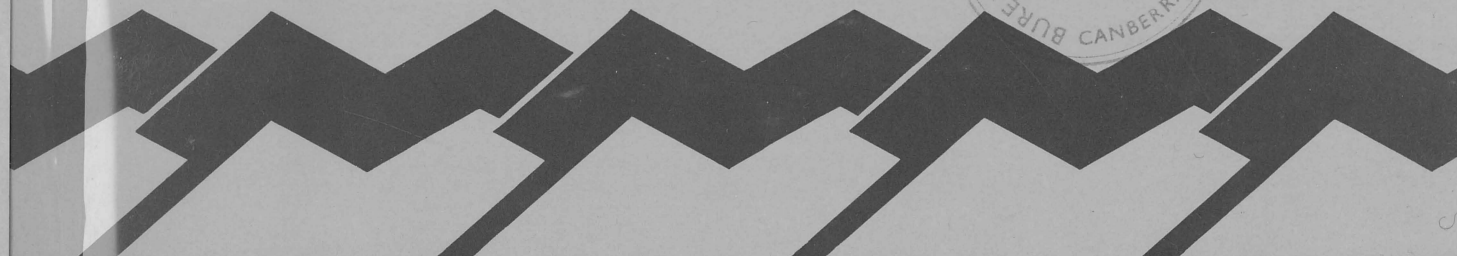
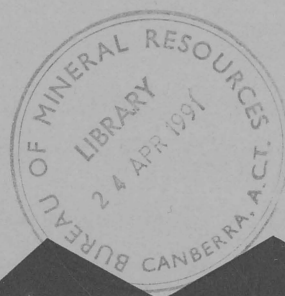


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**Are high heat producing granites essential to the
origin of giant lead-zinc deposits
at Mount Isa and McArthur River, Australia?**

(Pre-publication release)

by

M. Solomon and C. A. Heinrich

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N O T E

This paper has just been submitted for publication in the newly established 'Journal of Mining and Exploration Geology', in a special issue that will also contain other proceedings from the 8th conference of the International Association for Geology of Ore Deposits (IAGOD) held in Ottawa in August 1990. The present report has been revised after peer review but has not yet been formally accepted by the journal editor. The text is therefore preliminary and may differ in detail from the final published paper.



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Abstract

Giant, sediment-hosted lead-zinc deposits in northern Australia formed during development of mid-Proterozoic extensional basins that overlie Early Proterozoic basement. The basement in the Mount Isa area, exposed by folding and faulting, contains fractionated, high heat producing granites. These granites generate heat at a rate of about $6\mu\text{W m}^{-3}$, probably sufficient to form giant lead-zinc deposits either by (a) driving episodic convection of saline basement and basin fluids for periods of 10^5 - 10^6 years at temperatures of about 230°C , or (b) heating basin fluids moving under the influence of topographic relief or fault movement. The presence or absence of such granites may thus form a vital component of the genetic model. Ore-forming fluid flow was probably initiated by continent-scale, extensional basin fracturing.

Introduction

Giant, stratiform, sediment-hosted lead-zinc (sedex) deposits containing >10 Mt (10^6 tonnes) of both Pb and Zn first appear in the geological record in Australia at about 1680 Ma, e. g. H. Y. C., Lady Loretta, Hilton, Mount Isa, and Broken Hill (Page 1988; Page and Laing 1990). Supposedly older stratiform lead-zinc deposits in the Mount Isa area, e.g. Dugald River, have not been definitively dated and their age is uncertain. Like their younger counterparts in other continents (particularly the Irish lead-zinc province; Hitzman and Large 1986) the deposits consist of more or less stratiform lenses rich in sphalerite and galena, and apparently formed on or just below the basin floor within lacustrine or marine sequences of varying style that developed in epi- or intra-cratonic extensional basins (Gustafson and Williams 1981; Large 1983; Lambert 1983). As Sangster (1990) has noted, individual sedex deposits are similar in size to MVT districts but differ in being the product of sharply focussed fluid flow, commonly in major synsedimentary growth faults. Unlike MVT deposits, sedex ores formed *during* basin development rather than afterwards.

During the last five years there has been considerable discussion regarding the origin of the ore fluids and metals in sedex deposits, and the nature of the sedimentary environment (e. g. Lydon 1986; Wright et al. 1987; Jackson et al. 1987; Plimer and Lottermoser 1988; Willis et al. 1988; Sawkins 1984, 1989). A widely held view is that the ore fluids were derived by episodic basin dewatering (see review in Sangster 1990), consistent with their occurrence within large, extensional sedimentary basins. These basins are generally of carbonate-shale-sandstone type, and for such basins dewatering as a result of compaction is not a viable process, the thermal and mass fluxes being inadequate to generate the large deposits (Bethke 1985). These problems disappear for the relatively low temperature MVT deposits if copious flow is driven by the hydraulic head produced as result of tectonic uplift of basin margins (Bethke 1986), but the higher

temperatures required for forming sedex ores probably require unusually high geothermal gradients and/or deep fluid penetration beneath the basins.

The Irish lead-zinc deposits are unlikely to have formed from basin brines because there is no substantial basin (Andrew 1986), and Russell (1978) proposed that they formed as a result of convection following extensional basin fracturing. Russell et al. (1981) later extended this model to all giant lead-zinc deposits. In this model the convection cells are supposed to have extended downward to greater and greater depths through the life of the system. One dimensional, finite difference thermal modelling by Strens et al. (1987) indicates that the Russell model might account for giant deposits under favourable conditions such as large catchment area, high thermal gradient and adequate permeability.

Tectonic movement on faults provides a third possible driving force for ore fluid movement and sedex mineralization. Seismic activity along fault zones is known to cause major fluid flow, either by the mechanism of seismic pumping (Sibson et al. 1975), or by rupture stopping at dilational jogs (Sibson 1985).

In this communication we argue on the basis of solubility considerations and geological observation that all three driving mechanisms of fluid flow (the Bethke uplift model, the Russell convection model, and the Sibson fault models) require unusually high thermal inputs to form giant sedex deposits of the size of McArthur and Mount Isa. We propose that the Australian examples in the McArthur and Mount Isa basins were probably formed as a result of high heat flow in the basement resulting from radioactive decay in Early Proterozoic granites. Whether the ore fluids were convecting by thermal buoyancy, or being driven by a hydraulic heads related to topography and/or fault tectonics, is not yet clear although we consider the convection model most likely. We examine the geology of the McArthur and Mount Isa areas, the former yielding information

on basin structure and growth, the latter, being much more severely deformed, showing more clearly the geology of the basement. Chemical constraints on ore fluid composition and temperature provide information for future numerical modelling of the proposed systems.

The McArthur and Mount Isa Basins

The main ore-bearing horizons in the McArthur Basin and Mount Isa Inlier are approximately coeval, as shown by the dating of tuffs in the HYC and Mount Isa sequences at 1690 ± 29 Ma and 1670 ± 19 Ma respectively (Jackson et al. 1987; Blake 1987; Page 1988; Figs. 1, 2). The ore-bearing sequences lie within the McNamara and Mount Isa groups of cover sequence 3 in the Mount Isa Inlier, and within the McArthur Group in the McArthur Basin (Fig.2). Other supposedly older ore horizons (e.g. at Dugald River, Fig. 1) have not been accurately dated. The ore-bearing sequences consist largely of tidal to continental carbonates and shales with evaporitic minerals, and minor felsic tuffs. These accumulated in marine and/or lacustrine basins initiated during a period of extension that followed a complex history of sedimentation, volcanism and felsic plutonism. At H.Y.C, Mount Isa and Dugald River there is clear sedimentological evidence of evaporative conditions (Walker et al. 1983; Muir 1983; Neudert and Russell 1981).

The McArthur Basin

In the McArthur Basin, equivalents to cover sequence 3 consist of basal sandstones and volcanics (the Tawallah Group) overlain by the McArthur Group which hosts the H. Y. C. deposit. As in the Mount Isa Inlier the volcanic component decreases upward, being absent or consisting only of minor tuff beds near the ore horizon (Jackson et al., 1987). The Tawallah and McArthur groups are overlain by some 5 km of largely marine carbonates, cherts and sandstones that have been little disturbed or covered since the mid-Proterozoic (Crick 1989).

The lead-zinc deposits appear to be related to prominent faults that at H. Y. C. mark a sub-basin margin (Williams 1978; Jackson et al. 1987).

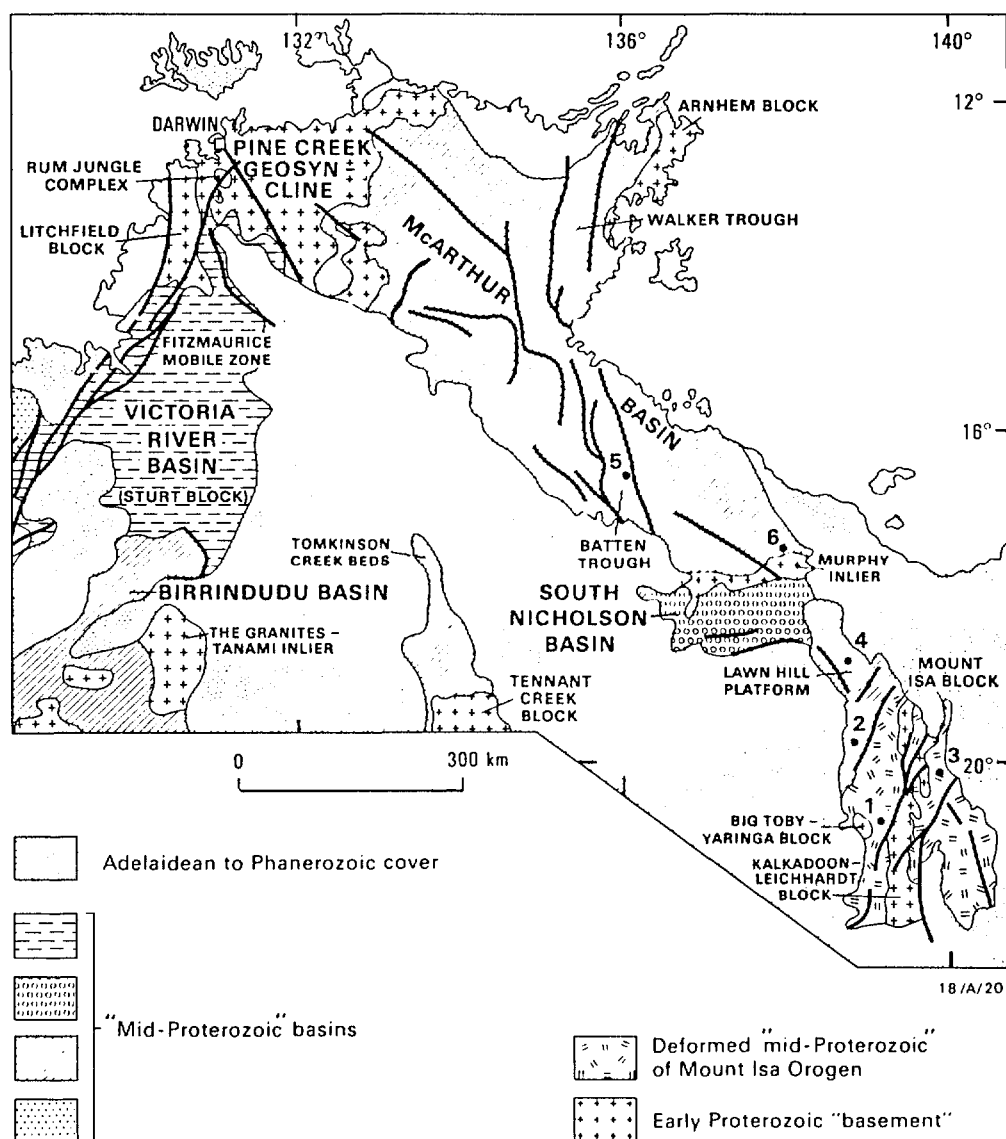


Figure 1. Map of northern Australia showing the main sediment-hosted lead-zinc deposits, from Plumb et al. (1990): 1 = Mount Isa and Hilton, 2 = Lady Loretta, 3 = Dugald River, 4 = Kamarga, 5 = H.Y.C. at McArthur River. Westmoreland uranium prospect = 6.

The Mount Isa Inlier

In the McArthur Basin the basement rocks are still largely concealed by relatively undeformed sediments but in the multiply deformed Mount Isa Inlier and in the Pine Creek Geosyncline (Fig. 1) the basement rocks are well exposed. The oldest rocks in the Mount Isa area belong to cover sequence 1, and were deformed and intruded by felsic plutons from about 1880 to 1850 Ma (Etheridge et al. 1987; Fig. 2). These plutons

McARTHUR BASIN	LAWN HILL PLATFORM WESTERN MOUNT ISA	EASTERN MOUNT ISA	
Roper/Nathan Gps.	South Nicholson Gp.	Williams 1480 Naraku 1560	cover sequence 3
DEFORMATION AND METAMORPHISM 1610 - 1550			
McArthur Gp. ~~~~~ Tawallah Gp.	McNamara/Mt. Isa Gps. 1670 ~~~~~ Surprise Creek Fm. Sybella > 1670? ~~~~~ Carters Bore Rhyolite 1678 Weberra 1700	Mt. Albert Gp.	
	Eastern Creek Volcs. Yeldham 1800-1820 Bottle tree Fm. 1790, 1808	Burstall 1730 Wonga 1745 Naraku Micro 1754 Corella Fm. Argylla Fm. 1766, 1783	cover sequence 2

Figure 2. Diagrammatic stratigraphy of the main rock groups and intrusive complexes in the McArthur basin and the Mount Isa area, from Blake (1987) and Wyborn et al. (1988). Numbers are ages in millions of years.

form part of a felsic intrusive suite that has been recognised over much of northern Australia; the magmas were not significantly fractionated and there was little associated mineralization (Wyborn 1988). Sawkins (1989) maintained that the first appearance of major lead-zinc deposits was related to a build-up of Pb in the crust brought about by this felsic magmatism. However the Pb contents of the intrusions mostly range between 5 and 50 ppm (L. A. I. Wyborn, pers. comm.), similar to the contents in older Early Proterozoic sediments in the Pine Creek geosyncline west of the McArthur basin (Ewers and Higgins, 1985; Ewers et al., 1985). Lead enrichment in the crust appears to have taken place earlier, probably in the Archaean.

Later intrusions in the Mount Isa area have been dated at about 1800-1820 Ma and 1740-1670 Ma, both older and younger than cover sequence 2 (e.g. the Yeldham and Wonga granites; Fig. 2). The related magmas were more fractionated than the 1880-1850 Ma magmas, with locally marked enrichment in U, Th, and K (Wyborn et al., 1988). Still younger granitoids that followed the lead-zinc mineralization, and the Mount Isa Orogeny at about 1600-1500 Ma, also have high contents of radioactive elements.

The post-1850 Ma, pre-ore granites

The post-1850 to pre-1680 Ma granitoids containing high U and Th contents include the Wonga and Naraku microgranites, the Burstall Granite and the Yeldham Granite (Wyborn et al., 1988; Table 1; Fig. 2). The Wonga, and Naraku microgranites, and the Burstall Granite, have been definitively dated as between 1750 and 1700 Ma old (Maas et al. 1987; Page 1988), making them older than the sedex deposits. In addition, the Yeldham Granite in the northwestern part of the Mount Isa Inlier is overlain unconformably by the ore-hosting McNamara Group (Jones 1986). Closer to the McArthur Basin, in the Murphy Inlier (Fig. 1), the Westmoreland Conglomerate at the

base of cover sequence 3 contains uranium probably derived from the basement (Plumb et al., 1990). On published information the U-Th-rich Sybella microgranite may be as young as cover sequence 3 but this is unlikely to be the emplacement age, and more detailed work is required to definitively determine the time of emplacement (Page and Bell 1986). Because the Sybella granite complex lies immediately west of the Hilton, Mount Isa and Mount Novit deposits its age is clearly an important question requiring further attention.

Table 1.

**AVERAGE U, Th AND K CONTENTS
OF POST-1850 MA, PRE-ORE GRANITES**

Granite (no. of samples)	U ppm	Th ppm	K wt %
Sybella Microgranite (12)	12	4	2.4
Wonga Microgranite (11)	11	66	2.3
Naraku Microgranite (3)	19	58	2.0
Yeldham Granite (1)	12	38	3.3
Burstall Granite (15)	10	70	5.1

Data from Scott and Scott (1985) and Wyborn et al. (1988)

There is a considerable range of U contents in the samples from the Sybella and Wonga microgranites (4-24 ppm for the Sybella), indicating there has been gain and loss of U, probably during subsequent metamorphism and deformation. Clearly more sampling is required to determine the primary U, Th and K contents, however, using the average values of Table 1 and the expression of Rybach (1974), the heat-producing capacities of these pre-ore, post-1840 Ma granites range from $5.7 \mu\text{Wm}^{-3}$ for the Yeldham Granite to $6.3 \mu\text{Wm}^{-3}$ for the Wonga microgranite.

Ore fluid parameters

Any genetic model must include examination of the composition and temperature of the ore fluids, in order to assess the mass and thermal fluxes required to form the ore deposits. Fluid inclusion homogenization temperatures have not been recorded for any of the large Australian lead-zinc deposits. The only possibly relevant data come from discordant vein and replacement deposits north and south of H. Y. C. in which the homogenization values range mostly between 100 and 170°C (Walker et al. 1983; Muir et al. 1985). The fluids are highly saline, reflecting the presence of evaporitic minerals in the sequence. Temperatures derived from stable isotope fractionations in the H. Y. C. deposit and nearby discordant deposits range from 100 to 325°C (Smith and Croxford 1973; Rye and Williams 1981) but are thought to be imprecise. Reflectance measurements on organic matter indicate positive thermal anomalies at the ore horizon in the McArthur Basin but the temperature-reflectance correlation is not well known (Crick 1989).

The sulphur isotopic composition of the abundant pyrite at Lady Loretta and H. Y. C. (and fine grained pyrite at Mount Isa) indicates that it all formed by biogenic reduction of sulphate in basin water (Smith and Croxford 1973; Carr and Smith 1977; Eldridge et al. 1988, 1989). The two generations of pyrite at H. Y. C. (the py_1 and py_2 of Williams 1978) have sulphur isotope

compositions distinctly different from that of the lead and zinc sulphides, indicating that base metals and combined sulphur have been introduced by exotic fluid(s). Broken Hill ore, which formed in sediments and volcanics largely without biogenic sulphides (Wright et al. 1987), has a very low iron sulphide content (average < 2 wt per cent, D. H. Mackenzie, pers. comm. 1990), implying that iron sulfide precipitation was not an essential part of the lead- and zinc-mineralizing process. Galena and sphalerite at H. Y. C. were precipitated after py_1 and py_2 , largely below the sediment-water interface and possibly by replacement of carbonates (Williams 1978; Eldridge et al. 1989; Logan et al. 1990; see also Neudert, 1983). The presence of fragments of bedded pyrite and galena-sphalerite-rich sediments in sedimentary breccias between stacked ore lenses show that this process took place soon after pyrite formation.

Except at Lady Loretta, where barite is present in part of the deposit (Carr 1981), the mineral compositions of the ores indicate an oxidation potential close to the pyrite-pyrrhotite boundary for the ore fluids. At H. Y. C. the pyrite-sulphur appears to have been derived from ambient basin water by biogenic sulphate reduction, while the galena-sphalerite-forming fluid contained reduced sulphur of independent origin, together with lead and zinc. There is no evidence to suggest that there were more than two fluids responsible for forming the H. Y. C. deposit. For a Na-K-Cl ($Ca-CO_2-HCO_3$) brine with 4 mol kg^{-1} total chloride, with pH buffered by equilibrium with quartz, alkali feldspars and muscovite (e.g. basal sandstones, granite basement), a temperature of 235°C is required for it to contain 10 ppm Pb with an equivalent molal concentration of reduced sulfur (Fig. 3). In Figure 3 an equal concentration of Zn is assumed to match the approximate composition of H. Y. C. ore, with molal concentrations of sulphur equal to that of (Zn + Pb) and assuming chloride complexes to dominate base metal sulfide solubility. If the solutions are pyrite saturated they will contain 1-10 ppm Fe depending on the oxidation potential (Walshe and Solomon 1981; Heinrich and Seward, 1990). Figure 3 shows a predicted precipitation paths for Pb and Zn as the

fluid cools from 235°C. Reaction with carbonates or feldspar at any point on the cooling paths will further increase the efficiency of sulphide deposition. To accumulate the 10 Mt Pb of the H. Y. C. deposit with the fluid composition outlined above requires the passage through the ore zone of 10^6 Mt of ore fluid at 235°C. Ten times as much fluid would be required if the temperature was only 180°C.

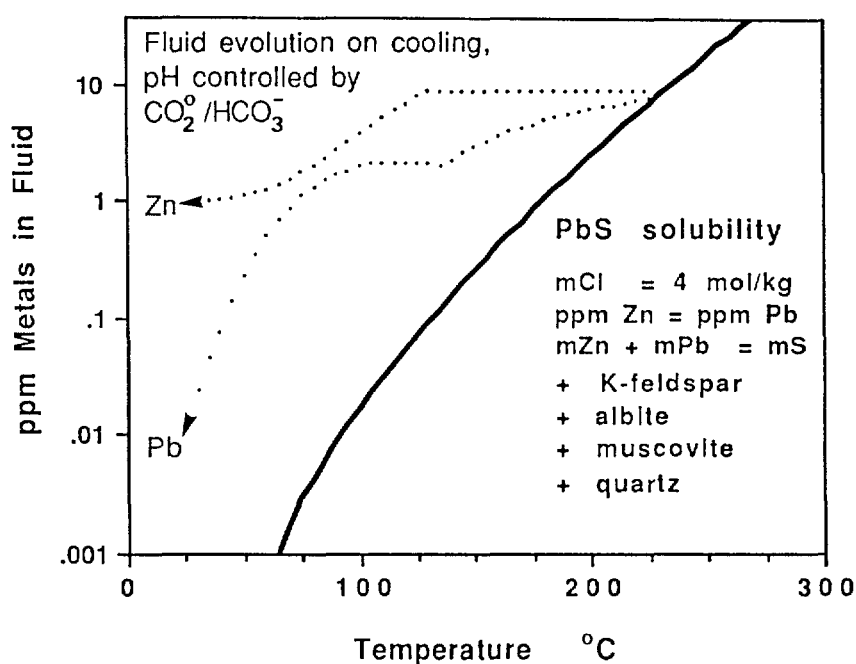


Figure 3. Maximum galena and sphalerite solubilities in a sulphide-bearing brine in equilibrium with a granitic source region (heavy line). Dotted lines show possible precipitation paths upon quenching of this fluid from 235°C; residual Pb and Zn concentrations are indicated, assuming equilibrium between fluid and precipitating sulfides but no wall-rock interaction. Reaction with carbonate or feldspar-bearing wall rock at any point along the cooling path would further reduce galena solubility, and below about 200°C also sphalerite solubility. Modelling based on experimental data from Seward (1984), Bourcier and Barnes (1987), Barrett and Anderson (1988) and others.

Source, paths and driving force for ore fluid flow

No direct relationship between magmatism and lead-zinc mineralization (e.g. significant volcanics, contact metamorphism, nearby coeval intrusives) has been observed for any of the deposits, and hence a magmatic fluid origin, or an origin by magmatic heating of basin fluids, is thought to be unlikely. The tuffs reported at H. Y. C. and Mount Isa are presumably derived from distant sources, as no other coeval magmatic rocks have been reported.

With respect to the hydraulic head model for MVT deposits (Bethke 1986), there is evidence of local topographic relief during mineralization at H. Y. C. in the form of sedimentary breccias interbedded with sulphide-rich lenses (Williams 1978), but no similar evidence is shown the other Australian deposits. In addition there are no regional unconformities or major changes in sedimentation at ore-forming time that would indicate the basin-scale relief invoked for gravity-driven expulsion of basin fluids (Bethke, 1986). It is acknowledged that this may reflect lack of detailed investigation or lack of exposure, and a gravity-driven flow model cannot be firmly excluded. However, if it is applicable, it probably cannot provide the required thermal flux without an enhanced heat source. The rate of decay of high initial geothermal gradients related to the initial extension, crustal thinning and magmatism of the McArthur and Mount Isa basins is probably too fast to have persisted through to ore-forming time. The much more long-lived radiogenic heat production from U-Th-enriched granites in the basement seems a likely source of energy in addition to heat conducted through the lower crust.

The heat generating values calculated for the pre-ore Mount Isa granites span the value of $6.0 \mu\text{Wm}^{-3}$ adopted by Fehn (1985) to model active fluid convection in some high heat-producing Cornish granites. Under a sediment overburden of about 5 km such granites can generate temperatures up to 300°C if heat flow is dominated by conduction only (Fehn et al. 1978; Solomon et al. 1991). If faulting during extension of the

basin sufficiently increases permeability throughout the system, then fluids in the basin and basement may convect (Fig. 4). Given the high Rayleigh numbers for such a system the convection will take the form of polyhedral or Benard cells (Combarous and Bories 1975), and the systems will be largely open at the top with recharge from the basin and basin margins.

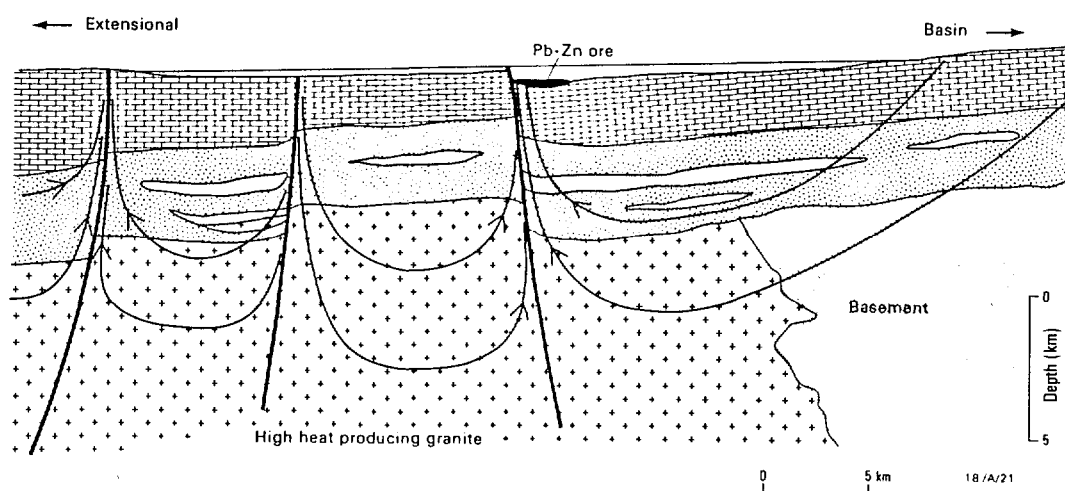


Figure 4. Possible stream lines during proposed ore-forming convection in basin sediments overlying a high heat producing granite.

Extrapolation of the model calculations of Fehn et al. (1978), Fehn (1985) and Strens et al. (1987) indicates that a convection system able to generate the required ore fluid temperature and mass flux requires (a) moderately high permeabilities to depths of 5-10 km, (b) large hot granites

(10^1 km diameter) and (c) substantial time (10^5 - 10^6 years). Two dimensional numerical analysis of the flow paths in the Australian situation is currently under investigation (Solomon, Heinrich and Swift, in prep.) but it is already clear that steady state convection will probably not be able to form the large orebodies in a geologically realistic period (Solomon et al. 1991). However, the stacking of ore lenses within the sediment column in all giant deposits (e.g. 14 lenses in 1 km sediment thickness at Mount Isa; Mathias and Clark 1975) indicates episodic convection. This allows regeneration of heat during formation of the deposits which is probably essential because of the strong temperature-dependence of base metal sulfide solubility (Fig. 3). The number of Benard cells established over a hot granite body is a function of the width of the granite and the depth of cover, i. e. the geometry of the permeable medium, and a possible arrangement is shown in Figure 4. The lead and zinc in the ore fluids is assumed to have been leached from rocks through which the fluids circulated, and mass balance calculations indicate that lead and zinc availability is not a limiting factor. Lead isotopic data from H. Y. C., Mount Isa and Lady Loretta (Gulson, 1985; Jones, 1986) are compatible with such a model because there is a relatively short period between the basement source rocks and mineralization (see Vaasjoki and Gulson, 1986).

Page (1988) identified a major hydrothermal event in northern Australia between about 1700 and 1650 Ma, a range that spans the ages of the H. Y. C. (1690 ± 27 Ma) and Mount Isa lead-zinc deposits (1670 ± 19 Ma). The basin extension and related fracturing suggested in our model for the Mount Isa and McArthur River areas may thus be of regional extent. Though our discussion has centred on the Mount Isa and McArthur River areas we note that the pre-Carboniferous basement to the Irish lead -zinc deposits contains high heat producing granites (O'Connor 1986), and that Brown et al. (1987) have suggested that fluid circulation in the North Pennine lead-zinc field in northern England was driven by radioactive decay in the older Weardale Granite.

Conclusions

1. High heat-producing granites stratigraphically underlie the ore horizon in the Mount Isa area, and we speculate they may also underlie ore in the McArthur Basin. They may drive post-magmatic convective circulation responsible for lead and zinc sulphide ore deposition (our preferred model), or provide the required additional heat to basin or basement brines circulating under the influence of large-scale topographic relief or other tectonic forces. Thermal energy input is probably the main limitation on the formation of giant sedex deposits, rather than metal availability.

2. For the convection model, qualitative extrapolation of earlier modelling studies (e.g. Strens et al. 1987) and preliminary modelling by Solomon et al. (1991) indicates that reduced brines at 235°C and initially buffered by granite can supply 10 Mt of lead and zinc, provided permeabilities are moderately high, the granite is $> 10^1$ km wide, the system is episodic and it operates for 10^5 - 10^6 years.

3. The convection model predicts large deposits only above hot granites, and the depth of cover and the width of the granite determine the number of cells (and hence number and spacing of deposits). This has important implications for mineral exploration and calls for a more sophisticated knowledge of local geology, particularly the timing and distribution of high heat-producing granites. Other fluid-flow models may still require hot granites beneath the basin but lead-zinc deposits may form at some distance from the granite margins if fluid flow is dominantly lateral.

4. The 1680 Ma period of lead-zinc ore formation in northern Australia appears to be part of a continent-wide hydrothermal event probably related to crustal extension (Page 1988; Wyborn et al. 1988).

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