systems is low' compared presumably with the Phanerozoic deposits.

McPhee Dome (Nullagine (2954))

Within the McPhee Dome, which is centred about 70 km southeast of Marble Bar, Warrawoona Group volcanic rocks host a variety of hydrothermal Cu, Mo, W and F prospects and deposits. Most of the larger base metal deposits of the McPhee Dome have been considered as primitive Archaean porphyry Cu mineralisation (Marston 1979, Barley 1982, Barley and Groves 1984). Marston (1979) indicated that these deposits are characterised by an ore assemblage dominated by pyrite with lesser chalcopyrite and/or molybdenite that occur as disseminations and fracture coatings in the host volcanics or in quartz or chalcedony veins and veinlets. Associated alteration assemblages are characterised by quartz, kaolinite, chlorite, epidote and carbonate. Marston (1979) notes that it is difficult to distinguish between primary hydrothermal alteration and weathering.

The geology and association of Cu, Mo and W in the Wallabidee Ridge, McPhee Creek East, Gobbos, Lightening Ridge, and Cookes Creek prospects is consistent with models for Phanerozoic porphyry Cu-Mo deposits. However, previous interpretations of the origin of the other Cu prospects of the western McPhee Dome, including Copper Gorge, Otways, Bridget North East (Marston 1979) and a Zn-Ag prospect at Quartz Circle (Ferguson 1999) are worth reconsidering in the context of high sulphidation epithermal models. At Quartz Circle (Ferguson 1999), both massive and vein type base metal mineralisation, including pyrite, sphalerite and galena, occur in coarse breccias. Stockwork of quartz vein Cu mineralisation is also present; a resource of 190,000 t of 0.44 g/t Au and 2.7% Cu (Louthean 1999) has been defined for this latter zone.

The possibility of epithermal type Au mineralisation spatially related to the porphyry Cu and Cu-Mo prospects of the McPhee Dome was recognised by Hunter Resources in the late 1980s (I 3831). Stream and rock chip geochemistry by Hunter Resources found some anomalous Au values but failed to identify any epithermal prospects as such. There is some indirect evidence of low temperature, hydrothermal mineralisation in the area from Noranda's exploration for Cu-Zn (I2761) near the Lionel Mining Centre. The Noranda exploration found two cinnabar occurrences and strong Hg in soil anomalies (0.21- 4.0 ppm with extreme values of 10 and 80 ppm Hg) in dolerite sediments and felsic rocks close to the contact between the Duffer Formation felsic sequence and the overlying Salgash Subgroup mafic volcanics.

Kelly Belt (Split Rock)

West of McPhee's Dome ca 3460-3475 Ma Lower Warrawoona Group volcanic rocks and the felsic, ca 3307 Ma Boobina Porphyry (Hickman and Lipple 1975, Pidgeon 1984, Thorpe et al. 1992a) are well exposed over a 50 strike km along the southeastern flank of the Corunna Downs Granitoid Complex. There are two clusters of small Cu mines and prospects (Copper Hills, which is centred at 807600mE, 7602200mN, and Kelly's, which is centred at 797200mE, 7587400mN) that are hosted in the ca 3465 Ma (Thorpe et al. 1992a) Duffer Formation felsic volcanic rocks and associate high level intrusive rocks.

The only significant production is from the Copper Hills mine, where 1960 t of Cu was produced mostly from supergene oxides and sulphides including malachite, azurite, chalcocite and bornite. Marston (1979) notes that primary pyrite and chalcopyrite is disseminated in the porphyries and on fractures. He also notes the absence of quartz vein stockworks in comparison with the Breens, McPhees and Coppin Gap deposits. Drill core shows sections of the mineralised porphyry are strongly chloritised and epidotised. The pervasive kaolinite-sericite overprint in outcrop is related by Marston (1979) to the oxidisation of sulphides during weathering.

The other prospects, Copper Hills South, Copper Hills West, Kellys and Ryans, show more evidence of small scale structural control with stronger mineralisation related to shears, breccias, veinlets, and stockworks. Towards the north end of the Kelly belt there is a swarm of WNW trending chalcedonic and quartz veins with characteristic epithermal textures which were mapped by Ingram (1972). The veins located in an area centred at 193000mE, 7617000mN are not obviously related to the Kelly Belt Cu prospects. Witt et al (1998) classify Copper Hills as epithermal style Cu mineralisation associated with sub-volcanic silicic intrusives. Marston (1979) interprets the Kelly belt Cu prospects as structurally controlled quartz stockwork tensional veins and shears, and the three Western McPhee Dome Cu prospects as stratabound. Although Marston (1979) describes the McPhee Dome prospects, Breens and Copper Hills as primitive Archaean porphyry Cu systems, he notes the lack of zoned hydrothermal alteration. However, the common features of mineralisation, alteration and host rocks suggest a common origin.

Meentheena Fluorite (Mt Edgar (2955) 239000mE, 7648000mN)

The Meentheena Fluorite deposits, which are located 75 km east of Marble Bar, are one of the two largest fluorite deposits in Western Australia. The deposits were discovered by conventional prospecting in 1971 and evaluated during the 1970s. A resource of 13,000 t of 50% CaF_2 has been indicated. Hickman's (1974) description of the deposits and their geological setting are the principal source of these notes. The fissure vein quartz fluorite deposits occur as conjugate vein sets, with orientations of 60° and 135°, that cut the Mt Roe Basalt. The pattern of veins may be related to regionally extensive north-trending faults, the Meentheena Fault and a sub-parallel splay fault. Low temperature siliceous quartz and quartz-fluorite veins extend over an area of about 4 km^2 which straddles the Nullagine River. The larger quartz fluorite veins, which are up to several tens of metres thick and 200 m in length, are more restricted and occur in two clusters, each within an area of about 0.5 km^2 either side of the Nullagine River about 2 km south of Tumbianna Pool.

Typical veins, as described by Hickman (1974), have an outer zone of quartz and a wider central zone of quartz and white fluorite with fluorite often showing banding parallel to the vein margins. Walls of the veins are silicified and brecciated with bleached country rock quartz and 'chert' in a matrix of white fluorite with late stage purple fluorite veins cutting the breccias. Several generations of quartz occur including 'platey' quartz. There are also thick veins, predominantly of calcite, on the margins of the mineralised area. In one of the larger fluorite veins, east of the Nullagine River, there are minor occurrences of primary and secondary Pb and Cu minerals, including galena, malachite, brochanthite, and atacamite.. Hickman (1974) suggested the veins are epithermal on the basis of mineralogy. Vein structures, textures, and alteration are all quite consistent with this interpretation. The Meentheena deposit has been dated at 2740 Ma (Pb model age, Richards and Blockley 1984), which is consistent with its relationship to the Mt Roe Basalt. Fluorite is a mineral which forms under a widely varying conditions (Dana and Ford 1958) and is not uncommon in high-level hydrothermal vein deposits. Hickman (1974) considers that the fluorite may be derived from remobilisation of fluorite in basement rocks, e.g. the fluorite-rich Cookes Creek granite (35 km south of Meentheena) or directly from a Proterozoic alkalic intrusives. In the absence of any direct or indirect evidence of alkalic intrusives, remobilisation from the older Archaean basement seems most likely.

Cinnabar and Mercury Anomalies

Elevated to strongly anomalous levels of Hg are characteristic of high-level low temperature hydrothermal deposits, both syngenetic and epigenetic. While nearly all the world's economic production is from regions with late Tertiary tectonism and volcanism, Hg minerals and Hg anomalism can be preserved in similar settings of older terranes. Strata bound Cu-Zn deposits of volcanogenic origin commonly contain in excess of 1 ppm Hg (Davey et al. 1981) and in the 1970s/1980s companies exploring for VMS mineralisation in the Pilbara commonly used Hg as a geochemical pathfinder. Literature research, largely of company reports in WAMEX files from this period, identifies a number of occurrences of cinnabar and/or anomalous Hg in geochemical samples following from these programs. The best documented occurrences are summarised in Table 2 and all are from within the Marble Bar or Nullagine 1:250 000 sheets. In most cases, descriptions are insufficient to categorise the occurrences, and it should be noted that some of the cherts with anomalous Hg could represent either cherty exhalites or sinters. Two occurrences, Split Rock and Just in Time, are probably related to the earliest period of Fortescue Group volcanism. The others may reflect older Archaean mineralisation.

Table 2. Cinnabar and Hg anomalies of the East Pilbara granite-greenstone terrane.

Name	Location	Reference	Description	Comments
Mercury Hill	North Shaw 2755 712000mE, 7637000mN; 710000mE, 7642500mN	WAMEX 3314, 4556 and 6657	Felsic tuffs with cherts and gossans that have anomalous Cu, Pb, Zn, Cd, Ag and Hg	Two 'prospects' and probably both cherty exhalites
Lionel	Nullagine 2954 202300mE 7595000mN	WAMEX 2761	Cinnabar in pyritic banded cherts within sediments/felsic volcanics. Cinnabar also occurs at the contact with dolerite/ultramafic. Soil sample values to 80 ppm Hg.	Two cinnabar occurrences about 500 m apart.
Miralga	North Shaw 2755 Marble Bar 2855 758700mE 7665400mN and 762700mE 7660100mN	WAMEX 3541	Barite-galena-cinnabar-quartz veins in thin felsic dyke with up to 295 ppm Hg. Narrow shear alteration zone contains 1.9 ppm Au, 920 ppm Hg, 23ppm As, 7.2% Zn, 1.8% Pb, 270 ppm Ag	Two localities, both of which may be epithermal vein systems. See also Groves (1987).
Just-in-Time	Marble Bar 2855 782200mE 7647200mN	Simpson 1951	Water worn granules of cinnabar found in 'alluvial gold'.	Found in 1912; first cinnabar occurrence in Western Australia. Hickman (1983) describes Just in Time as an auriferous conglomerate at base of Mt Roe Basalt.
Split Rock	Split Rock 2854 765000mE 7629400mN	Ingram 1972	Mercury reported from sediments in Fortescue Group mafic volcanics.	No other details.

Vein and Vein Stockworks in Granitoids

Extensive areas of the large granitoid complexes and batholiths of the East Pilbara granite-greenstone terrane are covered by thin sheets of Quaternery, colluvium and alluvium. Although regional geological and radiometric maps emphasise exposure of the granitoids, at a local scale often the only outcrops are of more resistant mafic dykes and 'quartz' veins, sheeted veins, stockworks. The siliceous veins have diverse origins. Probably most are related to late phases of granitoid intrusion. However, there are also siliceous veins with distinctive epithermal textures, which are clearly much later than the granitoid complexes. There are also quartz veins that locally contain base metal oxide and sulphide minerals which have an uncertain origin. For most of these minor base metal prospects, there is insufficient information to establish origin but some may be epithermal. Table 3, which is mainly from Ferguson (1999), summarises occurrences of base metal-quartz veins in the East Pilbara granite-greenstone terrane. Although none of these occurrences are economically important, some may be clues to previous unrecognised late, high-level hydrothermal systems in the North Pilbara granite-greenstone terrane.

DEPOSITS OF THE GREGORY RANGE INLIER

The most extensive epithermal vein systems in the study area are hosted in the late Archaean rocks of the Hamersley Basin on the eastern side of the Pilbara Craton. The low temperature-low pressure siliceous vein systems of the Gregory Range Inlier occur across a 30 km wide, NNW trending, strongly faulted complex of basalt sediments, felsic volcanics, high level felsic intrusions and granitoids that extends over 150 km (Fig. 7). Recent 1:100 000 scale geological mapping of the Isabella, Braeside and Pearana sheets (Williams and Trendall 1997, 1998a,b) have clarified the relationship of these rocks to the rest of Pilbara Craton from which they are separated by Phanerozoic rocks of the Wallal Embayment. The eastern margin of the Gregory Range Inlier is in contact with the Proterozoic Paterson Orogen.

Survey mapping, geochemical studies and geochronology have established that the Gregory Granitoid Complex (syenogranite, granophyre) and Koongaling Volcanic Member (felsic volcanics) are co-magmatic and essentially contemporaneous at ca 2.76 Ga (Nelson 1997). Included within the granite complex are substantial rafts of strongly metamorphosed schistose metasediments and amphibolites which may be either metamorphosed Hardey Formation (lower Fortescue Group) or remnants of older Archaean greenstones (Williams and Trendall 1998a,b).

Most of the major contacts in the Gregory Range Inlier are strike extensive NNW trending faults which Trendall (1991) interpeted to divide the Inlier into six structural fault slices. The major faults, which appear to have a long and complex history, are highlighted by ridges of quartz and multiple quartz veins. Quartz, cryptocrystalline quartz and chalcedony veins of the Gregory Inlier can be subdivided into at least three systems, the distribution of which follows three major rock packages: (1) lower Fortescue Group mafic volcanics and sediments, (2) Koongaling felsic volcanics and (3) the Gregory Granitoid Complex (Figure 7).

The Fortescue vein system occurs within the Newdegate slice (Williams and Trendall 1998a,b) between the Antiform and Barramine Faults. The veins occur mostly along NNW trending, steeply east dipping faults in shallowly west dipping Kylena and Maddina Basalts. The Fortescue veins include the Ag-enriched base metal veins of the historic mines and prospects of the Braeside Pb field.

The Koongaling vein system occurs within the Isabella and Tanguin tectonic slices (Williams and Trendall 1998a,b) between the Antiform and Camel Hump Faults. These veins also occur along NNW trending, steeply east dipping faults. Although generally similar to the Fortescue vein system, the Koongaling veins contain no economically significant precious or base metals.

The Gregory Granite vein system occurs within the Isabella and Tanguin tectonic slices (Williams and Trendall 1998a,b) between the Camel Hump Fault and the Archaean-Proterozoic unconformity on the westerm flank of the Paterson Orogen. The unusual quartz hematite Gregory Granite veins are quite unlike those of the Fortescue and Koongaling systems.

Table 3. Granite-hosted quartz veins of the East Pilbara granite-greenstone terrane.

Name	Location	Reference	Geology	Comments
Cookes Creek Pb-Ag-F	Nullagine (2954) 236000mE 7604500mN	Ferguson (1999)	Quartz-fluorite veins in ca 2.60 Ga Cookes Creek granite. Galena in late stage quartz fluorite veins.	Could be epithermal.
Hillside Pb	Tambourah (2754) 751900mE 7607600mN	Blockley (1971)	Coarse-grained galena pods on margins of east-trending quartz vein in granite gneiss that is close to a major NNE-trending dolerite dyke.	Within the central part of the Shaw Granitoid Complex close to internal contact with Cooglegoong Adamillite and Sn-Ta pegmatites.
Abydos Pb	White Springs (2654) 698700mE 7611100mN	Ferguson (1999)	Galena, cerrusite and anglesite disseminated or in small bunches within east-trending, narrow, steeply dipping quartz vein that trends 150° in granite gneiss of the Yule Granitoid Complex.	
Lynas Find Pb	Wallaringa (2656) 699900mE 7678500mN	Ferguson (1999)	Galena and cerrusite in quartz vein that trends 150° and dips 80°E in granite gneiss of the Carlindi Granitoid Complex.	The Pb model age is 2.74 Ga.
Tabba Tabba Pb	Wallaringa (2656) 694500mE 7713500mN	Ferguson (1999)	Galena in quartz vein in Carlindi Granitoid Complex.	
Wodgina Pb-Zn	Wodgina (2655) 656400mE 7631000mN	Blockley (1971)	Finely granular galena with sphalerite, anglesite, cerrusite, smithsonite and hemimorphite that occurs in a 1.5 m wide quartz vein in granite of the Yule Granitoid Complex.	'West Wodgina' location of Blockley (1971) is doubtful; it may be the same as the Middle Cu-Pb prospect (this table).
Bassets Cu-Pb	Wodgina (2655) 659400mE 7064700mN	I 2605	Disseminated malachite in 2 m wide lodes that extend over 250 m within NNW trending 'chert' bands in biotite adamellite or granodiorite of the Yule Granitoid Complex. Stronger Cu mineralisation occurs in 2 m x 80 m area.	Variously referred to as chert or a quartz reef.
Middle Cu-Pb	Wodgina (2655) 665200mE 7658500mN	I 2605	Disseminated galena (<1% Pb) and malachite in north-trending, 2-8 m quartz reef that extends 1400 m in porphyritic biotite adamellite or granodiorite of the Yule Granitoid Complex)	
Mt Francisco Cu	Wodgina (2655) 661000mE 7634300mN	Marston (1979)	Malachite in quartz vein and disseminated in ?biotite granite of the Yule Granitoid complex.	Production: 4.23 t of oxide ore grading 4.23% Cu.
Flat Rock Pb-Ag	Mt Bilroth (2454) 591300mE 7601600mN	Blockley (1971)	Galena in pods in quartz veins that strike 105° and 195° in granite close to the unconformity with the Fortescue.	Production: 1.15 t Pb and 0.38 kg Ag. Mineralisation is interpreted as pre-Fortescue Group.
Boodarri Station Cu	Wallaringa (2656) 667000mE 7715500mE	Marston (1979)	Disseminated malachite in 46 m long quartz vein that trends 340° in granitoid gneiss.	Production: 1.22 t of oxide ore grading 5.9% Cu.

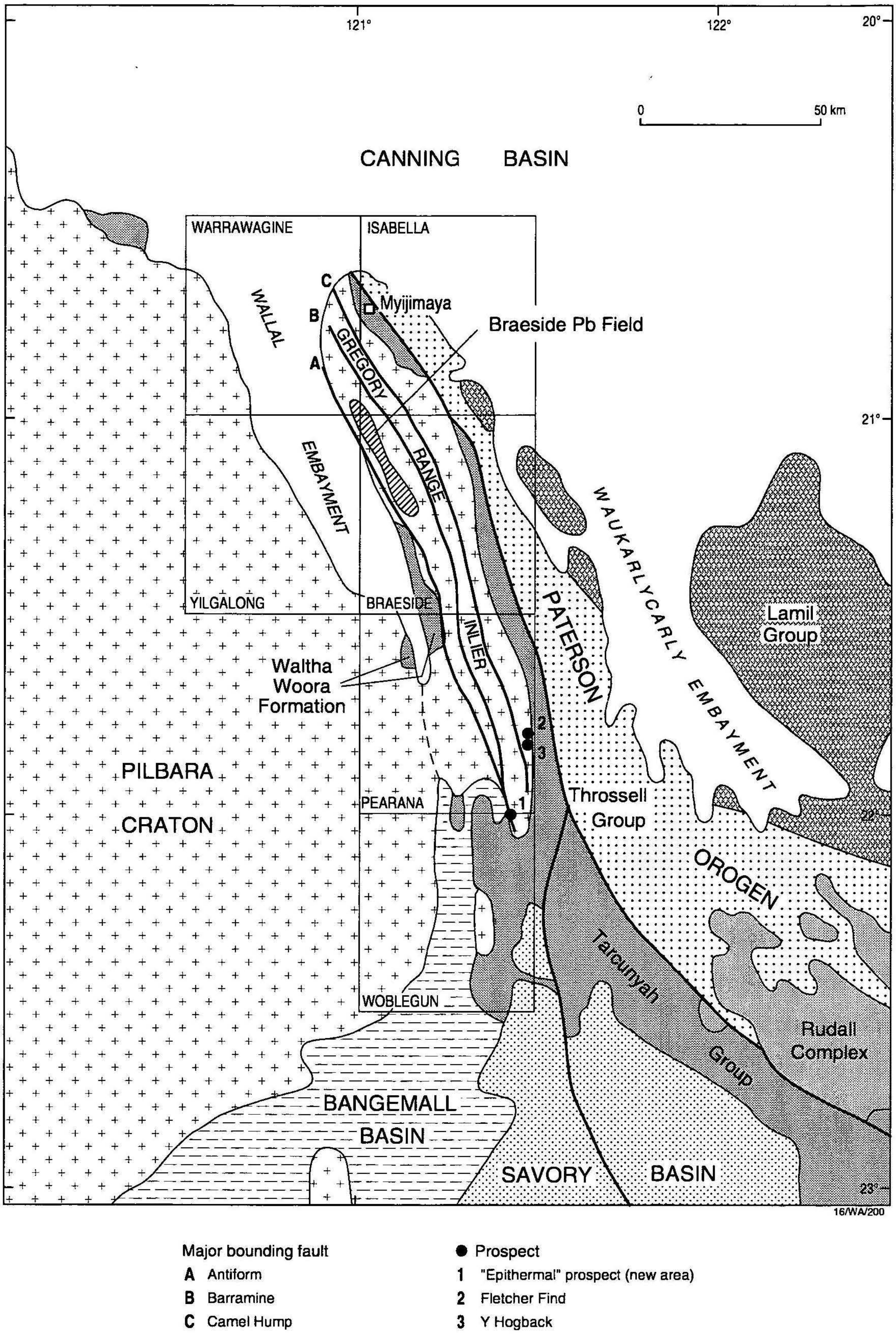

Figure 7. Epithermal deposits of the Gregory Range Inlier (modified after Williams and Trendall, 1998a).

In this review, regional and district geological setting of the vein systems is drawn largely from Williams and Trendall (1998a,b) and deposit details of the Fortescue system from Finucane (1938), Blockley (1971), Marston (1979), and Ferguson (1999). Details of the Koongaling and Gregory Granite vein systems are from Williams and Trendall (1998a,b) and unpublished Newcrest exploration reports.

Fortescue Vein Systems

The Ag-rich base metal veins of the Fortescue system extend over an area of about 250-500 km^2 including 5 x 34 km Braeside Pb field as defined by Blockley (1971). In all, some 24 base metal and Ag mines and prospects are recorded along the western margin of the Gregory Inlier by GSWA mapping on Warrangine (2), Isabella (2), and Braeside (18) sheets. Total recorded production from the Braeside Pb field is 3217 t Pb, 25 t Zn and 919 kg Ag (~30,000 oz) was produced mostly between 1947 and 1959. Ninety percent of this production is from the most southerly deposit, the Ragged Hills Mine.

The vein deposits are localised on 300-340°-trending faults that dip 75-85° to the east. Most veins occur between the major bounding Barramine and Antiform Faults and are hosted by Kylena or Maddina Basalt. Within the Braeside Pb field, most of the Fortescue rocks dip 5-30° to the west. Although some veins and composite veins are mapped over tens of kilometres, ore shoots of the individual prospects are quite restricted; typically they are 50-150 m in strike length. Although the composite body of quartz veins and veins swarms may be up to 15 m thick, massive and disseminated base metal sulphides and oxides occur within 1-2 m thick lenses. Blockley (1971) notes that in the larger vein systems the Pb minerals are confined to marginal veins and seem to be later than the main period of quartz emplacement. The control of ore shoots at a mine prospect scale is not recorded for most deposits other than a note by Blockley (1971) that Ragged Hills is a cymoid loop structure, that is a flexure within the composite veins. The vein quartz and sulphide lenses shows textures typical of open space filling: quartz-filled breccias, and banded and crustiform veins. The composite veins are dominantly quartz with lesser argentiferous galena, sphalerite, chalcopyrite, bornite and pyrite. Secondary base metal minerals extend to about 15 m vertical depth and include mostly cerrusite and angelsite, with lesser minor pyromorphite, smithsonite, malachite, cuprite and other minerals. The Moxam Well prospect (also known as Lightening Ridge) is notable for secondary V minerals including vanadinite, descloizite and mottramite. Blockley (1971) also notes that much of the galena is fine-grained (1-2 mm) and suggests it may have been tectonised by later movement on the controlling structures.

In outcrop, obvious silicification and chloritisation of the basalts does not appear to extend more than 5 m beyond the vein margins. The exploration geochemical signature of the Fortescue veins is simple: varying proportions of anomalous Pb, Zn, Cu and Ag. The more northerly mines and prospects on the Isabella and Warrangine sheets are mostly Cu rather than Pb deposits.

Lead isotope data from galena in veins and from amydales in Kylena Basalt give model ages 2.35 to 2.74 Ma with most determinations between 2.64 and 2.74 Ga (Williams and Trendall 1997), which are only slightly younger than the host Fortescue Group rocks.

Structures, textures, mineralogy, geochemistry and alteration of the Fortescue veins systems are all consistent with the base metal zone of Buchanan's (1981) model for low sulphidation vein deposits. They are interpreted to have formed deep in the epithermal system near the upper pressure-temperature limits.

Koongaling Vein System

A feature of the eastern flank of the Gregory and Isabella Ranges are strike extensive NNW trending ridges capped by white vein quartz outcrops. The Koongaling vein system extends over about 150 strike km across the Isabella, Braeside and Pearana 1:100 000 sheets. There are no historic base metal or precious metal prospects in the veins. They were first recognised as a distinct system by Newcrest geologists in the early 1990s during a campaign of geochemical prospecting for epithermal Au in the Gregory Ranges and were mapped by GSWA in programs by Williams and Trendall in 1991 and 1992. The veins are along both the major faults on the margin of the Isabella and Tanguin slices, the Barramine and Camel Hump Faults, and other sub-parallel and anastomosing faults within the slices. Within these tectonic slices the faults cut the Koongaling Volcanic Member, which contains alkaline rhyodacite and dacite and the granophyric unit of Gregory Granitic Complex.

Although the faults can be traced for tens of kilometres, the composite veins are typically 30-50 m, but up to 100 m, wide with strike lengths of 0.5-1.0 km and, exceptionally, to 2km.

The composite veins (Figure 8) exhibit a typical open space filling textures, including banded, crustiform (Figure 9) and colloform veins, breccias (Figure 10) and highly irregular stockworks reflecting multiple episodes of cracking, deposition and sealing of the hydrothermal systems.

Figure 8. Multiple veins in the Koongaling vein system.

The vein material is dominantly crystalline quartz, including amethystine quartz microcrystalline quartz, with minor, disseminated to banded, very fine-grained pyrite. Much of the more chalcedonic silica appears to be a replacement of carbonates. The most southerly of the Koongaling veins, Newcrest's Epithermal prospect (Woblegun (3153) 335200mE, 7559500mN) show well developed textures of platey calcite replaced by microcrystalline quartz. Both within and on the margin of the complex veins, there is strong alteration of country rock, including silicification and argillic alteration, but it is difficult to establish from outcrop the limits of this alteration. At the Epithermal prospect there is better exposure and here it can be seen that the width of mostly argillic alteration zones is several orders of magnitude wider than the widths of the siliceous veins.

Figure 9. Crustiform banding in the Koongaling vein system.

Extensive rock chip sampling of the Koongaling veins by Newcrest showed some elevated to anomalous Cu, Pb and Zn and some erratic high Ni and Mo values, but Au and Ag values were generally at or below their respective limits of detection, 1 ppb and 0.1 ppm, respectively.

Figure 10. Quartz-carbonate breccia in Koongaling vein system.

Although there are some strong similarities between the Fortescue and Koongaling vein systems, the latter are notably thicker, have greater strike extent, and probably a consistently wider alteration envelope. The two veins systems have probably developed in very similar hydrothermal systems. The Koongaling veins may represent higher levels in the Buchanan (1981) model for low sulphidisation epithermal vein deposits.

Gregory Vein System

On the Braeside and Pearana sheets east of the Camel Hump Fault and west of the escarpment of the Googhenama Formation (ca 1.0 Ga Tarcunyah Group) there is substantial outcrop of the Gregory Granitoid Complex in the dune pavement exposed in interdunal corridors. Rising above the dune pavement there are outcrops of several generations of siliceous veins that generally follow NNW trending faults. In two areas there are distinctive complex veins of cryptocrystalline quartz and hematite: south of

Memorial Bore (Braeside (3155) 322600mE, 7643000mN) and around Newcrest's Y Hogback prospect in the Fletchers Find area (Pearana (3154) 342200mE, 75705000mN). The Memorial Bore veins have been mapped by Williams and Trendall (1998a,b) as quartz-hematite (martite) veins.

The veins of the Y Hogback area (Figures 11 and 12) trend both NNW and NNE and dip generally steeply to the west. The relationship of these veins to the Fletchers Find Au prospect has not been established. In the same general area, Williams and Trendall (1998a) have mapped siliceous mylonites, and some of the quartz hematite veins may be a high level overprint of hematitisation and silicification over early faults and shears. Away from the ridges that contain more prominent veins and silicified argillically altered country rock, hematite alteration is common in the granitoids and rafts and xenoliths of the schistose metasediments and the amphibolites. There is also very strong hematitisation in the conglomerates and sandstones of the basal Tarcunyah Group and immediately underlying metamorphosed Archaean rocks.

Figure 11. Quartz-hematite veins near Fletchers Find, Gregory vein system.

Extensive geochemical prospecting by Newcrest over this area did not show any distinctly anomalous base or precious metal values in the quartz hematite veins. Newcrest prospecting along some faulted and quartz vein areas along the unconformity showed elevated to somewhat anomalous Cu, Ni and Co values but again no significant Au.

The Gregory quartz-hematite vein systems have no obvious affinities with the Fortescue or Koongaling vein systems other than their general orientation, although in the Y Hogback area the quartz-hematite veins dip west rather than east as in the Fortescue and most of the Koongaling vein systems. The quartz-hematite veins are probably high level and relatively low temperature hydrothermal deposits, and if the strong haematitisation around the Paterson unconformity is also of hydrothermal origin, the veins are Neoproterozoic in age.

Figure 12. Quartz-hematite veins at Y Hogback Prospect, Gregory vein system.

DISCUSSIONS, CONCLUSIONS AND RECOMMENDATIONS

In considering the conclusions of this review, the limitations and bias of the study data base should be recognised. While the review is part of a regional program to upgrade the geological database and evaluate the mineral potential of the North Pilbara granite-greenstone terranes the source data for this section on low temperature-low pressure siliceous veins is heavily dependent on what are often only incidental references in company exploration reports. Reports on mineral exploration in the region are very unevenly distributed both in time and space. Most of the epithermal and 'possible' epithermal vein occurrences reviewed here were not discovered during exploration for precious metal deposits of this type. Out of several thousand WAMEX open file company exploration reports for the Pilbara, only 3% have any direct or indirect reference to epithermal mineralisation and only three report on programs investigating the potential for such deposits in the region. Most company programs in the Pilbara during the 1970s and 1980s were exploration for VMS or porphyry Cu-Mo mineralisation. In the Pilbara overall and even on the major base metal finds, there has been relatively little drilling on most prospects and hence there is a dearth of geological data in the third dimension. Collectively these factors are a serious constraint in recognising epithermal mineralisation.

Regional Patterns of Mineralisation and Geological Controls

High level siliceous hydrothermal deposits, nearly all of the low sulphidation model (Buchanan 1981), are widely scattered across the North Pilbara Craton. While there is a variety of metallogenic associations, including some very unusual associations in the somewhat exotic deposits such as Elizabeth Hill Ag and Sullam Ni, the metal suite for most Pilbara epithermal deposits, Au-Ag-Pb-Cu-Zn-Sb-As, is quite unexceptional. The majority of deposits and prospects considered in this review are clustered around Whim Creek, Marble Bar, and Braeside. The relatively large number of epithermal prospects in the small area around Whim Creek, compared with other areas in the North Pilbara, is a direct result of exploration focus. However, this also follows from the preservation of sub-aerial and shallow water mafic and felsic volcanics and related high level intrusives which record multiple episodes of volcanism within a rift system active between ca 3.00 to 2.77 Ga. The variations between individual Whim Creek prospects may be due to different cycles of volcanism but more likely reflect various different levels of exposure within the Buchanan (1981) low sulphidation epithermal model.

In the Marble Bar district, the best documented occurrences of high level siliceous vein deposits occur within high level felsic intrusives related to felsic volcanics of the lower Warrawoona Group (Hickman 1983). In the district, there is a common link between the calc-alkaline volcanic centres of the Warrawoona Group and many of the base metal deposits variously interpreted as VMS or porphyry style. However, the recognition of Miralga Creek as an epithermal style Cu mineralisation associated with high level felsic volcanics, and accepting more limited evidence that Copper Hills and Breens deposits are of similar style, it seems probable that many, if not most, of the Cu and Zn prospects of the North Pole and McPhees Dome and Kelly Belt were formed in a similar systems. While the epithermal veins of Miralga Creek have the characteristics of low sulphidation systems, the geological setting of the Warrawoona Group calc-alkaline centres is also permissive for the high sulphidation model.

The epithermal mineralisation related to the calc-alkaline centres of the lower Warrawoona Group in the Marble Bar and Nullagine 1:250 000 sheets, is the oldest in the North Pilbara Craton and as observed by Groves (1987) probably the oldest well preserved epithermal systems in the world.

The well documented Ag-base metal vein deposits of the Braeside Pb field (east Pilbara) are without question epithermal and may represent deeper levels of the low sulphidation epithermal model of Buchanan (1981). However, immediately east of the Fortescue vein systems in separate tectonic slices, there are two other regionally extensive zones of epithermal mineralisation, the Koongaling and Gregory vein systems. In these tectonic slices the vein systems are preserved at much higher levels and both tectonic zones are quite under explored. Most of these Pilbara occurrences appear to have formed around ca 2.74 Ga, but there is some evidence that similar hydrothermal systems may have been active at later periods, possibly up into the youngest Proterozoic.

In the Whim Creek district, while it is possible that epithermal mineralisation related to the calc-alkaline volcanic centres of the Whim Creek Group is preserved, all of the currently documented prospects and occurrences are post folding of the Whim Creek Group and probably post deformation of the Louden Volcanics. In essence, the Whim Creek epithermal deposits are related to the development of proto Fortescue rifts on the North Pilbara Craton. These are dominantly north- to northeast-trending structures which form the locus for deposition of the early Fortescue volcanics and sediments particularly the Mt Roe Basalt, and the intrusion of late Archaean granitoids (e.g. the Opaline Well leucogranite). This association of high level siliceous veins and the lower Fortescue Group rocks is common across the entire North Pilbara Craton. Although in many areas the deposits may be hosted in the old Archaean greenstones, the mineralisation relates to the deposition of the younger Archaean rocks.

Mining History and Exploration Potential

The exploration and mining history of low temperature siliceous vein deposits of the North Pilbara Craton is unexceptional. Summarising earlier comments, the majority of the epigenetic veins with economic levels of Ag, Pb and Cu were found by conventional prospecting over some 50-60 years and these deposits have only produced minor Pb (1950s) and oxide Cu (1950s and 1960s). Nearly all of this production has been from deposits around Braeside and south and east of Marble Bar. Even accepting that the Normay Gold Mine is an epithermal deposit, Au production from low temperature veins in the Pilbara has been small.

The revival of Au exploration and mining in WA since the 1980s has had limited impact on the North Pilbara Craton. Witt et al (1998) estimates that from the early 1980s only 10% of exploration expenditure in Western Australia has been on the Pilbara Craton and only 6 of 142 new mining operations are in the Pilbara.

Exploration management perception is that because the Pilbara Craton is better exposed than the Yilgarn and to date has been less productive for Au and base metals that it has lower potential. While the discoveries at Elizabeth Hill (Ag) and Indee (Au) have had some impact on exploration management thinking, the original argument remains current and is, to some extent, a self fulfilling prophecy.

Exploration Recommendations

Following from this review, there are several specific conclusions and recommendations relevant to future mineral exploration in the Pilbara. They are:

- Most widespread low temperature high level hydrothermal activity in the Pilbara is associated with rifting of the North Pilbara Craton and deposition of the oldest of the Fortescue Group volcanics and sediments, and intrusions around ca 2.76 Ga. The Fortescue rocks and the older granite greenstone terranes along the proto Fortescue rift systems have received little attention from exploration companies. Results of exploration for precious metal epithermal deposits around Whim Creek and Munni Munni complex (Elizabeth Hill) indicate that these rifts and possibly later calc-alkaline centres in the younger Fortescue rocks are prospective for precious and base metals.
- The stratabound and structurally controlled base metal deposits in the oldest greenstones of Marble Bar and Nullagine 1:250 000 sheets, particularly the deposits within the Lower Warrawoona Group calc-alkaline volcanic centres, should be re-examined in the light of current continuum models for VMS, porphyry and epithermal precious and base metal mineralisation. Notwithstanding that base metal exploration in these areas has so far failed to locate any economic deposits, the systems still remain largely unexplored for precious metals.
- For contemporary mineral explorers, Ag-Pb-Cu vein deposits typical of the Braeside field (East Pilbara) are not attractive targets. However, Braeside field covers only a small section of the Gregory Inlier, which is a long lived structural zone (late Archaean to Neoproterozoic) with extensive high level siliceous vein systems. The Gregory Range Inlier vein systems are very under-explored.
- Silver deposits such as Elizabeth Hill should be attractive targets for small exploration and mining companies. While there remains unanswered questions on the genetic model for the Elizabeth Hill deposit, a simple exploration model based on deposit features and geological setting indicates a variety of other areas for prospecting within the North Pilbara.

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Note added in proof: Well developed epithermal textures have been recently documented in the Becher vein deposit to the southeast of the Mallina Homestead (D. Huston, pers. Comm., 1999)

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APPENDIX 1. WAMEX COMPANY EXPLORATION REPORTS.

Wamex Item No	*Title*	*Company*
I 967	Poverty Creek copper zinc exploration	Australian Inland Exp. Co Inc.
I 2605	Stannum nickel-copper copper-lead exploration	Australian Base Metals NL and Pancontinental Mining Ltd
I 2760	North Pole copper-lead-zinc exploration	Newmont Pty Ltd.
I 2761	Lionel Copper zinc exploration	Noranda Australia Ltd and Southern Gold Mines
I 3314	Mercury Hill copper zinc chromite gold exploration	Hancock and Wright Prospecting Pty Ltd
I 3541	Miralga gold base metal exploration	Noranda Australia Ltd
I 3831	McPhee Creek platinum gold exploration	Hunter Resources Ltd
I 4556	Mercury Hill gold base metals exploration	MIM Exploration Co Pty Ltd and Esmerelda Exploration Ltd
I 5997	Karratha gold/base and precious metal exploration	AGIP Australia Pty Ltd
I 6066	Whundo copper-zinc exploration	Dominion Mining Ltd
I 6567	Mercury Hill gold exploration	MIM Exploration Pty Ltd
I 6934	Bookingarra copper lead zinc gold exploration	Dominion Mining Ltd
I 7562	Mt Negri copper-zinc and gold exploration	Dominion Mining Ltd
I 9109	North pole gold base metals exploration	Sipa Resources Ltd
I 9424	Comet Well gold exploration	Xplore Pty Ltd