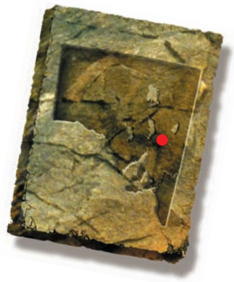

The diapir – base metal association in the northern Flinders Ranges

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Introduction

A substantial history of mining and exploration for Cu–Pb–Zn in the northern Flinders Ranges has defined a pattern of occurrences suggesting a strong association with Early Cambrian sediments and breccia bodies of tectonic origin referred to as diapirs by Webb (1960). Webb recognised that copper at the Blinman Mine occurred within a dolomitic host that was, in turn, completely enclosed by diapiric breccia. He also observed during mapping of the *Willochra* 1:63 360 map area that iron, manganese and base metal mineralisation was stratigraphically controlled in the basal Cambrian where dolomitic 'stinkstones' indicated sulphur-rich reducing conditions. At the same time, a geochemical sampling program was undertaken in 1960 by the Geological Survey of SA to investigate the potential for base metal mineralisation in the State's Cambrian sediments.

In 1961, L.G.B. Nixon observed that lead carbonate and sulphide ore was associated with sedimentary breccias in the Early Cambrian of the Ediacara Syncline. Furthermore, Nixon (1963) suggested that primary lead mineralisation at Ediacara was of the Mississippi Valley type (MVT). Dalgarno (1964) demonstrated that Cambrian facies were influenced by diapiric movements, and field mapping by R.P. Coats suggested that erosion of diapirs was responsible for copper enrichment during the Sturtian. These lines of evidence, together with the pioneering work of Webb, prompted Thomson (1962) to suggest that the high concentration of lead in the Early Cambrian was in part due to erosion of diapir domes enriched in heavy metals. Basement fault–shear lineaments associated with diapirs provided fracture systems that acted as pathways for metal-rich fluids, and as controls in localising base metal deposition. Cambrian base metal mineralisation was primarily confined to the Wilkawillina and Ajax Limestones, and was attributed to either an exhalative process contemporaneous with sedimentation or later telethermal mineralisation related to the Delamerian Orogeny (Thomson, 1965). This investigation was the precursor for current models of sedimentary exhalative (SEDEX) and MVT mineralisation adjacent to diapirs.

Johns (1972) summarised aspects of previous investigations by the Geological Survey of SA and reported many occurrences of Pb–Zn within the Early Cambrian of the northern Flinders Ranges. This report was followed up by exploration companies such as BHP Minerals Ltd (e.g. Roche et al., 1983), and later Geological Survey investigations (Morris, 1986; Robertson, 1988; Newton, 1991). Extensive geochemical work was undertaken and included stream sediment sampling followed by rock chip sampling and drilling. A major review of potential MVT Pb–Zn mineralisation in Cambrian successions of the northern Flinders Ranges was commissioned by the Geological Survey (Curtis and Jenkins, 1991), and is the basis for renewed interest that currently covers ~10 000 km^2 held under exploration licence in this area.

Known prospects for base metals in the northern Flinders Ranges constitute, for the most part, occurrences of sediment-hosted Pb–Zn, and are summarised by Curtis and Jenkins (1991). They conform largely to sediment-hosted models based on MVT mineralisation, but can also be classified with respect to different stages in diapir development. This paper comments on the nature of base metal occurrences adjacent to diapirs, and how they may be viewed in the context of the current model for salt tectonics in the Adelaide Geosyncline proposed by Dyson (1996a, 1998a, 1999).

Geological setting

The major diapiric structures (Coats, 1964, 1965) are located on the PARACHILNA and COPLEY 1:250 000 map areas in the northern Flinders Ranges (Fig. 1). The diapirs are often coincident with the cores of domes and anticlines. They also intrude the limbs of anticlines, keels of synclines, along faults and across fold axes of the host rock (Preiss, 1987). The diapirs were sourced from incompetent carbonate, clastic and evaporitic sediments of the Callanna Group at the base of the Neoproterozoic succession (Coats, 1973; Preiss, 1985). Together with the overlying Burra Group, these sediments represent deposition during rifting of the Neoproterozoic supercontinent. Depositional sequences of the Burra Group and overlying Umberatana and Wilpena Groups represent sedimentation that was contemporaneous with

Blinman Mine, located on a xenoclast of cupriferous dolomite within the Blinman Diapir. The former Mine Captain's cottage is at lower left, and the flat-topped smelter slag dump is at right. The subdued topography is typical of diapiric outcrop in the Flinders Ranges. (Photo 47917)

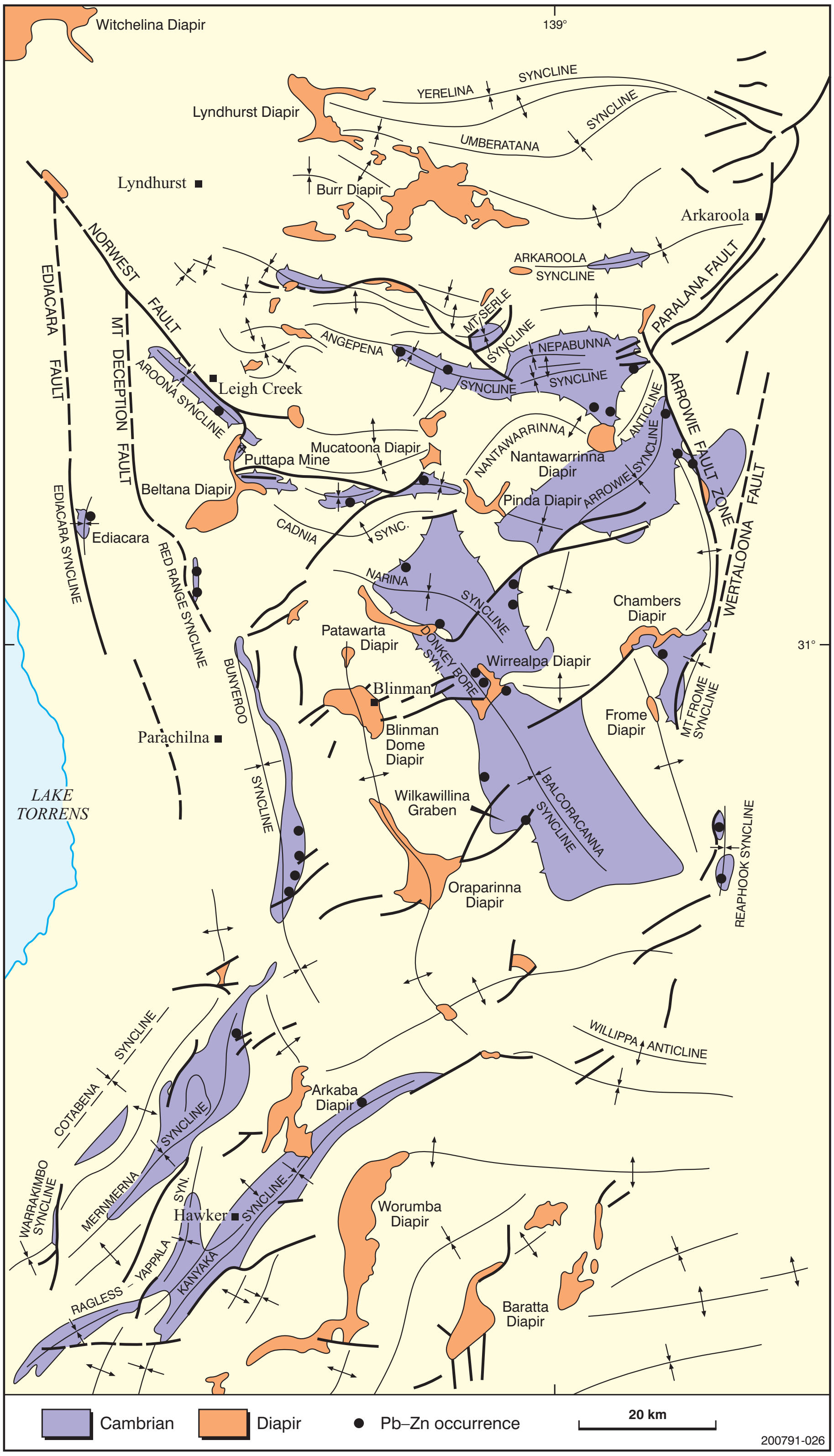


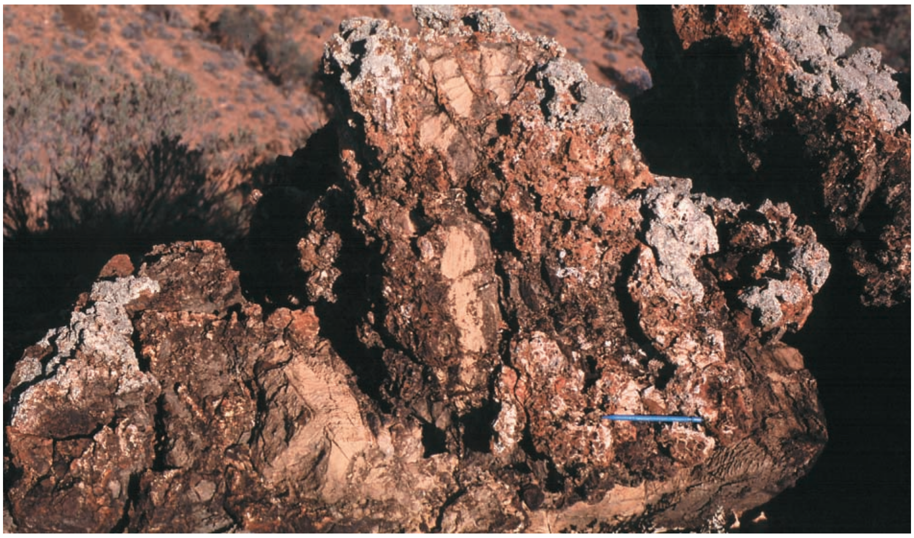
Fig. 1 Diapirs of the northern Flinders Ranges, and other localities referred to in the text (after Curtis and Jenkins, 1991).

diapirism, the latter during passive margin development of the Adelaide Geosyncline following breakup of the Neoproterozoic supercontinent (von der Borch et al., 1988).

There is an intimate relationship between diapirism and sedimentation in the Adelaide Geosyncline. The most recent model for diapirism (Dyson, 1996a) advocates a strong relationship between unconformities (or sequence boundaries) and diapirism that was first observed by both Coats (1965) and Dalgarno and Johnson (1968). In fact, many sequence boundaries and disconformities are most pronounced adjacent to diapirs where they are associated with the active and passive stages of diapirism (Dyson, 1996a). These stratal surfaces are significant with respect to exploration for base metals as they mark potential sites for syngenetic and epigenetic mineralisation. They are found adjacent to both intrusive and extrusive diapiric breccias. The diapiric breccias may be further classified as autochthonous or allochthonous respectively, the emplacement of which was dependent on the relative effects of extensional tectonics versus sedimentary loading (Dyson, 1998a). Renewed or continued extension resulted in the withdrawal of autochthonous breccia and subsequent formation of minibasins that were associated with extrusion of allochthonous breccia tongues interpreted to represent subaqueous salt glaciers (Dyson, 1998a). The Beltana Diapir represents such a minibasin and is the site for syngenetic copper and epigenetic zinc mineralisation (Dyson, 1999).

The diapir – base metal association in the northern Flinders Ranges

Sediment-hosted base metal mineralisation is found within or adjacent to major diapiric structures in the Adelaide Geosyncline. This includes the Arkaba, Beltana, Blinman, Chambers, Frome, Loch Ness, Mucatoona, Nantawarrinna, Oraparinna, Patawarta, Pinda, Wirrealpa and Worumba Diapirs (Fig. 1). These deposits can be grouped into five types — MVT, SST (sandstone-hosted type), RBT (redbed type), KST (Kupferschiefer type) and GRT (Green River type) — based on the nature of the sediment host and geochemistry of the ore fluids as defined by Eugster (1989). The distinction between those deposits influenced by acidic brines is gradational. Hence, this classification is not rigidly adhered to here. The role of diapirism in the formation of these deposits has not been well understood. Indeed, the mode of emplacement and timing of diapirism is controversial (e.g. Dalgarno, 1983a,b). Diapirs have been variably interpreted as intrusive breccias, synsedimentary slumps and even carbonatites. Instead, adherence to classical models such as MVT has been used to explain base metal occurrences in the northern Flinders Ranges (e.g. Roche et al., 1983; Curtis and Jenkins, 1991; Newton, 1991). Prime examples are the



Clasts of ferruginous breccia within a breccia pipe at Beltana Diapir where interstices contain coronadite ($PbMn_8O_{16}$). (Photo 47918)

Pb–Zn occurrences at Donkey Bore, Fountain Head and Old Wirrealpa Mines adjacent to the Wirrealpa Diapir that exhibit the characteristics typical of classical MVT (Roche et al., 1983; Curtis, 1989).

More recently, base metal occurrences associated with diapirs in the northern Flinders Ranges have been variously described as syngenetic and epigenetic. Dyson (1996a, 1999) suggested that synsedimentary mineralisation associated with diapirs could be classified as SEDEX and RBT deposits. Salt withdrawal grabens associated with some diapirs are host to RBT copper deposits (e.g. Mucatoona Diapir) and, following the effects of the Delamerian Orogeny, others (e.g. Wirrealpa Diapir) were transformed into third-order basins during which they were supplied with metalliferous brines from the diapir (Dyson, 1996a). Dyson (1999) identified a breccia pipe on the northwestern flank of the Beltana Diapir and suggested that it acted as a vent for flow of metalliferous brines via faults into the basal Bunyeroo Formation. The interstices of the breccia pipe contain Fe–Mn oxides and coronadite ($PbMn_8O_{16}$). This is reminiscent of vents observed in the Bunyeroo Formation which crops out in the Umberatana Syncline ~60 km north of Beltana (von der Borch and Dighton, 1999). Local compression along this flank of the diapir that preceded the Delamerian Orogeny was responsible for a 'pop-up' feature and possibly channelled fluids into overlying carbonate cap rocks of the Early Cambrian at Puttapa. These two styles of mineralisation have possible affinities with SEDEX and MVT deposits (Dyson, 1999).

The interaction between diapirs and sedimentation in the Adelaide Geosyncline provided the essential conditions for deposition of base metals, namely saline brines, metals and seal. Faults acted as conduits for brines (Curtis and Jenkins, 1991) that were in general chloride-rich and acidified by oxidation of pyrite or decomposition of organic matter. Metals could have been derived by basin dewatering by leaching of adjacent sediments (e.g. copper–redbed association). Callanna sediments were also, in part, highly organic (e.g. Boorloo Siltstone) and contain evidence of former abundant sulphate evaporites such as gypsum (Rowlands et al., 1980; Dyson, 1992). Sulphate was reduced in the presence of organic matter or light hydrocarbons to produce H_2S that in turn reacted with metal chloride complexes to precipitate metal sulphides.

Model for mineralisation

Base metal occurrences in the northern Flinders Ranges conform to current nomenclature for sediment-hosted mineral deposits (e.g. Eugster, 1989). However, the model defined herein classifies mineralisation with respect to individual stages of diapirism as outlined by Dyson (1996a). The distinction is made between autochthonous diapirs and allochthonous breccias that in turn can be related to the various stages of diapirism (Dyson, 1999). Both types of diapiric breccia are well represented in the northern Flinders Ranges and influenced potential sites for syngenetic, diagenetic and epigenetic mineralisation that was precipitated from saline brines.

Autochthonous

Autochthonous breccias are typically associated with the reactive, active and falling stages of diapirism that are initiated during extensional tectonics. The Blinman Dome Diapir (Webb, 1960; Coats, 1964) is a classic example of an autochthonous diapiric breccia where the rim stratigraphy is typically upturned at the contact. Such breccias rest directly on the original stratal surface on which the source material was deposited. The diapir is host to significant base metal deposits. Copper at the Blinman Mine is hosted by a dolomitic xenoclast within Callanna Group sediments (Webb, 1960). Diapiric structures also provided topographic highs as part of the chemical trap in diagenetic deposits. In the Willippa Anticline, metal-rich fluids were sourced from breccia of an unbreached reactive diapir and transported via fractures and faults to an oxidation–reduction interface represented by dolomite of the Burra Group in the core of the anticline, and into black shale and deep-water dolostone of the Tindelpina Shale which rims the structure (Dyson, 1996b). These occurrences could be classified as possible MVT and KST deposits, respectively (Fig. 2).

Grabens directly overlie some autochthonous diapiric breccias, and formed during continued extension, salt withdrawal or a combination of both. Pb–Zn and copper mineralisation associated with these grabens displays characteristics of MVT and RBT deposits, respectively (Fig. 3). In the Bunkers graben of the Oraparinna Diapir (Clarke, 1986), Pb–Zn mineralisation is found where offset growth faults of the graben are truncated by major unconformities within Cambrian limestone (Curtis and Jenkins, 1991; see Fig. 3). Other grabens are floored with anoxic sediments and copper mineralisation; a redox interface formed when anoxic sediments intertongued with redbeds

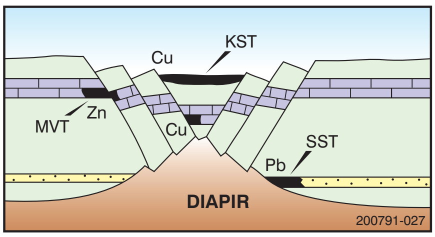


Fig. 2 *Reactive stage diapir and Cu–Pb–Zn deposited from metalliferous brines.*

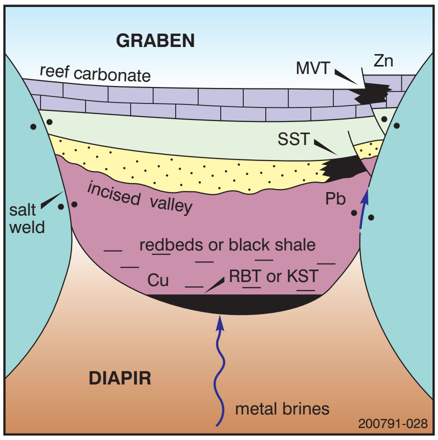


Fig. 3 Sites of Cu–Pb–Zn mineralisation associated with a falling stage graben that overlies an autochthonous diapir.

such as the Bunyeroo Formation at Mucatoona Diapir (Dyson, 1996a).

Allochthonous

Allochthonous diapiric breccias are sheet-like bodies emplaced at stratigraphic levels above the autochthonous source layer and are often still attached to the parent body (e.g. Pinda Diapir). They were initially emplaced during the passive stage of diapirism, and their development was completed during renewed extension, salt withdrawal or a combination of both. Allochthonous breccias are present in the northern Flinders Ranges as extruded tongues, Christmas tree diapirs and minibasins. These structures are host to several types of sites for mineralisation (Fig. 4) that also, for the most part, represent potential reservoirs for hydrocarbons (Dyson, in prep.).

Salt glaciers were extruded when sedimentation was low. Base metals may have been precipitated at the breccia–sediment interface or within adjacent sediments. At Wirrealpa Diapir, 100 m southwest of Old Wirrealpa Spring on the *Blinman* 1:63 360 map area (Dalgarno et al., 1964), Pb–Zn gossans are contained within enigmatic megabreccias characterised by the intertonguing and interbedding of 'layered diapiric breccias' with ooid and boulder grainstones rich in dolerite clasts (C.R. Dalgarno, geological consultant, pers. comm., 2000). The megabreccias are interpreted here as salt glaciers that were deposited by discrete pulses of diapiric activity during which onlapping Cambrian conglomerate and 'normal' diapiric breccia were re-sedimented as debris flows. At Pinda Diapir (Coats, 1973), copper occurs in redbeds of the Bunyeroo Formation adjacent to a tongue of allochthonous diapiric breccia interpreted as a salt glacier (Dyson, 1998a). Christmas tree diapirs are defined by laterals of salt glaciers that formed during alternation of the reactive–active and passive stages of diapirism. Some laterals can be intrusive in nature and may act as conduits for the flow of brines through vents at the sediment–water interface (Fig. 4).

Minibasins formed during salt withdrawal that often accompanied renewed extension, and their development was also punctuated by stages of passive diapirism with extrusion of breccia sheets. The Beltana Diapir (Dyson, 1999) is host to copper and Pb–Zn with characteristics of RBT and MVT, respectively. Similarly, Pb–Zn mineralisation at Wirrealpa Diapir is considered to be MVT (Curtis and Jenkins, 1991), but the role of diapirism has been uncertain. Recent work by the author suggests that major extension initiated the development of a salt withdrawal minibasin. Reactivation of a growth fault on the western flank of the minibasin early in the Delamerian Orogeny provided the pathway for metalliferous brines and the precipitation of Pb–Zn mineralisation on a karstic surface in the lower Wilkawillina Limestone (Fig. 5). Brines also migrated along salt welds

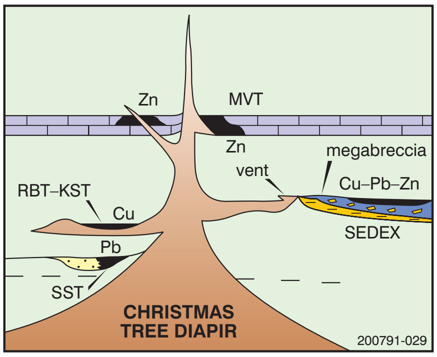


Fig. 4 A Christmas tree diapir and sites of Cu–Pb–Zn mineralisation.

that define the base of minibasins. Here, mineralisation precipitated along a major stratigraphic discontinuity that would previously have been interpreted as a normal fault (Fig. 5).

Brine chemistry

All five types of sediment-hosted base metal deposits as defined by Eugster (1989) are represented by diapir–sediment interaction in the northern Flinders Ranges. Acidified brines passed through redbed, sandstone and carbonate aquifers to precipitate copper, lead and zinc, respectively (Sverjensky, 1989). These further represent MVT, SST and RBT deposits, respectively. In general, RBT deposits are characterised by organic-rich sediments of local extent. Where basinwide transgressions are involved, the copper-rich sediments typically comprise black shale and are referred to as KST deposits (Eugster, 1989). Only GRT deposits are formed by reaction with alkaline brines, often inferred by the common association with evaporites such as shortite and trona. This assemblage of alkaline evaporites is typical of Callanna Group sediments, and comparisons were made by Rowlands et al. (1980) with Green River evaporites, the East African Rift system and Zambian Copper Belt.

Gossanous megabreccia near Old Wirrealpa Springs at Wirrealpa Diapir, interpreted as a salt glacier. (Photo 47919)

Gossan within the salt weld located at the base of the Rawnsley Quartzite, Loch Ness Diapir. (Photo 47920)

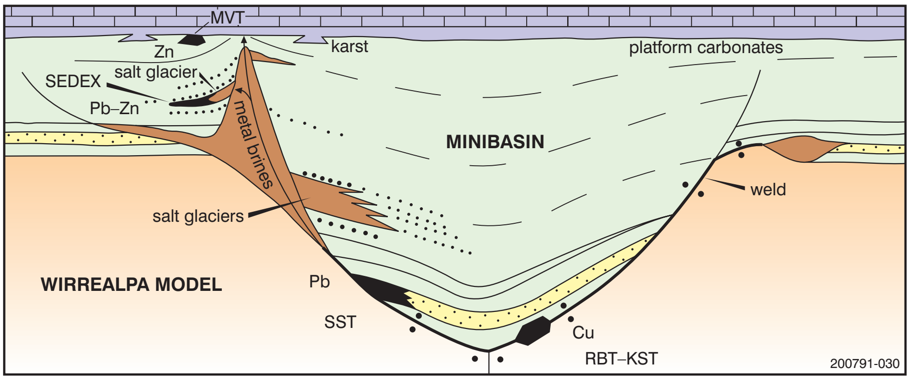


Fig. 5 *Model for Cu–Pb–Zn mineralisation associated with a salt withdrawal minibasin, based on the Wirrealpa Diapir.*

The redox state of the mineralised brines (sulphate or sulphide-predominant) in SEDEX deposits is important for controlling deposit size and minor element associations. Oxidised brines are more likely to have produced large tonnage Pb–Zn deposits, and commonly lack barite lenses and vent complexes. Deposits that formed in reduced siliciclastic and shale-dominated basins are more likely to be of lower tonnage and to contain barite, vent complexes and minor gold (Cooke et al., 1999). Barite is often associated with SEDEX deposits (Goodfellow et al., 1993). These latter characteristics are typical of many Pb–Zn deposits associated with diapirs in the northern Flinders Ranges, suggesting that they were more than likely derived from reduced, acidified brines. SEDEX deposits with similar characteristics have been inferred for the lower Kanmantoo Group in the Karinya Syncline (Dyson, 1998b).

Deposit types related to stratigraphy

Sediment-hosted base metal deposits in the northern Flinders Ranges can be classified with respect to the sediment host. For example, MVT deposits are associated with Early Cambrian carbonates of the Wilkawillina Limestone. Similarly, RBT deposits are typically found in the Bunyeroo Formation, the Parachilna Formation is host to SST deposits, the Tindelpina Shale is host to KST deposits, and GRT deposits are found in Callanna Group sediments that represent source material for diapirs.

Dolostones associated with base metal mineralisation are of two types. In the first, zinc mineralisation accompanied dolomitisation of reef limestone and karstic weathering surfaces that overlie sequence boundaries. The best known example is the Early Cambrian Wilkawillina Limestone and its equivalents (Curtis and Jenkins, 1991) that show rapid facies changes, and mineralisation may be associated with specific genetic facies and stratal surfaces that developed in response to growth of major diapiric structures. The second type of dolostone rims synclines interpreted as salt withdrawal basins (Dyson, 1998a) and was deposited under anoxic, deep-water conditions. Dolostone of the Nuccaleena Formation and Wearing Dolomite in each case overlies a maximum flooding surface which caps a major redbed cycle and contains copper mineralisation (Dyson, 1996a). These two types of dolostone host MVT and KST deposits, respectively.

The pyritic Tindelpina Shale has potential for SEDEX-style Cu–Pb–Zn adjacent to diapirs. A number of diapirs (e.g. Blinman, Worumba) were subaqueously exposed during deposition of the Tindelpina Shale, and metal-liferous brines could have been exhaled from vents. At Loch Ness Diapir, a megabreccia in the Tindelpina Shale contains three bands of gossan comprising intraclasts of black shale that are interpreted as synsedimentary slumps. Similarly, pyritic black shale of the Early Cambrian Midwerta and Oraparinna Shales is mineralised adjacent to diapirs. At Puttapa, a mineralised pyritic black shale unit in the Wilkawillina Limestone occurs below the main orebody (Horn, 1975), suggestive of a possible exhalative origin.

Shale-hosted SEDEX and carbonate-hosted MVT deposits represent both ends of the spectrum for sediment-hosted Pb–Zn deposits. Irish-type Pb–Zn deposits show many features transitional between the two end members (Hitzman, 1999), such as barite and vent complexes, and this style of mineralisation may be represented by some deposits in the northern Flinders Ranges such as the Puttapa Pb–Zn mine (Fig. 1). It further suggests that the fluid path and sediment host were major controls on deposit type and therefore explains why base metal deposits display characteristics of both SEDEX and MVT (Fig. 6). For example, if black shales were not present, fluids migrated upwards and laterally into carbonates where mineralisation was precipitated. Alternatively, copper mineralisation may occur proximal to vent complexes, and lead then zinc are found at increasing distance from the source suggesting metal zoning caused by differences in sulphide solubilities.

Discussion

The classification of sediment-hosted base metal deposits (Eugster, 1989) associated with major diapiric structures is difficult when based on the timing of

Megabreccia at the top of the Tindelpina Shale containing three gossanous bands, Loch Ness Diapir. (Photo 47921) mineralisation with respect to sedimentation, namely syngenetic, early to late diagenetic, or epigenetic. For example, debate over the origin of MVT deposits has focused on whether all MVT deposits are epigenetic (Eugster, 1989). MVT deposits may co-exist with SEDEX deposits where the MVT deposits were formed soon after the deposition of platform carbonates (Goodfellow et al., 1993), in which case they would be classified as early diagenetic. SEDEX deposits are analogous to sediment-hosted stratiform deposits (Brown, 1989; Holm et al., 1999) and may be synonymous with GRT deposits. Other types classified above are considered to be stratabound and in part stratiform (Brown, 1989).

The proximity to major diapiric structures (Beltana, Wirrealpa) was a positive influence on the formation of base metal deposits in the northern Flinders Ranges. Such structures were folded and faulted during the Delamerian Orogeny, and an intimate knowledge of Adelaidean and Early Cambrian stratigraphy and salt tectonics is required to interpret the structural configuration of the diapirs that will in turn help to determine the nature and timing of mineralisation. The model developed by mapping them in detail can then be applied to other diapiric structures; for example, Puttapa was discovered by applying a model based on the Wirrealpa Mine (C.R. Dalgarno, geological consultant, pers. comm., 1999). The recent discovery of a large breccia pipe at Beltana Diapir interpreted as a vent which was active during deposition of the basal Bunyeroo Formation (Dyson, 1999) may have significance with respect to Puttapa-style mineralisation. Compressional features (e.g. duck heads) which were generated during regional extension are found on flanks and adjacent to the Frome Diapir (Dalgarno, 1983b) and Beltana Diapir. Elsewhere, these features may have been mistaken for Delamerian structures. Such features have the potential to act as conduits for metalliferous brines.

Evaluation of base metal prospects in the northern Flinders Ranges has been constrained by the nature of previous exploration programs. Extensive geochemical surveys were carried out and, together with limited mapping, interpreted on the basis of empirical models for MVT deposits. Consequently, the full potential of a number of key prospects may not have been recognised. Since then, the relationship between mineralisation and salt domes has been well documented (e.g. Kyle and Posey, 1991; Wang et al., 1998), and the recognition of structures resulting from salt tectonics may become increasingly important in base metal exploration (B.P. Webb, University of Adelaide, pers. comm., 1998). Future investigations based on geochemical surveys may replicate the work and inherent flaws of past exploration. However, they may be more useful if considered in the context of the new model for base metal mineralisation in the northern Flinders Ranges. Hence, exploration for base metals in the northern Flinders needs to be undertaken with an adequate understanding of salt tectonics within a genetic stratigraphic framework.

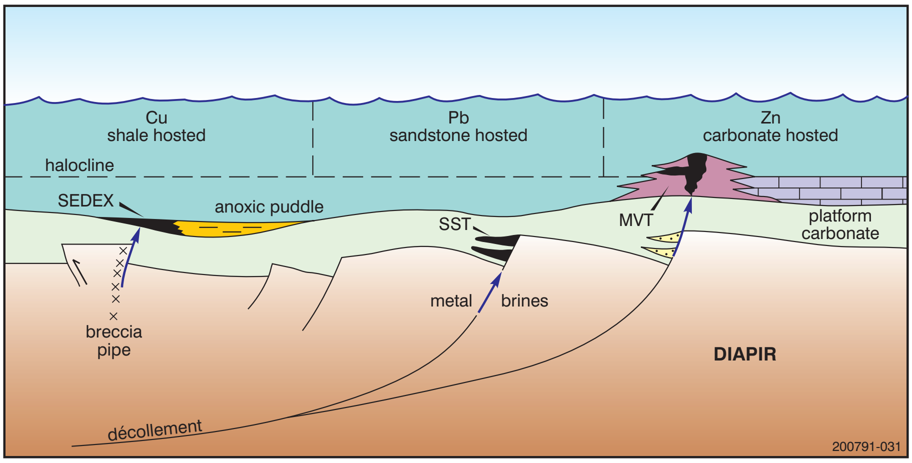


Fig. 6 Relationship between SEDEX and MVT mineralisation adjacent to diapirs.

Conclusions and prospects

A number of base metal occurrences in the northern Flinders Ranges, previously classified as syngenetic, diagenetic and epigenetic in nature, resulted from brine–sediment interaction with autochthonous and allochthonous diapiric breccias. These occurrences can be associated with specific stages in the evolution of major structures such as the Beltana and Wirrealpa Diapirs. The greatest potential for base metals in the northern Flinders Ranges is for Pb–Zn mineralisation within pyritic black shale and Cambrian limestone that display characteristics of SEDEX and MVT, respectively. Potential deposits will be small, totalling 1–2 Mt of combined Pb–Zn. However, a number of such deposits adjacent to major diapiric structures may lift the aggregate towards 10 Mt, with combined Pb–Zn grades ranging from 5 to 15%.

Previously, major prospects for base metals were identified on the basis of geochemical surveys that, in many cases, have been interpreted with little regard to detailed mapping. Exploration programs have also been constrained by models for MVT mineralisation, and by not applying a working model (e.g. Curtis and Jenkins, 1991). There is potential to use the current model for diapirism in the Adelaide Geosyncline (Dyson, 1996a, 1998a, 1999) as an exploration tool for base metals. In order to accomplish this, it will be necessary to understand the effect of salt tectonics on the genetic stratigraphy of the Adelaidean and Early Cambrian succession in the northern Flinders Ranges. Before detailed mapping is undertaken, the litho-stratigraphy should be reviewed and reconciled with sequence analysis. Mapping of major prospects then needs to take into account the evolution of diapiric structures within a genetic stratigraphic framework. A model based on this approach would be a powerful predictive tool in the exploration for base metals in the Flinders Ranges.

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