

Neoproterozoic Telfer-style Au (Cu) deposits

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EXPLORATION MODEL

Examples

Telfer (Main Dome and West Dome), Western Australia; Pine Creek and The Granites–Tanami goldfields, Northern Territory; Sabies-Pilgrim's Rest goldfield, South Africa.

Target

- Over 4 million ounces (125 tonnes) of Au produced.
- Current geological Au resources are 355 Mt of ore @ 0.46 g/t Au (5.2 Moz) for open pits, and 2 Mt of ore @ 17.1 g/t Au (1.2 Moz) for underground operations.
- Current geological Cu resources are 154 000 t for open pits and 33 000 t for underground operations.

Mining and treatment

- Open pit and underground mining.
- Thin (<3 m), shallowly dipping, stratiform to stratabound orebodies ('reefs') are stripped off pit walls by bulldozers (reef-mining).
- Stockwork and pod mineralisation with insufficient grade, continuity, and thickness to be mined as reefs are removed by open-pit block-mining.
- Underground ore removed by 'drift and fill' mining.

Regional geological criteria

- Associated with Neoproterozoic (700–600 Ma) orogenesis.
- Located in weakly metamorphosed (lower to sub-greenschist facies) and deformed sedimentary basins.
- Shallow marine to carbonate-shelf/slope turbiditic sequences host mineralisation.

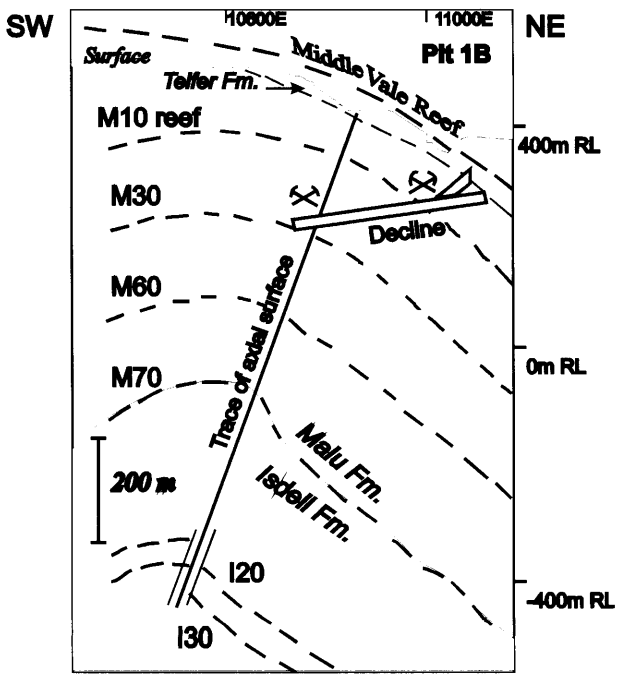

Figure 1. Cross-section of the stacked-reef ore system at Main Dome. Note the underground mining of the M10 and M30 reefs (redrawn and modified from an unpublished Newcrest Ltd report).

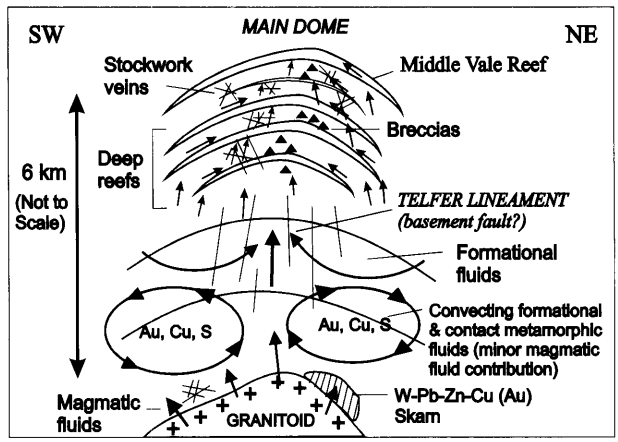

Figure 2. Schematic cross-section of the Telfer mineralisation model. Arrows represent the various fluid pathways.

- Strike-slip faults (geophysical expression) may be significant.
- Doubly plunging anticlines (i.e. domes) prominent.
- Neoproterozoic granitoids in the vicinity.
- Related styles of mineralisation in the district include porphyry Cu–Au, Au skarn, W–Pb–Zn skarn, and stratiform sulphide–Au replacement reefs (mantos).

Local geological criteria

- Hypogene mineralisation occurs late in the deformation event responsible for dome formation.
- Preferred host rocks generally calcareous and carbonaceous siltstones of the ~1000–750 Ma Yeneena Group.
- Local structural controls on ore distribution include zones of folding, dilation, and bedding-plane slip.
- Vertical extent of deposit is at least 1.5 km.
- Mineralisation is inferred to be 700–600 Ma, the age of proximal regional granitoids.

Mineralisation features

- Series of vertically stacked, stratiform to stratabound, high-grade quartz–sulphide (± secondary Fe oxides) reefs centred on anticlinal hinges.
- Reefs linked by lower grade stockwork vein arrays and sheeted vein sets.
- Mineralogy in both reef and vein styles of mineralisation is similar.
- Hypogene ore assemblage consists mainly of Au, pyrite, chalcopyrite, and pyrrhotite, with lesser galena, sphalerite, scheelite, and Pb–Co–Ni sulphides.
- Common gangue minerals include quartz, sericite, calcite, dolomite, ankerite, tourmaline, and albite.
- Supergene enrichment important, but not critical, in producing high Au and Cu grades.
- Supergene minerals include chalcocite, bornite, enargite, malachite, azurite, and chrysocolla.
- Mineralogical zonation is weak. Higher concentrations of galena, sphalerite, and scheelite are noted at greater depths.

Alteration

- No distinct vertical or lateral zonation.
- Silicification, sericitisation, carbonatisation, and pyritisation dominant, with lesser tourmalinisation and albitisation. Minor monazite and xenotime.
- Original composition of sedimentary host rock influences predominating type(s) of alteration.

Deposit geochemical criteria

- Carbonate and silica alteration widespread; lesser sericitic alteration.
- Relative to host rocks, major reefs are enriched in Au, Cu, As, Bi, Co, Ni, La, Ce, Y, B, Pb, Zn, W, Mo, and Sn.
- Sulphide Pb isotopes indicate a small component of 'magmatic Pb' in the ore fluids.
- Sulphide S isotopes (–7 to 10‰) consistent with a predominantly sedimentary source of S.
- High S/Se ratios (>100 000) of vein pyrite discriminate Telfer from porphyry-centred ore systems.
- Tourmaline B isotopes (–14 to –12.6‰) exclude S of marine evaporitic origin in the ore fluids.
- Carbonate C and O isotopes indicate C in ore fluids from primary marine carbonate in host rocks. Oxygen is a mixture of formational, magmatic, and contact-metamorphic fluids.

Surficial geochemical criteria

- Arid weathering and near pervasive Quaternary and Permian sedimentary cover are problematic for soil geochemistry.
- Silicified and ferruginised gossans typically show enrichment in Au, As, Cu, Co, W, Bi, and Sb.
- Lanthanides, Th, Ti, U, Zr, and Sn are also useful indicators in some instances.

Geophysical criteria

- Regional geophysics (gravity, magnetics) useful for defining regional stratigraphy (i.e. the magnetic Wilki Formation) and identifying buried intrusive rocks.
- The narrowness of the reefs, the deep oxidative weathering, and the presence of electrically resistive beds make direct detection of mineralisation by geophysical methods very difficult (Sexton 1994).
- Mineralisation has no gravity or magnetic signature.
- Direct current resistivity techniques were of limited use during initial mapping of quartz–sulphide reefs.
- Electromagnetic pulse surveys at Main Dome detected subtle responses coincident with the Middle Vale Reef (MVR), but these were too small to be of practical value (Sexton 1994).

Fluid chemistry and source

- Fluid-inclusion studies show ore fluids are complex mixtures of H_2O, CO_2, CH_4 and a variety of salts.
- Moderate to high salinity (~15–54 wt.% NaCl eq.).
- Contain up to 20 mol.% CO_2 and several mol.% CH_4.
- Low fO_2 (no primary magnetite, hematite or sulphate).
- pH acid to mildly alkaline.
- Pressure of ore formation estimated at 2±1 kbar.
- Fluid unmixing ('boiling') very minor or absent.
- Au and Cu likely transported as chloride complexes. Some complexing of Au with reduced S ligands also possible as fluid cools.
- Ore deposition the result of cooling, dilution, and changes in pH and fO_2 due to fluid mixing and interaction with host rocks.
- High salinity due to both heated formational brines and evolved granitic fluids.
- Reduced and carbonic nature of fluids reflects dissolution of marine carbonate and oxidation and/or hydrolysis of reduced carbonaceous matter in sedimentary host rocks (yields CH_4 and CO_2).

Comments on genesis

- Originally considered a syngenetic exhalative deposit modified by regional deformation and dome formation (e.g. Tyrwhitt 1985).
- Subsequent studies showed mineralisation replacive and epigenetic in origin, with ore fluids probably derived mainly from a granitic source (e.g. Goellnicht et al. 1989, Goellnicht 1992).
- Dimo (1990) considered Telfer to be the distal Au halo of a giant porphyry Cu–Au system.
- More recent geochemical studies led Rowins (1994) and Rowins et al. (1995, 1997) to propose that the ore fluids and contained solutes are from predominantly sedimentary sources. The granitoids act primarily as a source of heat to initiate and drive the hydrothermal convection cells in which metal leaching occurs.
- Appears to be a unique age for major Au mineralisation in Australia and the world.

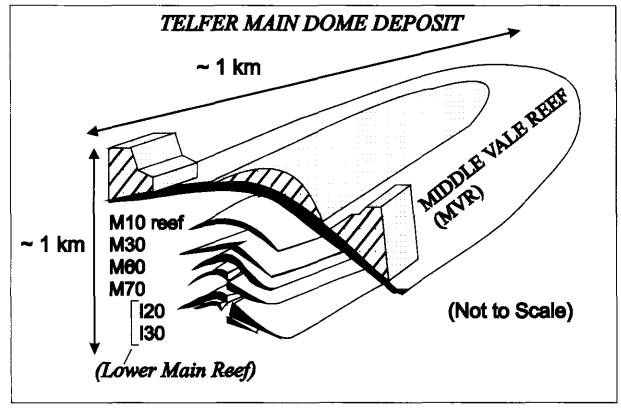

Figure 3. Schematic 3-D representation of the stacked-reef ore system at Main Dome. View is to the north-northwest and only the major reefs are shown (redrawn and modified from an unpublished Newcrest Ltd report).

Introduction

The Telfer Gold Mine, in the Paterson Province of north-central Western Australia (see fig. 1 in Goellnicht et al. 1989), is one of Australia's largest Au deposits with more than 4 Moz (or 125 t) of Au produced since mining began in 1977. Gold is mined from a series of vertically stacked, stratabound to stratiform, Au–Cu horizons (termed 'reefs') linked by zones of intense stockwork and sheeted veining. Mineralisation is localised in two en-echelon, asymmetric, doubly plunging anticlines, referred to as Main Dome and West Dome. Together, they define the NW-trending Telfer Dome. The reef style of mineralisation, the Meso–Neoproterozoic age of the marine sedimentary host rocks, and its geological setting within a polymetallic (Au, Cu, W, Pb, Zn, U) province distinguish Telfer Dome mineralisation from other major Au deposits of the world.

The origin of the Telfer orebody has been contentious since the mineralisation was discovered in 1972. Several genetic models have been proposed, including a modified syngenetic exhalative hypothesis (Tyrwhitt 1985) and, more recently, an epigenetic replacement hypothesis (Goellnicht et al. 1989, Dimo 1990, Goellnicht 1992). In this latter model, metals, S, and alkali elements in the ore fluid are derived predominantly from a granitoid source, as opposed to a sedimentary one. Support for an epigenetic origin and the involvement of granitic fluids came largely from the recognition that quartz–sulphide reefs commonly are not stratabound, and also the finding that Telfer ore fluids are saline (up to 54 wt.% NaCl. eq.), high-temperature (225–450°C), and contain a small proportion of Pb from magmatic sources (Goellnicht et al. 1989). Both Dimo (1990) and Harley & Charlesworth (1992) proposed that Telfer mineralisation represents the distal Au halo of a giant Neoproterozoic porphyry Cu–Au system. Interestingly, such a porphyry deposit does occur ~15 km north of Telfer at 17 Mile Hill (Rowins et al. 1993, Rowins 1994).

New isotopic and mineral compositional data on sulphides and alteration minerals, together with recent information on the morphology of the Telfer orebody from deep (up to 1.5 km) exploration diamond drillholes, however, militate against ore fluids and solutes being mainly magmatic in origin (Rowins 1994, Rowins et al. 1995, 1997). Significantly, deep drillholes at Main Dome and West Dome did not intersect elements of a porphyry-style 'feeder' system, such as more widespread zones of stockwork veining (as opposed to the restricted zones linking some reefs) and intense potassic and propylitic types of hydrothermal alteration. In this paper, the role of granitoids in the mineralisation process at Telfer is more clearly defined and pertinent exploration criteria for the discovery of new *Telfer-style* orebodies are discussed.

District and mine geology

The Paterson Province (~36 000 km^2) is part of the ~700 Ma Paterson Orogen (Williams & Myers 1990). This orogen is either a collisional zone between the Western Australian Plate and the northern Australian Province to the northeast (e.g. Myers 1993) or an intracratonic setting with orogeny related to crust–mantle delamination and subduction during a period of crustal shortening (e.g. Etheridge et al. 1987, Wyborn et al. 1987).

The Telfer Mine lies in the northeastern tectonic zone (hereafter called the Telfer district) of the Paterson Province. It is hosted by the Yeneena Group, a >9 km thick Neoproterozoic sequence of weakly metamorphosed marine sedimentary rocks which overlie the complexly deformed Mesoproterozoic basement gneisses of the Rudall Complex (Williams & Myers 1990, Clarke 1991). After deposition, the Yeneena Group was intruded by dolerite and then underwent lower to sub-greenschist facies metamorphism and folding and thrusting during the Paterson Orogeny (D_4 of Clarke 1991), producing a province-wide northwesterly structural trend. This trend is expressed as regional lineaments on Landsat images and image-processed gravity and aeromagnetic data. Some lineaments may reflect sub-vertical basement faults, but their typical lack of surface expression hinders a definitive conclusion. A district-scale NW-trending corridor, approximately 15 km wide and centred about the Telfer Dome, is informally termed the Telfer Lineament.

Synchronous with the Paterson Orogeny was the intrusion of granitoids in the Telfer district. Nelson (1995) gave ages of 621±13 Ma (SHRIMP U–Pb zircon) and 633±13 Ma (SHRIMP U–Pb zircon) for the Mt Crofton and Minyari monzogranites, respectively. Goellnicht (1992) gave an age of 617±64 Ma (Pb–Pb mineral isochron) for the O'Callaghan Granite. Some granitoids truncate D_4 structures in the Yeneena Group, implying that felsic magmatism continued after cessation of major deformation. Volcanic rocks are not recognised in the Telfer district. Detailed descriptions of the granitoid plutons are given in Goellnicht et al. (1991) and Goellnicht (1992).

From 1977 until 1992, mining at Telfer focussed on the shallow quartz–sulphide reefs and low-grade stockwork vein arrays in the 'Mine Sequence' of the Telfer Formation (see fig. 3 in Dimo 1990). The Mine Sequence is an informal term for the succession of calcareous, argillaceous, and locally carbonaceous siltstones, sandstones, and dolomitic rocks which host mineralisation in the upper 500 m of the mine. The major Au-bearing horizon, the Middle Vale Reef (MVR), is hosted by the Middle Vale Siltstone Member, and the E_{1A}, E_1, and E_2 reefs (collectively, the E-reefs) are hosted in the stratigraphically higher Outer Siltstone Member. The MVR, described in detail by Goellnicht et al. (1989), is a laterally extensive, semi-conformable, thin sheet of massive pyrite mineralisation. The highest grades occur in quartz–pyrite–chalcopyrite mineralisation on the steeper northeast limb of Main Dome. The highest stratigraphic section of the MVR comprises laminated, crudely banded or massive pyrite, with minor chalcopyrite, pyrrhotite, galena, sphalerite, free Au, and interstitial quartz. The lower section comprises fractured, milky white, coarse-grained vein quartz with minor interstitial sulphides. Along strike, the reef thins to a concentration of concordant and slightly discordant quartz veins. The lateral stratigraphic equivalents (i.e. down-dip) of both the MVR and the E-reefs are carbonate and mixed chert–carbonate units with sparsely disseminated pyrite and carbonaceous material. Carbonate C and O isotope studies indicate that the mudstones and siltstones of both the Middle Vale Siltstone Member and the Outer Siltstone Member were preferentially replaced during infiltration of epigenetic mineralising fluids, which resulted in the formation of the bulk of the quartz and pyrite in the concordant reefs (Rowins 1994). Thus, stratabound reef formation is controlled not only by bedding-plane slip, but also by replacement of favourable sedimentary horizons.

Oxidation and supergene enrichment have enhanced ore grades in the Mine Sequence (up to 90 g/t Au and 20% Cu), although hypogene Fe±Cu sulphide ores may possess similar grades. Mining was open cut until early 1990, but now includes both open cut (West Dome) and underground (Main Dome).

The deeper level mineralisation in the Malu and Isdell Formations underlying the Telfer Formation is referred to as the 'Telfer Deeps' (Figs 1, 3). In many cases, reefs cannot be correlated between Main Dome and West Dome. Because the deep reefs have not always undergone intensive supergene Au enrichment, their ore grades may be low (5–25 g/t Au) relative to the supergene ores higher up the sequence. Some of the highest ore grades (10–30 g/t) and thickest parts (1–3 m) of the deep reefs occur along the inferred hinge zones of both domes, coincident with zones of extensive brecciation and axial planar faulting.

The deep reefs and associated vein mineralisation are petrographically and mineralogically similar to stratigraphically higher equivalents, with several minor exceptions. Galena, sphalerite, scheelite, and a combination of Pb, Co, and Ni sulphides are more abundant in several of the deeper reefs, as is hematised

albite in some deep discordant veins at West Dome.

The main alteration assemblages at Telfer are silicification, sericitisation, carbonatisation, and pyritisation; tourmalinisation and albitisation are minor. The original composition of the sedimentary host to mineralisation has influenced which types of alteration are predominant. Reefs and veins in argillaceous (pelitic) sandstones and calcareous and dolomitic siltstones of the Isdell Formation are associated with sericite and carbonate, whereas mineralisation in quartzose sandstones of the Malu Formation is more closely associated with quartz.

The relative timing of mineralisation at Telfer can be deduced from interrelationships between metamorphism, deformation, and the main stages of veining and host rock replacement. Based on microstructural studies of the MVR, and constant orientations of Main Dome stage veins (vein descriptions in Goellnicht et al. 1989) across limbs in both Main Dome and West Dome, Goellnicht et al. (1989) inferred that mineralisation formed either after or late in the doming event.

Genetic model

Sulphur, C, O, B, and Pb isotopic studies on ore sulphides and related alteration minerals (carbonate and tourmaline), in conjunction with tourmaline and pyrite mineral chemistry, led Rowins (1994) to conclude that solutes in the ore fluid were derived chiefly from the sedimentary host rocks rather than the Neoproterozoic granitoids. Support for this interpretation includes:

(1) a wide range of $\delta^{34}S$ values from hypogene pyrite in veins and reefs from Main Dome (–2 to 9.3‰) and West Dome (–7 to 10‰), which overlaps those of diagenetic/syngenetic sulphides in carbonaceous host rocks (–23.8 to 11.2‰, most between 3 and 11‰);
(2) S/Se ratio of >100 000 in hypogene pyrite, implying a sedimentary source of S and Se in the ore fluids;
(3) Pb-isotope compositions of ore-associated sulphides from Main Dome and West Dome, which are almost as radiogenic as those of the upper Yeneena Group host rocks, implying Pb contributions from magmatic sources were minor;
(4) carbonate $\delta^{13}C$ and $\delta^{18}O$ values from mineralised veins and reefs, which typically range from –3 to 3‰ and 13 to 18‰, respectively. The calculated $\delta^{13}C$ and $\delta^{18}O$ values of coexisting equilibrium fluids (250–450°C) are consistent with C derived via dissolution of primary marine carbonate in the host rocks (i.e. rock-buffered), with O comprising a mixture of formational, contact-metamorphic, and lesser magmatic fluids (i.e. fluid-buffered);
(5) mineralisation-related dravitic tourmaline, which is consistent, based on major-element source-rock discrimination diagrams, with Ca, Mg, Al, and Fe having been scavenged from pelitic and psammitic rocks;
(6) calculated $\delta^{11}B$ values of fluids (–9.0 to –0.6‰) in equilibrium with mineralisation-related tourmaline (–14.0 to –12.6‰), which excludes B of marine evaporitic origin in the ore fluids, and implies that B is liberated from clastic host rocks during the Paterson Orogeny.

In the model for *Telfer-style* mineralisation, granitoids are interpreted to act essentially as heat sources that drive thermal convection cells in which heated contact-metamorphic/saline formational fluids scavenge Au, Cu, and S from the surrounding sedimentary wall rocks (Fig. 2). Although this model has similarities to the convective porphyry copper model of Cathles (1981), the Main Dome and West Dome deposits cannot be considered distal parts of a giant porphyry Cu–Au deposit. The vertically stacked, replacement reef style of mineralisation, together with the lack of hornfels, proximal granitoids, and potassic and propylitic alteration assemblages characteristic of porphyry Cu deposits, indicates that the Telfer Dome deposits did not form in the near-porphyry environment. These data do imply, however, highly focussed fluid flow to the domal sites of mineralisation after an initial period of extensive deep fluid circulation, in which S and metals were scavenged from the sedimentary wall rocks adjacent to the pluton(s). A regional-scale structure capable of focussing fluids may be the NW-trending Telfer Lineament, upon which the Telfer Dome is situated. During the Paterson Orogeny, periodic reactivation of this basement structure would allow for episodes of widespread fluid circulation at depth under essentially lithostatic fluid pressures, followed by rapid ingress of fluids into the structure, triggered by a decrease in fluid pressure during reactivation.

Evidence for efficient fluid focussing on a mine scale comes from the extensive brecciation and axial planar faulting along the anticlinal hinge zones of both Main Dome and West Dome. This locus of brecciation and faulting suggests strongly that the anticlinal hinge zone is the central conduit through which pulses of hot, buoyant, hydrothermal ore fluid ascended, before infiltrating upward into chemically favourable horizons (carbonaceous and calcareous siltstones) and structurally favourable sites (dilational zones) where deposition of metals occurred. Gold and Cu likely are transported as chloride complexes, with reduced S complexes possibly transporting Au upon cooling of the fluid (e.g. Huston & Large 1989). The uncertainty concerning Au transport arises from apparent changes in the solubility of Au chloride complexes at lower temperatures. Meinert (1989) advocates a switch from Au transport as a chloride complex to a reduced S complex to explain the distal position of Au mineralisation, relative to base-metals, in many skarns and porphyry Cu systems. Solubility data for Au suggest that it is transported as a chloride complex above ~300°C in fluids with suitable Cl activity (Huston & Large 1989). However, near 300°C, there is a solubility minimum of chloride-complexed Au, and reduced S complexes become more effective ligands. Consequently, Au solubility in the fluid increases again and Au is transported further away from the plutonic heat source. Gold may be deposited from these cooler fluids by any mechanism that destabilises reduced S complexes. At both Main Dome and West Dome, pH and redox changes are most likely, given the abundance of carbonaceous and calcareous lithologies in the host Telfer, Malu, and Isdell Formations. Transport of Cu and other base metals is probably dominated by chloride complexes throughout all stages of fluid evolution (Burnham & Ohmoto 1980). Mechanisms that destabilise base-metal chloride complexes are not necessarily the same as those that destabilise Au bisulphide complexes and, therefore, complex metal zonation is a possibility at Telfer and in similar ore systems.

To summarise, the formation of *Telfer-style* mineralisation requires the coincidence of a number of important geological factors. These include:

(1) emplacement of a large plutonic complex near a periodically reactivated, regional-scale, fluid-focussing structure;
(2) permeable sedimentary host rocks, in which heated formational and contact-metamorphic fluids can circulate in large, thermal convection cells and leach metals and S;
(3) host rocks with background Au of the order of ~2–7 ppb (see Romberger 1988 for leaching requirements and background concentrations of Au in potential source rocks);
(4) abundant aquifers of saline formational waters in the sedimentary sequence (to provide the ligands required for Au and Cu transport as chloride complexes) and;
(5) chemical (calcareous and carbonaceous lithologies) and structural traps (anticlinal hinge zones) for the deposition of Au and Cu sulphides from ore fluids.

Implications for exploration

Given that granitoids are probably at least 5 km from Telfer, and are not the major sources of S and metals, it is unlikely that they are first-order vectors to this type of mineralisation. Thus, there is a fundamental difference in exploration strategy for *Telfer-style* mineralisation with respect to *porphyry Cu–Au-style* deposits, such as 17 Mile Hill. In the latter case, it is important to target prospective granitoids and then execute a sampling and drilling program aimed at identifying possible metal zonation around the intrusion. For *Telfer-style* mineralisation, however, emphasis should be placed on the identification of regional structures and, in particular, domes. *Telfer-style* deposits will not occur without such regional-scale structures to focus rapidly and transfer hot, metalliferous, saline fluids into chemically and structurally favourable sites at higher stratigraphic levels.

Once a dome is identified, its potential to host replacement reefs and associated veins will depend on the interaction of a complicated set of geological factors (which include its proximity to a granitoid pluton). In hindsight, it is clear why the origin of the Telfer deposit generated such controversy. The complex nature of ore formation renders simple models inadequate and probably means that *Telfer-style* deposits will be rare. For example, a dome may be only weakly mineralised if located too far from a plutonic complex; insufficient heat and/or conductivity problems would prevent transport of ore fluids to the domal hinge areas and, consequently, fluids would deposit their metals at an early stage of evolution and not necessarily in the concentrations required to form an orebody. Too small a plutonic complex would inhibit the development of the large-scale thermal convection cells needed to scavenge metals and S from the surrounding sedimentary rocks. In other cases, convecting fluids simply may not leach source rocks with adequate background metal and S abundances or protores before their upward flow to favourable sites in the domes, where deposition of metals occurs.

Geochemical data particularly useful in discriminating between whether a dome contains *porphyry Cu–Au-style* or *Telfer-style* mineralisation include:

(1) hypogene sulphide Pb-isotope compositions;
(2) hypogene sulphide $\delta^{34}S$ values and;
(3) hypogene sulphide S/Se ratios.

The sulphide Pb-isotope data for Main Dome and West Dome contrast with those from the 17 Mile Hill porphyry Cu (Au) deposit in that ore sulphides contain very little Pb from magmatic sources. Similarly, if the $\delta^{34}S_{sulphide}$ values cluster tightly together within the range of magmatic sulphides, such as occur in miarolitic cavities of the Mt Crofton Granite (0 to 2‰; Rowins 1994), and in sulphides from 17 Mile Hill (0±3‰), then a porphyry Cu–Au deposit can be inferred. *Telfer-style* mineralisation shows much wider scatter. Similarly, sulphide S/Se ratios are <20 000 for porphyry Cu–Au deposits, whereas ratios >100 000 are likely for Telfer analogues.

Analogues of Telfer-style mineralisation

A survey of the literature shows that analogues of the Main Dome and West Dome deposits, in terms of both process of formation and style of mineralisation, are rare or nonexistent. The location of mineralisation in fine-grained siliciclastic sedimentary rocks at or near anticlinal hinge zones does raise the possibility that the ores are in part saddle reefs, similar to those in the Victorian and Hill End goldfields in Australia (e.g. Cox et al. 1991, Lu & Seccombe 1993, Forde & Bell 1994) and the Nova Scotia Meguma Group in Canada (Keppie 1976, Kontak & Smith 1989). The source of Au in saddle reefs is uncertain and there is lively debate on the evolution of the vein system (e.g. Cox et al. 1991, Forde & Bell 1994). In both Victoria and Nova Scotia, early workers regarded the mineralisation as genetically related to granitoids. More recently, however, Au and quartz in reefs are being attributed to fluids derived through metamorphic devolatilisation of either the sedimentary host rocks or deeper underlying crustal rocks (e.g. Kontak & Smith 1989, Cox et al. 1991).

Although some saddle-reef characteristics approximate those at Main Dome and West Dome, the style of folding at Telfer is much more open and the domes are an order of magnitude larger. More problematic, however, are the differences in ore-fluid temperature and composition: fluids in typical turbidite-hosted saddle reef deposits are considerably cooler (<400°C) and of much lower salinity (<6wt.% NaCl eq.) than at Telfer (e.g. Cox et al. 1991, Lu & Seccombe 1993). The mineralisation temperatures of up to 450°C at Main Dome cannot be the product of the sub-greenschist facies regional metamorphism during the Paterson Orogeny. This, plus the Pb-isotope evidence, implicates granitoids in the ore-forming process at Telfer and precludes a metamorphogenic model as applied to saddle reef mineralisation.

The Main Dome and West Dome deposits also have been compared to the Palaeoproterozoic 'flat reef' gold deposits in the Sabies-Pilgrim's Rest goldfield of South Africa (Goellnicht et al. 1989, Harley & Charlesworth 1992, Boer et al. 1993). Like Telfer, these reefs are epigenetic in origin, consist of quartz–pyrite–carbonate assemblages, and form centimetre to metre thick, shallowly dipping bodies, localised along bedding-plane shear zones (i.e. reefs are conformable to bedding) up to several kilometres long. Bedding-discordant veins and stockwork vein systems link some reefs. Silicification, sericitisation, and pyritisation are the dominant alteration styles associated with both reef- and vein-style mineralisation. The composition and physiochemical condition of the ore fluids also show many similarities to those at Telfer, although there is evidence from fluid-inclusion studies (Boer et al. 1993) for phase separation (i.e. boiling) in ore fluids at the Sabies-Pilgrim's Rest goldfield. Models emphasising magmatic processes, akin to those for porphyry Cu–Au systems (e.g. Harley & Charlesworth 1992), supported by stable isotope evidence for mostly magmatic fluid (e.g. Boer et al. 1993), conflict with those emphasising fluid mixing processes, akin to those for *Telfer-style* deposits discussed above, based on fluid-inclusion data (e.g. Anderson et al. 1992). Thus, detailed genetic comparisons with Telfer are difficult.

Geographically closer Au deposits with similar structural controls, and controlling structures that approach the scale of those at Telfer, are those of the Pine Creek goldfield in the Northern Territory. There, a variety of mineralisation styles, which include both bedding-subparallel saddle reefs/replacement bodies and discordant vein stockworks, are located commonly in doubly plunging anticlines, with discontinuous Au mineralisation extending several kilometres along hinge lines (e.g. Alexander et al. 1990, Matthäi et al. 1995). Fluid-inclusion studies (e.g. Sheppard 1992, S. Ho pers. comm. 1995) indicate that ore fluids were complex mixtures of H_2O, CO_2, CH_4 and a variety of salts, with moderately to highly saline fluid associated with Au deposition at ~250–400°C; i.e. similar to Telfer. Furthermore, genetic models that involve granitoids as heat sources, not major reservoirs of ore metals, have also been proposed for these deposits (e.g. Wall 1989). Gold deposits of the Granites–Tanami Inlier in the Northern Territory also share some features with Telfer (Wall 1989), and warrant further investigation as possible Telfer analogues.

Conclusions

There are no exact analogues of Telfer, but some smaller scale deposits, particularly those at Pine Creek, have several features in common. Mineralisation in the Telfer Dome consists of a series of vertically stacked, semi-stratiform to stratabound reefs, partially linked by stockwork and sheeted vein sets. These morphological data for the Telfer orebody together with the S, C, O, B, and Pb isotopic data, and the tourmaline and pyrite compositional studies, indicate that most components in the

ore fluid are leached from surrounding sedimentary rocks by formational/contact-metamorphic fluids circulating in granitoid-driven thermal convection cells. Deep basement faults permit the focussing of large volumes of ore-bearing fluids to the eventual sites of mineralisation in the domes (favourable sedimentary lithologies and structures) away from the near-porphyry environment. Although granitoids are not a major source of the S and metals in *Telfer-style* deposits, they do play a critical role in their formation and cannot be disregarded in any exploration model.

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References

Alexander, K.R., Kavangh, M.E. & Rolfe, G.L., 1990. The Cosmo Howley gold deposit, In: Hughes, F.E. (editor), Geology of the mineral deposits of Australia and Papua New Guinea. Australasian Institute of Mining and Metallurgy, Monograph 14, 751–753.

Anderson, M.R., Rankin, A.H. & Spiro, B., 1992. Fluid mixing in the generation of mesothermal gold mineralization in the Transvaal Sequence, Transvaal, South Africa. European Journal of Mineralogy, 4, 933–948.

Boer, R.H., Meyer, F.M., Robb, L.J., Graney, J.R. & Vennemann, T.W., 1993. The nature of gold mineralization in the Sabie-Pilgrim's Rest goldfield, eastern Transvaal, South Africa. Economic Geology Research Unit, University of Witwatersrand, Johannesburg, Information Circular 262, 33pp.

Burnham, C.W. & Ohmoto, H., 1980. Late-stage processes of felsic magmatism. Mining Geology (Japan) Special Issue, 8, 1–11.

Cathles, L.M., 1981. Fluid flow and genesis of hydrothermal ore deposits. Economic Geology, 75th Anniversary Volume, 424–457.

Clarke, G.L., 1991. Proterozoic tectonic reworking in the Rudall Complex, Western Australia. Australian Journal of Earth Sciences, 38, 31–44.

Cox, S.F., Wall, V.J., Etheridge, M.A. & Potter, T.F., 1991. Deformational and metamorphic processes in the formation of mesothermal vein-hosted gold deposits—examples from the Lachlan fold belt in central Victoria, Australia. Ore Geology Reviews, 6, 391–424.

Dimo, G., 1990. Telfer gold deposits, In: Hughes, F.E. (editor), Geology of the mineral deposits of Australia and Papua New Guinea. Australasian Institute of Mining and Metallurgy, Monograph 14, 643–651.

Etheridge M.A., Rutland, R.W.R. & Wyborn, L.A.I., 1987. Orogenesis and tectonic processes in the Early to Middle Proterozoic of northern Australia. American Geophysical Union, Geodynamics Series, 17, 131–147.

Forde, A. & Bell, T.H., 1994. Late structural control of mesothermal vein-hosted gold deposits in Central Victoria, Australia: Mineralization mechanisms and exploration potential. Ore Geology Reviews, 9, 33–59.

Goellnicht, N.M., 1992. Late Proterozoic fractionated granitoids and their role in the genesis of gold and base-metal mineralization in the Telfer district, Western Australia. Ph.D. Thesis, University of Western Australia (unpublished).

Goellnicht, N.M., Groves, D.I., McNaughton, N.J. & Dimo, G., 1989. An epigenetic origin for the Telfer gold deposit, In: Keays, R.R., Ramsay, W.R.H. & Groves, D.I. (editors), The geology of gold deposits: the perspective in 1988. Economic Geology Monograph 6, 151–167.

Goellnicht, N.M., Groves, D.I. & McNaughton, N.J., 1991. Late Proterozoic fractionated granitoids of the mineralized Telfer area, Paterson Province, Western Australia. Precambrian Research, 51, 375–391.

Harley, M. & Charlesworth, E.G., 1992. Thrust-controlled gold mineralisation at the Elandshoogte Mine, Sabie-Pilgrim's Rest goldfield, South Africa. Mineralium Deposita, 27, 122–128.

Huston, D.L. & Large, R.R., 1989. A chemical model for the distribution of gold in volcanogenic massive sulphide deposits. Ore Geology Reviews, 4, 171–200.

Keppie, J.D., 1976. Structural model for the saddle reef and associated gold veins in the Meguma Group, Nova Scotia. Canadian Institute of Mining and Metallurgy, Bulletin, 69, 103–116.

Kontak, D.J. & Smith, P.K., 1989. Sulphur isotopic composition of sulphides from the Beaver Dam and other Meguma-Group-hosted gold deposits, Nova Scotia: implications for genetic models. Canadian Journal of Earth Sciences, 26, 1617–1629.

Lu, J. & Seccombe, P.K., 1993. Fluid evolution in a slate-belt gold deposit—a fluid inclusion study of the Hill End goldfield, NSW, Australia. Mineralium Deposita, 28, 310–323.

Matthäi, S.K., Henley, R.W., Bacigalupo-Rose, S., Binns, R.A., Andrew, A.S., Carr, G.R., French, D.H., McAndrew, J. & Kavanagh, M.E., 1995. Intrusion-related, high-temperature gold quartz veining in the Cosmopolitan Howley metasedimentary rock-hosted gold deposit, Northern Territory, Australia. Economic Geology, 90, 1012–1045.

Meinert, L.D. 1989. Gold skarn deposits—geology and exploration criteria, In: Keays, R.R., Ramsay, W.R.H. & Groves, D.I. (editors), The geology of gold deposits: the perspective in 1988. Economic Geology Monograph 6, 537–552.

Myers, J.S., 1993. Precambrian history of the West Australian Craton and adjacent orogens. Annual Review of Earth and Planetary Sciences, 21, 453–485.

Nelson, D.R., 1995. Compilation of SHRIMP U–Pb zircon geochronology data, 1994. Geological Survey of Western Australia, Record 1995/3, 244 pp.

Romberger, S.B., 1988. Geochemistry of gold in hydrothermal deposits. United States Geological Survey, Bulletin 1857-A, A9–A25.

Rowins, S.M., 1994. A geochemical study of Late Proterozoic gold and copper mineralization in the Telfer District, Western Australia, with a special emphasis on porphyry copper–gold-style deposits. Ph.D. Thesis, University of Western Australia (unpublished).

Rowins, S.M., Groves, D.I., McNaughton, N.J., Brown, P.E., McLeod, R.L. & Hall, D., 1993. Evidence of unusually carbonic and reduced ore fluids in the Late Proterozoic Seventeen Mile Hill porphyry copper-style deposit. Telfer district, Western Australia. 2nd National Meeting of the Specialist Group in Economic Geology, Geological Society of Australia, Abstracts, 34, 68–70.

Rowins, S.M., Groves, D.I. & McNaughton, N.J., 1995. Neoproterozoic orogenesis and gold–copper mineralization in the Telfer Dome, Western Australia. Precambrian '95 International Conference on Tectonics and Metallogeny of Early/Mid Precambrian Orogenic Belts, Program and Abstracts Volume, 52–53.

Rowins, S.M., Groves, D.I., McNaughton, N.J., Palmer, M.R. & Eldridge, C.S., 1997. A reinterpretation of the role of granitoids in the genesis of Neoproterozoic gold mineralization

in the Telfer Dome, Western Australia. Economic Geology, 92, 133–160.

Sexton, M.A., 1994. Geophysical characteristics of the Telfer gold deposits, Western Australia, In: Dentith & seven others (editors), Geophysical signatures of Western Australian mineral deposits. University of Western Australia, Geology Department and University Extension, Publication 26, 33–41.

Sheppard, S., 1992. An early Proterozoic shoshonitic lamprophyre-granite association and its relationship to the Tom's Gully gold deposit, Mt. Bundy, N.T., Australia. Ph.D. Thesis, University of Western Australia (unpublished).

Tyrwhitt, D.S., 1985. Exploration, development, and geology of the Telfer Gold Mine, Great Sandy Desert, Western Australia, In: Prospecting in arid areas, First International Conference, Rabat, Morocco. Institution of Mining Metallurgy (London), 11–19.

Wall, V.J., 1989. Fluids and metamorphism. Ph.D. Thesis, Monash University (unpublished).

Williams, I.R. & Myers, J.S., 1990. Paterson orogen. In: Geology and mineral resources of Western Australia. Geological Survey of Western Australia, Memoir 3, 274–286.

Wyborn, L.A.I., Page, R.W. & Parker, A.J., 1987. Geochemical and geochronological signatures in Australian Proterozoic igneous rocks, In: Pharaoh, T.C., Beckinsale, R.D. & Rickard, D. (editors), Geochemistry and mineralization of Proterozoic volcanic suites. Geological Society (London), Special Publication 33, 377–394.

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