by Laurie J. Hutton¹, Terence J. Denaro¹, Courteney Dhnaram¹ and Geoff. M. Derrick²

Mineral Systems in the Mount Isa Inlier

¹Geological Survey of Queensland, Department of Employment, Economic Development and Innovation, GPO Box 15216, City East, QLD 4002, Australia. E-mail: laurie.hutton@deedi.qld.gov.au; terence.denaro@deedi.qld.gov.au; courteney.dhnaram@deedi.qld.gov.au

²G M Derrick Geology, 10 Central Ave, Graceville, QLD 4075, Australia. E-mail: geoffd@powerup.com.au

Northwest Queensland contains several world class mineral deposits, being one of the worlds leading producers of Zn, Pb, Cu and Ag. Rather than focus on mineral deposit models, as has been done in the past, we are using the mineral system approach (Barnicoat, 2008), where the whole system is studied at a variety of scales and a variety of processes, which culminate in the deposition of mineralisation. Seven Mineral Systems are identified, namely:

1. *Shale/siltstone/dolomite hosted Zn-Pb-Ag systems – Western Fold Belt*
2. *Ag-Pb-Zn in high-grade metamorphic terrains – Eastern Fold Belt Province*
3. *Structurally-controlled epigenetic iron oxide-Cu-Au – Eastern Fold Belt and Kalkadoon-Ewen Provinces*
4. *Structurally-controlled epigenetic Cu±Au mineralising system – Western Fold Belt Province*
5. *Phosphate Mineralisation in the basal Georgina Basin sequence*
6. *U and Rare Earth element (REE) mineralisation.*
7. *Fe Ore – South Nicholson Group*

Introduction

The NW Queensland Mineral and Energy Province (NWQMEP) can be regarded as the premier Zn-Pb-Cu region in the world (Geological Survey of Queensland, 2011).

The NWQMEP evolved as a Paleoproterozoic–Mesoproterozoic province of the North Australian Craton (NAC), from c. 1900–1500 Ma, in a largely far-field extensional back-arc to intracontinental setting over-riding the NE-dipping convergent margin of the Gawler Craton to the far S (Betts et al., 2003). Three major stacked superbasins developed on c.1900–1860 Ma crystalline basement – the Leichhardt Superbasin (1800–1750 Ma), the Calvert Superbasin (1740–1670 Ma), and the Isa Superbasin (1670–1595 Ma), containing extensional and sag-phase sedimentary packages with some volcanics and magmatic rocks, separated by unconformities. From c. 1680 Ma, an E-facing rifted continental margin may also have developed along the eastern margins of the NAC.

Basin development was largely terminated by compressional tectonism of NNW-SSE and E-W orientations from 1600–1500 Ma, accompanied by major felsic magmatism in the E. These events – the Isan Orogeny – produced the current geological setting of the Mt Isa

Inlier, comprising a central Kalkadoon-Leichhardt basement block flanked by eastern and western fold belts (Figure 1). More comments on the geodynamic setting of the Mount Isa Inlier are given in Gibson et al. (2012).

Thick pre-mineralisation clastic successions became important metal reservoirs and fluid aquifers (Polito et al., 2006) during formation of the world-class Pb-Zn deposits of the Isa Superbasin. Extensional environments also provided a complex network of syndepositional faults that were later reactivated to provide fluid conduits feeding metalliferous oxidised brines into reduced third-order sag basins of the Isa Superbasin (Figure 2), or the deeper water rifted basins of the eastern craton margins.

Most Cu deposits formed in the late tectono-magmatic cycle in shear, breccia and dilational structural environments, in new and reactivated fault systems. Oxidised warm to hot saline fluids ($\pm$ Fe) of magmatic and metamorphic origins were highly effective transporters of Cu and Au into structurally favourable (i.e., brittle) and reactive (e.g., magnetite-hematite) host rocks.

As well as being a major producer of Cu-Pb-Zn, the NWQMEP is also a significant producer of Ag and Au, the former as byproduct of the Pb-Zn deposits, and the latter as part of the Cu deposits. Younger Fe ore and phosphate deposits formed within and adjacent to the Mt Isa Inlier in Mesoproterozoic and Cambrian times respectively. More detailed aspects of mineralisation and mineral systems appear below.

Singer (1995) defined various criteria for the ranking of mineral deposits. World class Zn deposits for example contain a minimum of 1.7 Mt of Zn metal, and at least 6 such deposits occur in the NWQMEP – George Fisher, Century (Figure 3), Mt Isa (Figure 4), Dugald River, Cannington, and Lady Loretta, all of which make the NWQMEP the largest known repository of economically mineable Zn in the world. The George Fisher, Mt Isa, Cannington and Century deposits are also world class Pb deposits (>1Mt Pb), with the first 3 also containing large resources of Ag (632, 643 and 870 M ozs respectively). The province is also host to significant Cu deposits, including the world class (>2 Mt Cu) Mt Isa deposit (255 Mt @ 3.3% Cu), and Ernest Henry (127 Mt @ 1.1% Cu, 0.55 g/t Au).

Several Mineral Systems are postulated to occur within the NWQMEP. The following is a description of these systems.

Shale/siltstone/dolomite hosted Zn-Pb-Ag systems: Western and Eastern Fold Belt

These deposits are characterised by stratiform to stratabound massive sulfide lenses in carbonaceous shales and dolomitic siltstones at varying stratigraphic levels within the Isa Superbasin. They include the Mount Isa Pb-Zn (Isamine, George Fisher), Century, Dugald River, Kamarga, and Lady Loretta deposits.

Figure 1 Map showing selected mines and deposits in NW Queensland.

Figure 2 Diagram showing aspects of genesis of the sediment hosted Pb-Zn deposits in the Mount Isa Inlier.

Tectonic/Geological Environment

The deposits typically occur in an intracontinental rift to passive margin environment. There is strong basement control on basin architecture and the orientation of faults active at the time of basin formation. The rift environment provides a source for the fluids and fluid pathways; deposition of the orebodies typically occurs late in the extensional cycle and may be related to either sedimentation or inversion of the basins.

All significant occurrences are hosted by 2–8 km thick successions of the Isa Superbasin, ranging in age from c. 1660 Ma (Dugald River, Lady Loretta) to 1590 Ma (Century) (Queensland Department of Mines and Energy et al., 2000). These successions are interpreted to represent the products of sedimentation related to thermal subsidence following extension and rifting (Queensland Department of Mines and Energy et al., 2000). Within the sag successions, Zn-Pb-Ag deposits are typically localised in districts or ‘sub-basins’ of 100–200 km² area that are characterised by:

1. Underlying clastic and silty units in the Calvert Superbasin commonly show a network of growth faults and subtle half-graben structures upon which the sag-phase successions were deposited, with local unconformity.
2. Sag-phase basins form large accumulations of basal clastics overlain by thick and extensive packages of siltstone, dolomite and dolomitic siltstone.
3. Within the broader sag-phase basins smaller (third order) sub basins develop which are characterised by abundant pyritic and carbonaceous shale and dolomitic siltstone which are immediate host rocks to Pb-Zn mineralisation (Huston et al., 2006).

Source

The source of the metals in most sediment-hosted Zn-Pb-Ag deposits has usually been attributed to clastic rocks in upper crustal sequences which underlie the deposits (for example, Zn from shale, basalt; Pb from arkose, grit, felsic volcanics, granites; Derrick, 1996).

Figure 3 Aerial View of the pit at Century Mine, NW Queensland.

Figure 4 View of the Black Star pit – part of the Isa Mine complex.

Fluid Pathways

The pre-existing Leichhardt and Calvert Superbasins provided permeable aquifers and fluid reservoirs for many of the metals that are hosted by the Isan Superbasin or deposited during the Isan Orogeny (Polito et al., 2006).

Depositional Mechanisms

Depositional mechanisms for Zn-Pb-Ag mineralisation are varied:

- Extension and thermal input during early superbasin development did not result in the formation of mineral deposits but rather were the storage compartments for fluids drawn down into the system (Murphy et al., 2011; Polito et al., 2006).
- The main processes contributing to Zn-Pb-Ag mineral deposition were fluid cooling, dissolution of host rock carbonate (with consequent pH increases) and thermochemical sulfate reduction due to the interaction of oxidised Zn-Pb-Ag-transporting saline fluids with organic matter and also mingling with migrated but locally sourced hydrocarbons; inorganically precipitated carbon was also produced (Hinman et al., 1994; Dixon and Davidson, 1996; Hinman, 1998; Broadbent et al., 1998). These processes emphasise the significance of organic-rich and calcareous successions as potential hosts and reductants.
- Deposits such as Century and Mount Isa exhibit paragenetic stages from early, layer-parallel sphalerite, sphalerite breccias with minor galena and pyrrhotite to vein and breccia-hosted galena with sphalerite, pyrrhotite and euhedral pyrite. A paragenetic evolution from early sphalerite to late galena with euhedral pyrite is consistent with a thermally prograding event, increasing extent of thermochemical sulfate reduction and saturation of hydrothermal pyrite (Murphy et al., 2011).
- While layer-parallel mineralisation is widespread in the deposits, coarser-grained layers and veins of galena and lesser sphalerite are also developed as a consequence of proximity to possible feeder zones along bounding faults, and/or to recrystallisation and replacement of earlier sulfides by later generations of sulfides formed during metamorphism, especially at Mt Isa and George Fisher.
- Carbonate-hosted replacement deposits such as Kamarga may

have formed by neutralisation of hot acid fluids (Jones et al., 1999).

- Although syndepositional to early diagenetic mineralising processes have generally been favoured for formation of these deposits (Waltho and Andrews, 1993; Hinman et al., 1994; Dixon and Davidson, 1996; McGoldrick and Large, 1998; Betts and Lister, 2002), there is a growing body of evidence for a late diagenetic (reminiscent of Mississippi Valley-type deposits) to syntectonic replacement mechanism as an alternative explanation for the formation of the stratabound Zn-Pb-Ag orebodies (Xu, 1996; Broadbent et al., 1998; Rohrlach et al., 1998; Jones et al., 1999). The timing of the mineralising Pb-Zn systems has been fully discussed by Large et al. (2005) and Huston et al. (2006). Alternatively, syngenetic-early diagenetic mineralisation may have been remobilised and enriched, in a manner similar to models generally invoked for Broken Hill-style deposits. At Duguld River, the deposit occurs in metamorphosed carbonaceous shale with a substantial part of the resource resulting from significant structural upgrading, perhaps during the Isan orogeny.

Ag-Pb-Zn in high-grade metamorphic terrains: Eastern Fold Belt Province

Deposits comprise massive to semi-massive galena, sphalerite, pyrrhotite and pyrite and/or magnetite layers or stacked lenses hosted by thin-bedded calcareous paragneiss and migmatitic quartzofeldspathic gneiss, considered to be metamorphosed immature siliciclastic sediments. Amphibolite, porphyry and pegmatite lenses occur within the gneissic terrain. The complex gangue mineralogy includes calc-silicate mineral assemblages containing garnet (Mn-enriched)-fluorite-hedenbergite-pyroxmangite-quartz-magnetite-fayalite-pyrrhotite-gahnite (Walters et al., 2002). These stratabound deposits are typically thin, but laterally extensive and were deformed and metamorphosed together with their host rocks (Hoy, 1996). Deposits in the Mount Isa Inlier include Cannington, Pegmont, and Altia (Figure 1). These deposits have similarities to world class Broken Hill mineralisation >1,000 km south (Gibson et al., 2012) and are commonly referred to as 'Broken Hill Type' (or BHT) deposits. They

are important sources of Pb, Zn and Ag with Cannington being the world's largest and lowest cost single mine producer of Ag and Pb and a significant producer of Zn.

Tectonic/geological environment

Broken Hill-type deposits appear to be restricted to the eastern margin of Proterozoic Australia (Fraser et al., 2007), where mineralisation formed in feldspathic clastic rocks that were deposited in a deep water turbiditic basin. The region is modelled in extension as a thin, brittle upper crust above a thermally weakened lithosphere, where connectivity between the two vertically stacked domains appears to be largely along steep crustal scale faults (Murphy et al., 2011). While siliciclastic sedimentary packages are dominant, they also contain rift-related basic layered sills and exhalative Fe formations enriched in Mn and P (Hatton and Davidson, 2004).

Depositional Mechanisms

Two models for the generation of BHT deposits are:

- The modified synsedimentary/syndiagenetic model (Boden, 1996; Bailey, 1998) with initial introduction and zoning of base metal and Ag mineralisation with Zn dominant and Pb-Ag dominant horizons. This pre-metamorphic zoning could have been developed by processes associated with a volcanogenic sulfide system or a basin dewatering diagenetic system with mineralisation controlled by primary porosity or matrix replacement, associated with the emplacement into the sequence of a series of tholeiitic basic sills (amphibolite). Introduction of the mineralisation is followed by regional deformation and metamorphism. During a post-metamorphic metasomatic event, initial metasomatism of mineralised rocks resulted in anhydrous alteration characterised by hedenbergite-garnet-quartz and the deposition of very minor pyrrhotite and rare sphalerite. This was followed by high and low temperature hydrous stages.
- The skarn model (Williams et al., 1996) comprises an original metasedimentary package (consisting of an Fe-Mn-(Ca)-rich fraction) and an outer Fe- and Mn-rich peraluminous metasediment derived from quartz-pelite mixtures with local feldspathic fractions; regional deformation with peak metamorphism reaching upper amphibolite facies; peraluminous anhydrous Fe-rich alteration (quartz-sillimanite-potassium feldspar-biotite-garnet-graphite); anhydrous Ca-rich alteration (quartz-apatite-pyroxmangite-hedenbergite-fayalite-hornblende-garnet); hydrous Fe-Ca-K alteration (hornblende-biotite-pyroxmalite-dannemorite); and a mineralising phase with sphalerite, galena, pyrrhotite, chalcopyrite.

A large coherent halo of stratabound almandine (pink garnet)-quartz-apatite-biotite-graphite alteration occurs as an envelope around the mineralised package at Cannington. This alteration has penetrative

tectonic fabrics and is overprinted by later alteration. Quartz-garnet-pyroxene-pyroxenoid alteration affects partial melt segregations that occurred during peak metamorphism, suggesting that these skarn-like alteration assemblages developed under fairly deep-seated (ductile) conditions at a late stage of the Isan Orogeny. Peraluminous Fe-Mn-rich metasediments form compositionally banded K-feldspar-sillimanite-quartz-biotite-garnet assemblages. Goerthite-quartz assemblages are also diagnostic of this mineralisation. Recent studies and age dating continue to favour a synsedimentary/syndiagenetic origin for BHT deposits (Huston et al., 2006), formed at or just below the sea floor. Despite the extensive polyphase folding and high grade metamorphism evident in BHT deposits, feeder zones and a replacement/exhalative footwall system have been recognised at Broken Hill (Groves et al, 2008).

Structurally-controlled epigenetic iron oxide-Cu-Au systems (IOCG): Eastern Fold Belt and Kalkadoon-Ewen Provinces

Deposit styles within these systems comprise epigenetic mineralisation as hydrothermal replacements, veins and breccias. Two major but contrasting groupings are identified:

1. An economically significant grouping of larger deposits commonly referred to as IOCG deposits (iron oxide-Cu-Au), and which include the world-class Ernest Henry deposit (Figure 5), Osborne, Mt Elliott, Roseby, Eloise, Rocklands, Mt Dore and Starra deposits. Recent discovery of the Merlin Mo-Rh deposit adds to the economic significance of this deposit grouping.
2. Smaller deposits (i.e., unlikely to ever achieve production status in the foreseeable future) are voluminous and widespread throughout the Kalkadoon-Ewen basement province, and in the Eastern Fold Belt. They form as narrow 1–5 m quartz vein-type deposits in N-, NW- and NE-trending shear zones, and are closely associated with dilatant structures along the margins of dolerite

Figure 5 View of part of the open cut pit at Ernest Henry.

and amphibolite bodies which occupy the same structures. Host rocks include older granite and volcanics, and metasedimentary cover rocks.

Many of these deposits formed the basis of a historic small-scale (“gouger”) Cu mining industry during the early to mid-20th Century.

Tectonic/geological environment

The grouping of smaller deposits throughout the basement and eastern fold belts are located in largely intracontinental and continental margin environments within the North Australian Craton.

Most of the larger IOCG deposits formed in an E- or SE- facing passive continental margin dominated by shallow shelf to deeper water turbiditic sequences. Within the shelf and slope, local rifting promoted the stacking of and juxtaposition of chemically reactive lithologies, including ironstones, carbonaceous siltstones, volcanoclastics, carbonates and mafic sills and dykes (Davidson and Large, 1998). These sequences are 1760–1650 Ma, equivalent to the Calvert and Isa Superbasins.

Basin inversion from 1600–1500 Ma resulted in deformation, crustal thickening and the intrusion of voluminous, mainly felsic, magmas to crustal depths of 5–10 km (Mark et al., 2006) – the Williams and Naraku Batholiths. Duncan et al. (2011) suggest that metal-rich reservoirs formed in the SE end of the subduction zone, along the southern margin of the NAC, to be tapped by metamorphic and magmatic events during the Isan Orogeny.

Most IOCG deposits are related spatially to the Williams/Naraku batholiths (1545–1490 Ma) but mineralising fluids could have been metamorphic (e.g., Osborne, 1600 Ma) or magmatic in origin (e.g., Ernest Henry main stage Cu-Au, 1525 Ma; Duncan et al., 2011). Most IOCG deposits formed in the time range 1550–1500 Ma, as part of the Isan Orogeny.

Depositional Mechanisms

The major mineralising event in this system occurred within the Isan Orogeny (1600–1500 Ma, from peak metamorphism 1600–1550 Ma through to major granite intrusion (Williams and Naraku Batholiths) from 1545–1490 Ma. Most Cu-Au mineralisation is preceded by region-wide Na-Ca alteration manifested as albite-diopside-calcite-actinolite assemblages which are overprinted by Cu-Au±Fe.

The region-wide small-scale Cu deposits are generally unrelated to granite plutons, but form as narrow (1–5 m) quartz-calcite-chlorite filled shears in a diverse range of host rock age and composition. They contain little or no magnetite, and show a spatial and possible genetic relationship to basic dykes and sills; in addition, mineralising fluids were likely to be saline because of metamorphism of extensive scapolitic (?evaporative) metasedimentary cover sequences, and likely contributions from regional deep-crustal sources.

The IOCG deposits by contrast contain abundant magnetite (and hematite), and formed in larger structures associated with dilatancy, rheology contrasts, brecciation and replacement of brittle host rocks (e.g., 1740 Ma intermediate volcanics at Ernest Henry). Ore fluids were high temperature (300–500°C), highly saline (26–70 wt% NaCl) and oxidised (Mark et al., 2006). Magnetite formed in some deposits from mineralising fluids (e.g., Ernest Henry), while in others fluid replaced existing host-rock ironstones. Metal formed by pH changes

due to wallrock interaction, redox changes and reduction of some fluids by carbonaceous rocks (e.g., Mt Dore).

Two IOCG events are recognised:-

1. Ironstone-hosted deposits such as Osborne and Starra formed c. 1600–1565 Ma (Perkins and Wyborn, 1998; Gauthier et al., 2001; Duncan et al., 2009; Baker et al., 2010), and possibly as early as 1680 Ma (Oliver and Rubenach, 2009).
2. Breccia and shear-hosted deposits such as Mt Elliott, Ernest Henry, Lady Ella and Mt Dore formed post-peak metamorphism and synchronous with the period of granite emplacement (1555–1485 Ma) (Perkins and Wyborn, 1998; Wang and Williams, 2001; Duncan et al., 2009; Baker et al., 2010).

Older mineralising events in this system are sparse. The Tick Hill Au-only deposit (511,000 ozs mined at 22 g/t Au) formed in a high strain domain possibly related to the Wonga event extension from 1750–1730 Ma, and could be related to roof zones of Wonga-age granites (Forrestal et al., 1998).

Structurally-controlled epigenetic Cu±Au mineralising system: Western Fold Belt Province

At Mount Isa, the ore forming system involves similar chemical processes to other sediment-hosted Cu systems, but represents the relatively high temperature end of the spectrum of syn-diagenetic to low-grade metamorphic ore-forming environments (Queensland Department of Mines and Energy et al., 2000). Historically, theories on the genesis of the Mount Isa Cu orebodies have ranged from igneous telemagmatic replacement to syngenetic deposition followed by remobilisation. A variation on this model is the progressive build-up of the Cu ores as a feeder system to syngenetic Pb-Zn. Today, the deposit is almost universally regarded as replacement late in the deformation history of the Isan Orogeny (Perkins, 1990).

Tectonic/geological environment

There is strong fault control on deposit location at a range of scales. The regional faults are numerically modelled as fluid pathways which, in extension, draw down fluids; in compression, the convective cells break down and fluids are expelled upwards, typically ponding in permeable hanging wall positions. Discrete element modelling at the district to deposit scales indicates that stress anomalies associated with a particular compression direction during D₄ deformation played a critical role in the localisation of Cu deposits (Murphy et al., 2011). Fault bends, jogs and intersections are regarded as key localisation features.

Derrick (2008) has shown that the Isa and Mammoth Cu deposits are controlled by an array of earlier growth faults developed in basin extension from 1770–1700 Ma, reactivation and inversion of these normal faults in the Isan Orogen at 1500 Ma produced favourable sites of folded faults and accompanying dilatancy and jogs e.g., along the folded Paroo Fault which forms the immediate footwall to Isa Cu mineralisation.

The Lady Annie, Mount Kelly group of deposits occur in the Paradise Creek Formation, a time equivalent of the Lower Mount Isa Group. The Mammoth and Esperanza deposits occur in fractured quartzite in the Myally Formation, a setting different to the Mount Isa and Lady Annie deposits. The Mammoth orebody is the only

significant deposit not hosted by Mt Isa Group equivalents. It occurs in the c. 1760 Ma Whitworth Quartzite of the Myally Subgroup, in which dilatant vein sets form a crackle-fractured breccia in competent and brittle feldspathic quartzite, within a complex fault zone.

Source

The Mount Isa Cu mineralisation occurs within the Urquhart Shale within the Mount Isa Group. The deposit comprises crosscutting chalcopyrite within a zoned siliceous to dolomitic alteration halo ("silica-dolomite"). Within the Isa mine, the mineralisation lies above a shallow basement fault separating the Mount Isa Group from the Eastern Creek Volcanics (Perkins, 1990). A common interpretation is that the Cu has been sourced by leaching from the Eastern Creek Volcanics (e.g., Smith and Walker, 1971) and therefore the proximity to this unit is a prerequisite for Cu ore formation. Traces of chalcopyrite and either bornite or pyrite locally occur in veinlets, mainly in intensely hematitised metasediments within the Eastern Creek Volcanics (Heinrich et al., 1995).

Fluid Pathways

For Mount Isa-style deposits, a protracted development of an alteration system beginning with an early K-feldspar and mica alteration, then formation of fractures and dolomite veins and ending with late massive proximal dolomitisation and silicification occurred during the Isan Orogeny. The phase of dolomitic alteration in the host rocks was associated with epidote-sphene and chlorite-albite alteration in the Eastern Creek Volcanics (Heinrich et al., 1995). As the ore fluids moved away from their source they were focussed along brittle/ductile shear zones, interacting to varying degrees with a range of rock types, partly modifying their character. Limited silica-dolomite alteration is also evident in some of the smaller deposits (e.g., Mt Kelly, Lady Annie), in crack-seal breccia and fibrous extensional veins (van Dijk, 1991). Many of the smaller deposits are hosted within a 1670–1655 Ma stratigraphic triplet, comprising basal carbonaceous siltstone, massive algal chert and dolomite. Late mineralising Cu-rich fluids intersecting this zone in fault and shear settings may deposit Cu in dilatant sites along competency boundaries of the chert, by pH change from dolomites, and reduction of the fluid by carbonaceous matter.

Depositional Mechanisms

It is postulated (Heinrich et al., 1993; Matthai et al., 2004; Wilde et al., 2006) that ore deposition was due to mixing of an oxidised brine that circulated within metabasalts with a sulfur-rich fluid from overlying Mount Isa Group metasedimentary rocks or a younger Mesoproterozoic basin at the site of deposition.

Copper deposition was primarily a function of wall-rock reaction; mixing is a necessary consequence of the evolving permeability and porosity regime rather than an essential element of ore deposition. Cu ore precipitation involved one or a combination of depositional mechanisms including:

- cooling;
- a number of wall-rock reactions (reduction by carbonaceous matter, replacement of quartz and dolomite). Dissolution of carbonate minerals, feldspar, and micas buffered pH at somewhat neutral values, optimising Cu extraction (Wilde et al., 2006);

- fluid mixing between magmatic and one or more fluids of a different origin (mantle/metamorphic/basinal evaporate/meteoric) (Kendrick et al., 2006).

Phosphate Mineralisation in the basal Georgina Basin sequence

Phosphorite deposits in the Georgina Basin have been described by de Keyser and Cook (1972), Southgate (1988), Southgate and Shergold (1991) and Draper (1996). The deposits in the Mount Isa region are in the Cambrian age Beetle Creek Formation, Border Waterhole Formation and Thornton Limestone. They consist of beds of consolidated pelletal phosphorites interbedded with chert, carbonate, shale, siltstone and volcanic materials. The phosphorite beds average 11m (but range up to 36 m) thick and consist of dense pellets of apatite in a cherty and carbonate matrix. The phosphorites range from dense pelletal rocks consisting almost exclusively of francolite (one of the collophane group minerals) to siliceous and calcareous phosphorite, phosphatic chert and phosphatic siltstone, and grade into fossiliferous limestone. Chert (silica) and clay are the main dilutants and the deposits have comparatively low levels of heavy metals (for example, <5 ppm Cd). The phosphorites comprise apatite + fluorapatite + francolite + dolomite + calcite + quartz + clays (montmorillonite or illite) ± halite ± gypsum ± Fe oxides ± siderite ± pyrite ± carnolite (Queensland Department of Mines and Energy et al., 2000).

Tectonic/geological environment

Phosphate deposits occur in an intracontinental or shallow continental margin setting and require predominantly carbonate sedimentation (Draper, 1996; Southgate and Shergold, 1991).

General criteria for phosphate deposition are as follows:

- A low paleolatitude
- A broad shallow downwarp adjacent to a seaway
- High productivity in the vicinity
- Minimal terrigenous sedimentation in a shallow marine environment
- A major transgression
- A trap such as a bay or carbonate bank.

Early Cambrian NW-SE rifting initiated widespread sedimentation in the Georgina Basin and the phosphatic sediments developed in shallow water basins and shelves adjacent to the Proterozoic land mass. The Duchess-Phosphate Hill deposit formed in the S, in the Burke River embayment, while other deposits (e.g., Lady Annie, Lady Jane, Thornton, Phantom Hills) formed along the W and NW margins of the Proterozoic land mass.

Depositional Mechanisms

Phosphate deposits and occurrences are present in two predominantly carbonate sequences. In each of these sequences, the 'retrogradational parasequence sets of the transgressive systems tract' (Southgate and Shergold, 1991) comprise a repeating suite of phosphorite, phosphatic limestone and organic rich shales. There is a subaerial exposure surface between the two sequences. The phosphate bearing facies were controlled by relative sea level, paleogeography

and paleotectonics and there is evidence of structural compartmentalisation of phosphatic facies.

Recently, a blanket of Y+ REE-rich material has been found overlying phosphate mineralisation in the Georgina Basin in western Queensland. As well as Y, the deposit also contains Neodymium (Nd) and Dysprosium (Dy) (Alston, 2011). The origin of the REE enriched blanket is not known.

Uranium and Rare Earth element (REE) mineralisation

Uranium mineralisation is known from several different settings in the Mount Isa Inlier. These are:

Tectonic/geological environment

Unconformity-related mineralisation

The unconformity-related mineralisation at Westmoreland (Hills and Thakur, 1975; Rheinberger et al., 1998; Wall, 2006; Polito et al., 2005) is spatially related to either:

- NE-trending structures with proven or suspected tholeiitic dyke filling;
- NE- and NW-trending structures;
- volcanic sills;
- E-trending structures with volcanic dyke filling;
- quartz breccias of NW-trending regional faults; and/or
- proximity of the contact between the uppermost unit of the Westmoreland Conglomerate and the overlying Seigal Volcanics.

Faults at the deposit scale may be related to larger strike-slip fracture zones extending for tens of kilometres. Mineralised zones do not show any signs of pervasive deformation but are displaced by later faulting.

Mineralisation in the principal deposits is present as horizontal, vertical or hybrid styles. Horizontal-style mineralisation is relatively extensive and sheet like, up to 20 m thick, within the uppermost portion of the Westmoreland Conglomerate and close to the Seigal Volcanics contact. This style of mineralisation flanks the NE-trending Redtree Dyke and is best developed immediately adjacent to and on one side of the dyke only. Vertical-style mineralisation forms subvertical, relatively irregular lenses to 30 m thick that are hosted by sandstone of the Westmoreland Conglomerate, although some mineralisation extends into the dolerite dykes. These lenses are adjacent to the Redtree Dyke and their geometry closely mimics that of the dyke-joint system. Hybrid mineralisation is developed in the overlap zone between the horizontal and vertical styles of mineralisation and is, in detail, a combination of both styles. The overlap zone can be up to 50 m thick (Queensland Department of Mines and Energy et al., 2000).

Shear-hosted mineralisation

Lenticular to tabular, stratabound uraniferous beds and zones are hosted by metamorphosed basic volcanics and pelitic and psammitic sediments of the Eastern Creek Volcanics in the Leichhardt River Fault Trough in the Calton Hills-Paroo Creek and Spear Creek-Mica Creek areas. Secondary U mineralisation is generally not readily discernible at the surface of the known deposits, which were located with radioactivity detectors. Most deposits are uneconomic to

subeconomic, but some such as Valhalla, Skal, Anderson's Lode (Counter) and Warwei-Watta represent significant U resources.

Skarn-hosted mineralisation

The Mary Kathleen U deposit lies S of the D₃, NE-trending Cameron Fault, and is sited in the axial surface of a tight, slightly asymmetrical syncline (the Mary Kathleen Syncline) that can be traced southward for >5 km. The western limb of this structure is cut off by the Mary Kathleen Shear, and the eastern limb by the 1737±15 Ma Burstall Granite. Slightly younger rhyolite dykes W of the granite have similar compositions and an identical radiometric age (Solomon et al., 1994). The Burstall Granite and associated rhyolite dykes also have elevated U contents (7 and 12 ppm U, respectively).

The orebody is hosted by a reduced (magnetite-poor) calcic exoskarn formed by replacement of calcareous rocks of the Corella Formation. The ore comprises fine-grained uraninite disseminated through allanite-apatite enriched rocks that cross-cut the garnet-diopside skarn (Queensland Department of Mines and Energy et al., 2000).

Similar skarn-hosted REE-Cu-Au mineralisation occurs to the S, at the Elaine Dorothy prospect.

Mineralisation

Unconformity-related Mineralisation

Pitchblende is the main ore mineral and occurs in both the Westmoreland Conglomerate and altered basic dyke rocks. In the sandstones, it occurs interstitial to detrital grains, along fractures, and in veins up to 10 mm thick. It is present as massive, structureless, or rarely euhedral grains, as colloform masses and as thin films of sooty pitchblende. Pitchblende in the dyke rocks occurs as fine aggregates, as thin films and as veins. Secondary U minerals occur as fine disseminations and filling pore spaces. The most abundant secondary U minerals are torbernite, metatorbernite and carnotite. The upper, weathered parts of mineralised systems contain uraninite, torbernite and carnotite, with traces of autunite, bassettite, ningyoite and coffinite. The deeper and unweathered portions of the deposits contain uraninite, autunite, ningyoite, bassettite and coffinite, and minor brannerite. Other ore minerals include pyrite, marcasite, chalcopyrite, galena, sphalerite, Co-Ni sulfarsenides, bismuth, bismuthinite, bornite, chalcocite, digenite, covellite and Au. Thorium is present in alteration products of detrital Th-bearing minerals as thorogummite and florencite. Hematite is abundantly present as the specular type or as a finely disseminated earthy variety and is intimately associated with the primary mineralisation (Queensland Department of Mines and Energy et al., 2000).

Shear-hosted mineralisation

Shear-related deposits are hosted in metabasalts and interbedded metasediments within N-trending to E-W structures in the Eastern Creek Volcanics, and in steep N-S trending mylonite zones in metabasalt and metasediments at Valhalla.

Skarn-hosted mineralisation

The orebody at Mary Kathleen consists of elongate lensoidal ore

shoots that are up to 50 m thick and roughly parallel the margins of a broader garnet mineralised zone. The relationship of the ore shoots to stratigraphy is obscured by garnetisation in the upper part of the orebody but the ore lenses are broadly stratiform at depth. The ore is largely a replacive breccia with clasts of early skarn breccia in an allanite-garnet ore matrix.

The spatial relationships between ore, the Mary Kathleen Shear and the axial trace of the Mary Kathleen Syncline indicate that ore formation postdated major folding and was synchronous with shearing under amphibolite facies conditions, consistent with a syn-regional metamorphic age for ore genesis.

The primary structural control on ore formation was the development of ore in and around tensile veins and/or secondary shears in a competent skarn host, along a major boundary between skarn-dominated rocks to the E and regionally metamorphosed, 'un-skarned' metasediments and Wonga Granite to the W (Oliver et al., 1986). Uraninite-bearing ore at Mary Kathleen has a U-Pb age of 1550–1500 Ma (late D_2 – D_3), compared with 1737 ± 15 Ma for the Burstall Granite, 1700 ± 60 Ma for banded skarn and 1620–1500 Ma for the main regional metamorphism and deformation.

Depositional Mechanisms

U-REE enrichment is related to reaction of highly saline and oxidised fluids (Isan Orogeny) with earlier, slightly reduced (magnetite-poor) skarn (Oliver et al., 1986).

Iron Ore: South Nicholson Group

Oolitic Fe formations occur in the Mesoproterozoic South Nicholson Group of the South Nicholson Basin in the Constance Range area. Up to 10 (generally <4) lenticular, Fe-rich beds occur in the 45–180 m thick Train Range Ironstone Member, some 275–520 m above the base of the Mullera Formation. The Train Range Ironstone Member also contains thinly bedded, alternating dark grey shales, siltstones and sandstones. One to four ironstone beds are present at any one place and the potentially economic ore occurs in the "Main Ironstone Member" – the lowest Fe-bearing unit of significant thickness (Harms, 1965).

Tectonic/geological environment

Limited observations of the Train Range Ironstone Member suggest that much of the ironstone represents deposition in the upper parts of shallowing-up cycles, i.e., in prograding parasequences during sea level highstands. The presence of both chamositic and sideritic ooidal ironstones indicates growth of Fe minerals on siliceous nuclei in shelfal environments, perhaps on offshore or nearshore bars. The existence of sandstones with rip-up clasts of ironstone as an intraformational conglomerate suggests that erosion and redeposition of pre-existing layers occurs, indicating either a renewed transgressive phase, or local development of channels within an overall prograding succession. Sediment starvation at times of maximum flooding also generates Fe-rich deposits (Burkhalter 1995), and Carter and Zimmerman (1960) state (p 13) that "some of the smaller lenses appear to be concretionary". Although they speculate that these could result from later weathering, it is also possible that they represent sediment-starved horizons, i.e., maximum flooding surfaces within the basinal sediments (Sweet, 2012).

Mineralisation

Outcropping ironstones are a variable mixture of ochrous red hematite, finely crystalline blue-black hematite, limonite, quartz grains, quartz cement, shale and clay minerals, and rare relict siderite. The ironstones vary in appearance from oolitic forms to a sandstone with a hematite matrix, and have been derived from primary ironstone by surface weathering. Grades range from 20–62% Fe, depending on the silica content of the parent rock (Harms, 1965). Oxidised ironstone extends to 12–30 m vertically. The transition zone appears to have some Fe enrichment, and the near-surface zone has probably been enriched in silica.

Below the water table, the ironstones contain oolites of ochrous or finely crystalline hematite, siderite and/or chamosite, and silica grains in a matrix of siderite, hematite, minor microcrystalline quartz and carbon. Oolites range from 0.2–3 mm in diameter and successive shells may consist of different Fe minerals. Veins of quartz-pyrite, siderite-pyrite and calcite cut the ironstones. Disseminated syngenetic pyrite occurs along bedding planes, especially in carbonaceous shales associated with the ironstone beds, and in siderite-rich bands. Siderite partially or completely replaces some or all of the other Fe minerals. It also replaces quartz grains and appears to have formed late in the deposition or during diagenesis.

The highest grade beds are oolitic and contain 50–55% Fe at the surface. Lower grade beds contain <20–25% Fe and are siliceous. Fifteen individual deposits have been investigated and resources were calculated for three deposits, which contain a total resource of 368 Mt @ 45.4% Fe and 9.1% SiO_2 , including 40 Mt of oxidised ore @ 57.0% Fe and 10.0% SiO_2 (Queensland Department of Mines and Energy et al., 2000).

Acknowledgements

We acknowledge the helpful suggestions provided by an anonymous reviewer. The second reviewer has become an author to the paper.

References

- Alson, T., 2011, Maiden Yttrium and Rare Earth Inferred resource at Krucible's Korella Deposit, Mount Isa district, Queensland: Australian Stock Exchange Announcement, 5th April, 2011.
- Bailey, A., 1998, Cannington silver-lead-zinc deposit, in Berkman, D.A. and Mackenzie, D.H. (eds), *Geology of Australian and Papua New Guinean Mineral Deposits: The Australasian Institute of Mining and Metallurgy, Monograph 22*, pp.783–792.
- Baker, T., Conon, C., Fricke, C. and Reid, A., 2010, The 1.5 to 1.5 Ga iron oxide-copper-gold-uranium event: what controls giants versus minnows, in Cook, N.J. et al. (eds), *Giant Ore Deposits Down-under: 13th Quadrennial IAGOD Symposium 2010*, Adelaide: Symposium Proceedings.
- Betts, P.G. and Lister, G.S., 2002: Geodynamically indicated targeting strategy for shale-hosted massive sulfide Pb-Zn-Ag mineralization in the Western Fold Belt, Mt Isa terrane: *Australian Journal of Earth Sciences*, v. 49, pp. 985–1010.
- Betts, P.G., Giles, D. and Lister, G.S., 2003, Tectonic environment of shale-hosted massive sulphide Pb-Zn-Ag deposits of Proterozoic northeastern Australia: *Economic Geology*, v. 98, pp. 557–576.
- Boden, S.B., 1996, Paragenetic relationships at the Cannington Ag-Pb-Zn deposit, Mt Isa Inlier, northwest Queensland, in Baker, T., Rotherham, J., Richmond, J., Mark, G. and Williams, P. (eds), *MIC 96, New developments in metallogenic research: the McArthur, Mt Isa, Cloncurry minerals province*, Extended Conference Abstracts: Economic Geology Research Unit, Contribution 55, pp. 15–19.

- Broadbent, G.C., Myers, R.E. and Wright, J.V., 1998, Geology and origin of shale-hosted Zn-Pb-Ag mineralisation at the Century deposit, northwest Queensland: *Economic Geology*, v. 93, pp.1264–1290.
- Burkhalter, R.M., 1995, Ooidal ironstones and ferruginous microbialites: origin and relation to sequence stratigraphy (Aalenian and Bajocian, Swiss Jura mountains): *Sedimentology*, v. 42, pp. 57–74.
- Carter, E.K. and Zimmerman, D.O., 1960, Constance Range iron deposits, northwestern Queensland: Bureau of Mineral Resources, Record 1960/75.
- Davidson, G.J. and Large, R.R., 1998, Proterozoic copper-gold deposits: AGSO Journal of Australian Geology and Geophysics, v. 17, pp. 105–113.
- de Keyser, F. and Cook, P.J., 1972, Geology of the Middle Cambrian phosphorites and associated sediments of northwest Queensland: Bureau of Mineral Resources, Geology and Geophysics, Bulletin 138.
- Derrick, G.M., 1996, The 'Geophysical' Approach to Metallogeny of the Mt Isa Inlier – What Sort of Orebody do you Want? *in* Diversity, the Key to Prosperity: Australasian Institute of Mining and Metallurgy, Publication Series No. 1/96, pp. 349–366.
- Derrick, G.M., 2008, Copper deposits of the western succession, Mount Isa – styles, origins, footprints, *in* Exploration on the Edge: CODES Seminar Proceedings, October, 2008, 12 pp.
- Dixon, G. and Davidson, G.J., 1996, Stable isotope evidence for thermochemical sulphate reduction in the Dugald River (Australia) stratabound shale-hosted zinc-lead deposit: *Chemical Geology*, v. 129, pp. 227–246.
- Draper, J.J., 1996, Queensland Mineral Commodity Report – Phosphate: Queensland Government Mining Journal, v. 97, pp. 14–25.
- Duncan, R., Hitzman, M., Nelson, E., Stein, H., Zimmerman, A. and Kirwin, D., 2009, Re-Os molybdenite ages for the southern Cloncurry IOCG district, Queensland, Australia: protracted mineralisation over 210 Myr, *in* Williams, P.J. et al. (eds), Smart Science for Exploration and Mining: Proceedings of the 10th Biennial SGA Meeting, Townsville, Australia, v. 2, pp. 626–628.
- Duncan, R., Stein, H., Evans, K., Hitzman, M., Nelson, E. and Kirwin, D., 2011, A new geochronological framework for mineralisation and alteration in the Selwyn – Mount Dore corridor, eastern fold belt, Mount Isa Inlier, Australia: genetic implications for iron oxide copper-gold deposits: *Economic Geology*, v. 106, pp. 169–192.
- Forrestal, P.J., Pearson, P.J., Coughlin, T. and Schubert, C.J., 1998: Tick Hill Gold Deposit, *in* Hughes, F.E. (ed), Geology of the Mineral Deposits of Australia and Papua New Guinea: The Australian Institute of Mining and Metallurgy, pp. 699–706.
- Fraser, G.L., Huston, D.L., Gibson, G.M., Neumann, N.L., Maidment, D., Kostic, N., Skirrow, R.G., Jaireth, S., Lyons, P., Carson, C., Cutten, H. and Lambeck, A., 2007, Geodynamic and metallogenic evolution of Proterozoic Australia from 1870–1550 Ma: a discussion: *Geoscience Australia, Record 2007/16*.
- Gauthier, L., Hall, G., Stein, H. and Schaltegger, U., 2001, The Osborne deposit, Cloncurry district: a 1595 Ma Cu-Au skarn deposit, *in* Williams, P.J. (ed), A Hydrothermal Odyssey, New Developments in Metalliferous Hydrothermal Systems Research: James Cook University, Economic Geology Research Unit, Contribution 59, pp. 58–59.
- Geological Survey of Queensland, 2011, North-West Queensland Mineral and Energy Province Report: Queensland Department of Employment, Economic Development and Innovation, Brisbane.
- Gibson, G.M., Henson, P.A., Neumann, N.L., Southgate, P.N. and Hutton, L.J., 2012, Paleoproterozoic–earliest Mesoproterozoic basin evolution in the Mount Isa region, northern Australia and implications for reconstructions of the Nuna and Rodinia supercontinents: Episodes (this volume).
- Groves, I.M., Groves, D.J., Bierlein, F.P., Broome, J. and Penhall, J., 2008, Recognition of the hydrothermal feeder to the structurally inverted giant Broken Hill deposit, New South Wales, Australia: *Economic Geology*, v. 103, pp. 1384–1394.
- Harms, J.E., 1965, Iron ore deposits of Constance Range, *in* McAndrew, J. (ed), Geology of Australian Ore Deposits. Eighth Commonwealth Mining and Metallurgical Congress, Australia and New Zealand, 1965: The Australasian Institute of Mining and Metallurgy, Melbourne, pp. 264–269.
- Hatton, O.J. and Davidson, G.J., 2004, Soldiers Cap Group iron formations, Mt Isa Inlier, Australia, as windows into the hydrothermal evolution of a base-metal bearing Proterozoic rift basin: *Australian Journal of Earth Sciences*, v. 51, pp. 85–106.
- Heinrich, C., Bain, J.H.C., Fardy, J.J. and Waring, C.L., 1993, Br/Cl chemistry of hydrothermal brines associated with Proterozoic meta-sediment hosted copper mineralisation at Mt. Isa, Australia: *Geochimica et Cosmochimica Acta*, v. 57, pp. 2991–3000.
- Heinrich, C.A., Bain, J.H.C., Mernagh, T. P., Wyborn, L.A.I., Andrew, A. S. and Waring, C.L., 1995, Fluid and mass transfer during metabasalt alteration and copper mineralisation at Mount Isa, Australia: *Economic Geology*, v. 90, pp. 705–730.
- Hills, J.H. and Thakur, V.K., 1975, Westmoreland Uranium Deposits, *in* Knight, C.L. (ed), Economic Geology of Australia and Papua New Guinea, 1. Metals: The Australasian Institute of Mining and Metallurgy, Melbourne, pp. 343–347.
- Hinman, M.C., 1998, Speculation on syn-diagenetic processes of sulphate reduction at the HYC Ag-Pb-Zn deposit, Northern Territory: Geological Society of Australia, Abstracts, v. 49, p. 212.
- Hinman, M.C., Wall, V.J. and Heinrich, C., 1994, The interplay between sedimentation, deformation and mineralisation at the McArthur Pb-Zn (-Cu) deposit: 12th Australian Geological Convention, Perth, September 1994, Geological Society of Australia, Abstracts, v. 37, pp. 176–177.
- Hoy, T., 1996, Broken Hill-type Pb-Zn-Ag+/-Cu, *in* Lefebvre, D.V. and Hoy, T. (eds), Selected British Columbia Mineral Deposit Profiles, Volume 2 – Metallic Deposits: British Columbia Ministry of Employment and Investment, Open File Report 1996-13, pp. 117–120.
- Huston, D.L., Stevens, B., Southgate, P.N., Muhling, P. and Wyborn, L., 2006, Australian Zn-Pb-Ag ore-forming systems; a review and analysis: *Economic Geology*, v. 101, pp. 1117–1157.
- Jones, D., Bull, S. and McGoldrick, P., 1999: The Kamarga deposit: a large, low grade, stratabound zinc resource in the Proterozoic “Carpentaria Zinc Belt” of northern Australia, *in* Stanley, C.J. (ed), Mineral Deposits: Processes to Processing: A.A. Balkema, Leiden, The Netherlands, pp. 873–876.
- Kendrick, M.A., Duncan, R. and Phillips, D., 2006, Noble gas and halogen constraints on mineralising fluids of metamorphic versus surficial origin: Mt Isa, Australia: *Chemical Geology*, v. 235, pp. 325–351.
- Large, R.R., Bull, S.W., McGoldrick, P.J., Walters, S., Derrick, G.M. and Carr, G.R., 2005, Stratiform and Strata-Bound Zn-Pb-Ag Deposits in Proterozoic Sedimentary Basins, Northern Australia: *Economic Geology*, 100th Anniversary Volume, pp. 931–963.
- McGoldrick, P. and Large, R., 1998, Proterozoic stratiform sediment-hosted Zn-Pb-Ag deposits: AGSO Journal of Australian Geology and Geophysics, v. 17, pp. 189–196.
- Mark, G., Oliver, N.H.S. and Carew, M.J., 2006, Insights into the genesis and diversity of epigenetic Cu-Au mineralisation in the Cloncurry district, Mt Isa Inlier, northwest Queensland: *Australian Journal of Earth Science*, v. 53, pp. 109–124.
- Matthai, S.K., Heinrich, C.A. and Dreisner, T., 2004, Is the Mount Isa copper deposit the product of forced brine convection in the footwall of a major reverse fault? *Geology*, v. 32, pp. 357–360.
- Murphy, F.C., Hutton, L.J., Walshe, J.L., Cleverley, J.S., Kendrick, M.A., McLellan, J., Rubenach, M.J., Oliver, N.H.S., Gessner, K., Bierlein, F.P., Jupp, B., Aillères, L., Luankamp, C., Roy, I.G., Miller, J.M., Keys, D. and Nortje, G.S., 2011, Mineral system analysis of the Mt Isa-McArthur region, Northern Australia: *Australian Journal of Earth Science*, v. 58, pp. 849–873.
- Oliver, N.H.S., Wall, V.J. and Pearson, P.J., 1986, The Mary Kathleen uranium-REE deposit; a product of regional metamorphism: Geological Society of Australia, Abstracts, v. 15, pp. 149–150.
- Oliver, N.H.S. and Rubenach, M.J., 2009, Distinguishing basinal- and magmatic-hydrothermal IOCG deposits, Cloncurry district, northern Australia, *in* Williams, P.J. et al. (eds), Smart Science for Exploration and Mining: Proceedings of the 10th Biennial SGA Meeting, Townsville, Australia, v. 2, pp. 647–649.
- Perkins, W.G., 1990, The Mount Isa copper orebodies, *in* Hughes, F.E. (ed), Geology of the Mineral Deposits of Australia and Papua New Guinea: The Australasian Institute of Mining and Metallurgy, Monograph Series, v. 14, pp. 935–941.
- Perkins, C. and Wyborn, L.A.I., 1998, Age of Cu-Au mineralisation, Cloncurry district, eastern Mt Isa Inlier, Queensland, as determined by ⁴⁰Ar/³⁹Ar dating: *Australian Journal of Earth Sciences*, v. 45, pp. 233–246.
- Polito, P.A., Keyser, T.K., Rheinberger, G. and Southgate, P.N., 2005, A

- paragenetic and isotopic study of the Proterozoic Westmoreland Deposits, southern McArthur Basin, Northern Territory, Australia: *Economic Geology*, v. 100, pp. 1243–1260.
- Polito, P.A., Keyser, T.K. and Jackson, M.J., 2006, The role of sandstone diagenesis and aquifer evolution in the formation of uranium and zinc-lead deposits, southern McArthur Basin, Northern Territory, Australia: *Economic Geology*, v. 101, pp. 1189–1209.
- Queensland Department of Mines and Energy, Taylor Wall and Associates, SRK Consulting Pty. Ltd. and ESRI Australia, 2000, North-West Queensland Mineral Province Report: Queensland Department of Mines and Energy, Brisbane.
- Rheinberger, G.M., Hallenstein, C. and Stegman, C.L., 1998, Westmoreland uranium deposits, *in* Berkman, D.A. and Mackenzie, D.H. (eds), *Geology of Australian and Papua New Guinean mineral deposits: The Australasian Institute of Mining and Metallurgy, Monograph Series*, v. 22, pp. 807–813.
- Rohrlach, B.D., Fu, M. and Clarke, J.D.A., 1998, Geological setting, paragenesis and fluid history of the Walford Creek Zn-Pb-Cu-Ag prospect, Mt Isa Basin, Australia: *Australian Journal of Earth Sciences*, v. 45, pp. 63–81.
- Singer, D.A., 1995, World class base and precious metal deposits: a quantitative analysis: *Economic Geology*, v. 90, pp. 88–104.
- Smith, S.E. and Walker, K.R., 1971, Primary element dispersions associated with mineralisation at Mount Isa, Queensland. Bureau of Mineral Resources, *Geology and Geophysics, Bulletin* 131.
- Solomon, M., Groves, D.I. and Jaques, A.L., 1994, *The Geology and Origin of Australia's Mineral Deposits: Oxford Monographs on Geology and Geophysics*, No. 24, Clarendon Press, Oxford.
- Southgate, P.N., 1988, A model for the development of phosphatic and calcareous lithofacies in the Middle Cambrian Thornton Limestone, northeast Georgina Basin, Australia: *Australian Journal of Earth Sciences*, v. 35, pp. 111–130.
- Southgate, P.N. and Shergold, P.N., 1991, Application of sequence stratigraphic concepts to Middle Cambrian phosphogenesis, Georgina Basin, Australia: *BMR Journal of Australian Geology and Geophysics*, v. 12, pp. 119–144.
- Sweet, I.P., 2012, The geology of the South Nicholson Group, northwestern Queensland. *Queensland Geological Record* (in press).
- van Dijk, P.M., 1991, Regional syndeformational copper mineralisation in the western Mt Isa block, Australia: *Economic Geology*, v. 86, pp. 278–301.
- Wall, V.J., 2006, Unconformity related uranium systems: Downunder and over the top. ASEG, *Extended Abstracts*, pp. 1–12.
- Walters, S., Skrzeczynski, R., Whiting, T., Bunting, F. and Arnold, G., 2002, Discovery and geology of the Cannington Ag-Pb-Zn Deposit, Mount Isa Eastern Succession, Australia: Development and application of an exploration model for Broken Hill-type deposits, *in* Goldfarb, R.J. and Nielsen, R.L. (eds), *Integrated methods for discovery: Global exploration in the 21st Century: Society of Economic Geologists, Littleton, Colorado*, pp. 93–116.
- Walther, A.E. and Andrews, S.J., 1993, The Century zinc-lead deposit, northwest Queensland, *in* Duncan, I.J. (ed), *Proceedings of the Australasian Institute of Mining and Metallurgy Centenary Conference, Adelaide: Australasian Institute of Mining and Metallurgy*, pp. 41–61.
- Wang, S. and Williams, P.J., 2001, Geochemistry and origin of Proterozoic skarns at the Mount Elliott Cu-Au (Co-Ni) deposit, Cloncurry district, NW Queensland, Australia: *Mineralium Deposita*, v. 36, pp. 109–124.
- Wilde, A., Jones, P.A., Gessner, K., Aillères, L., Gregory, M.J. and Duncan, R.J., 2006, A geochemical process model for the Mt. Isa copper orebodies: *Economic Geology*, v. 101, pp. 1547–1567.
- Williams, P.J., Chapman, L.H., Richmond, J., Baker, T., Heinemann, M. and Pendergast, W.J., 1996, Significance of late orogenic metasomatism in the Broken Hill-type deposits of the Cloncurry district, NW Queensland, *in* Pongratz, J. and Davidson, G. (eds), *New Developments in Broken Hill Type Deposits: CODES Special Publication 1*, pp. 119–132.
- Xu, G., 1996, Structural geology of the Dugal River Zn-Pb-Ag deposit, Mount Isa Inlier, Australia: *Ore Geology Reviews*, v. 11, pp. 339–361.

Laurie Hutton graduated from the University of Queensland in 1972, completing honours the following year. Since then he has been involved in regional geological mapping in Queensland. From 1975–1981, he was involved in the geological mapping programme at Mount Isa. In 2004, he was awarded a Doctor of Philosophy for a thesis on granitoid studies in the Pentland area of Queensland.

Courteney Dhnaram graduated from Queensland University of Technology in 2005 and joined the Geological Survey of Queensland soon after, starting in the Mineral Resources section completing geological and mineral occurrence mapping in the Esk Trough region. She has undertaken mineral occurrence mapping in the Ravenswood, Charters Towers and Bowen regions.

Terry Denaro graduated from the University of Queensland with a BSc (Honours) degree in 1976. Since then, he has worked on various geotechnical and mineral resource assessment projects within the Geological Survey of Queensland. Terry is currently a project leader in the Greenfields Prospectivity Unit.

Geoff Derrick graduated from the University of Queensland (1963) and worked with BMR-AGSO (1964–1980) in the Kimberley and Mt Isa regions. He has specialised in the Mt Isa Inlier and sedex-type Pb-Zn deposits. Current interests include lectures and workshops describing the discovery and nature of ore deposits in the Mt Isa Inlier.