The distribution of SEDEX Pb-Zn deposits through Earth history

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Abstract. The emergence of SEDEX ores in the rock record at about 1.8 to 2.2 Ga can be related to the hydrosphere and atmosphere progressively becoming oxidized and therefore sulfide-poor and sulfate-rich, evolution of sulfate-reducing bacteria, and fundamental changes in the Earth crust. The reason for the apparent change in tectonic setting of SEDEX deposits from intracratonic rifts in the Proterozoic to passive margins is unclear. Phanerozoic SEDEX deposits formed in paleolatitudes that mirror modern evaporative belts, suggestive of a brine reflux origin for passive margin SEDEX deposits.

Keywords. Sediment hosted lead-zinc deposits, SEDEX

1 Introduction

The reasons for the uneven distributions of certain classes or ore deposits in the geological record are generally attributed to secular variations in geological processes that controlled the formation and destruction of these deposits (e.g. Meyer 1981; Sangster 1990; Hutchinson 1992; Barley and Groves 1992; Titley 1993). We examine the secular distribution of SEDEX lead-zinc deposits (Fig. 1) that is based on the metal resource data (Leach et al. 2005) for 148 SEDEX (sedimentary exhalative deposits) lead-zinc deposits. Despite the inherent "exhalative component" in the term "SEDEX", direct evidence of an exhalite component in the ore or alteration assemblage is not recognized for many SEDEX deposits. The age of mineralization is commonly considered to be synsedimentary, however, some deposits formed in a subseafloor diagenetic environment (i.e. Red Dog, Alaska) and some formed during burial diagenesis (i.e. Century, Australia). Nevertheless, the age of formation is assumed to be the same or very close to the age of the host rocks.

SEDEX ores are mainly restricted to two groups: one in the Proterozoic and another in the Phanerozoic (e.g. Goodfellow 1994 and references therein, Large et al. 2005 and references therein, Leach et al. 2005 and references therein). The Proterozoic group (at about 1.4 to 1.8 Ga) includes the large deposits in the Mt. Isa-McArthur basin of Australia (Large et al. 2005) the Sullivan deposit in Canada and the deposits in the highly metamorphosed rocks of the Aravalli-Delhi belt of northwestern India. The Phanerozoic ores includes the large Red Dog, Alaska deposits and the deposits in the Selwyn basin, Canada. The older age group corresponds to SEDEX deposits in failed continental rifts (rift-sag basins), whereas deposits of the younger age group formed along passive continental margins (e.g. Large et al. 2005 and references therein, Huston et al. in prep.).

We discuss the possible reasons for the emergence of SEDEX deposits and examine the tectonic factors that may have influenced their distribution in the rock record. Recent fluid inclusion studies of the Red Dog deposit together with analysis of the distribution of SEDEX deposits using GIS and plate reconstructions provide insights into why some Phanerozoic basins are fertile for SEDEX and others barren.

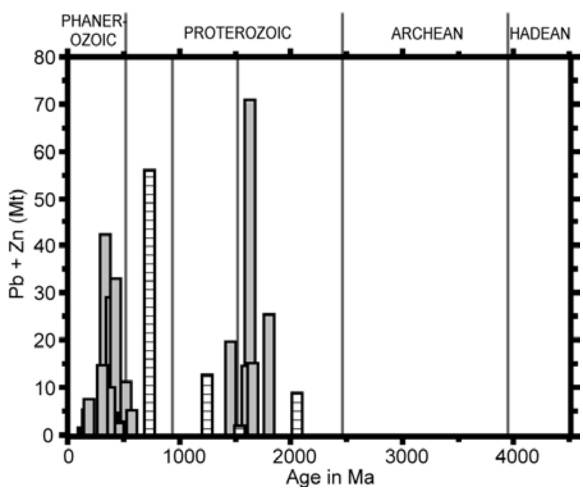

Figure 1: Distribution the combined lead and zinc in SEDEX deposits vs. their presumed age. Data from Leach et al. 2005. The bars represent the mid-points of the ages of the deposits. Bars with horizontal lines include deposits with extreme uncertainty (~ ± 300 my) for the ages of the ores.

2 Emergence of SEDEX deposits evolution of the hydrosphere and atmosphere

SEDEX lead-zinc deposits form mainly from oxidized (reduced-sulfur poor) fluids; therefore, their appearance is likely a consequence of the evolution of the Earth, particularly changes in the composition of the hydrosphere and atmosphere. SEDEX deposits and their closely affiliated ores, MVT deposits, are not known to have formed prior to about 2.2 Ga (Leach et al 2005 and references therein). The oldest significant SEDEX deposits (~1.8 Ga) are those of Aravalli-Delhi belt of India (e.g. Goodfellow 1994 and references therein, Leach et al 2005 and references therein). The early Proterozoic (2.5-1.8 Ga) is a major period of change in Earth's history. Prior to 2.4 Ga, the atmosphere and (for the most part) the hydrosphere, were reduced. Between 2.4 Ga and 1.8 Ga, the atmosphere became oxygenated, with the hydrosphere also progressively becoming oxidized, sulfide-poor and sulfate-rich. Importantly, chemical changes in the hydrosphere probably did not occur uniformly, but instead were more rapid in restricted basins (Fig. 2) than the open ocean (Rye and Holland 1998; Farquhar et al. 2001; Huston and Logan 2004 and references therein). Prior to 2.2 Ga, the reduced oceanic chemistry prevented formation of SEDEX deposits. With the minor exception of a sulfate-rich upper oceanic layer prior to 3.2 Ga, the oceans were generally reduced and virtually sulfate-free during the Archean and earliest Proterozoic (Huston and Logan 2004). Changes in oceanic geochemistry probably led to the flowering of SEDEX deposits, beginning at ~1.8 Ga in India, with continuing between 1655 and 1575 Ma in Australia. Huston and Logan (2004) suggested that the oxygenation of the hydrosphere proceeded unevenly, beginning with small basins and culminating at ~1.8 Ga with final oxygenation of deep oceanic basins. The earliest, small SEDEX deposits may have formed in small basins, with the general oxygenation of the seawater allowing the formation of large deposits beginning at 1.8 Ga. A second aspect that may be important is the evolution of sulfate-reducing bacteria by this period. These bacteria may have been critical in the production of H_2S at the site of deposition, allowing deposition of ore metals.

The specific tectonic factors controlling the emergence of SEDEX deposits are elusive, because the two settings in which they are known—rifts and passive margins—appear to have existed back as far as 3 Ga (e.g. Kusky and Hudleston 1999; Tinker et al. 2002). Nonetheless, there are some potentially important tectonic changes that occurred about 1.8 Ga. The emergence of SEDEX deposits came at a time when global radiogenic heat production was about 1.5 times as great as today (Pollack 1997) and plates, accordingly, may have been smaller. Furthermore, by 1800 Ma, it was likely that the first cycle of supercontinent breakup and reassembly was nearing completion (Meert and Mukherjee 2004) and over 80% of the preserved continental crust had formed (Collerson and Kamber 2000).

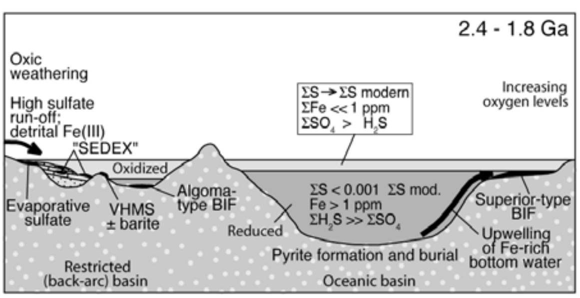

Figure 2: Model for evolution of the hydrosphere between 2400 and 1800 Ma. During this period the hydrosphere became progressively oxygenated, with this process occurring initially in small basins prior to spreading to oceanic basins. In this model, SEDEX deposits would have formed initially in small basins.

3 Passive continental margins and the Mesoproterozoic to Neoproterozoic "gap"

A preliminary survey of passive margins through time (Bradley and Rowley 2004) revealed two main intervals when the earth had passive margins: ~2650 to ~1750 Ma, and ~1050 Ma to present (Fig. 3). Curiously, passive margins of the older age group appear to be barren of SEDEX deposits, whereas those of the younger group host important deposits. Rift basins are common through Earth

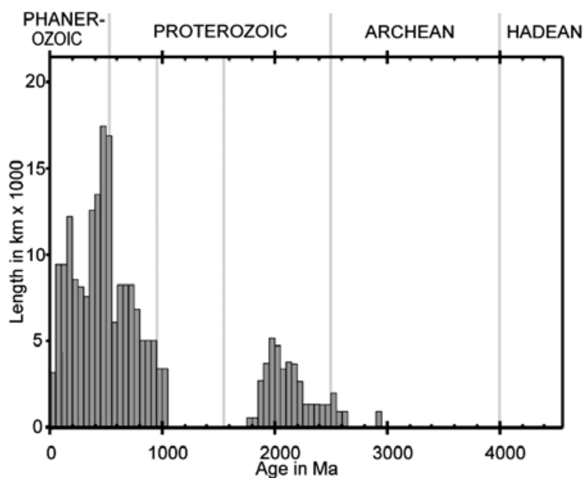

Figure 3: Histogram showing lengths of ancient passive margins plotted against geologic age. Not shown are extant passive margins, which formed between 180 Ma and the present and which today total 180,000 km in length. The deep-water facies belts of these modern margins (where SEDEX deposits might be found) have not yet been uplifted during collision. Also not represented are a few margins in the late Archean (e.g. North China craton) and Mesoproterozoic (e.g. Urals) that are poorly dated.

history (Sengor and Natalin 2001) and yet only during a comparatively short interval in the late Paleoproterozoic did they host significant SEDEX deposits.

The apparent change in tectonic setting of SEDEX deposits remains a mystery, as does the meaning of the Mesoproterozoic to Neoproterozoic "gap" in the number of SEDEX deposits (Fig. 1). Although the Mesoproterozoic to Neoproterozoic does contain significant SEDEX ores (e.g. 542-900 Ma includes Gorevsk deposit in Russia and 900 and 1600 Ma includes Balmat deposit in the USA), this is a relatively quiet time for SEDEX formation and other types of ores (e.g. MVT, VMS, SEDEX barite). This gap could be partly due to deposit preservation and destruction. SEDEX ores that form in passive continental margins may have a higher potential for destruction relative to ores in intracontinental rifts due to the eventual plate convergence and uplift of orogenic fold belts along continental boundaries. However, if this were the main explanation for the Mesoproterozoic to Neoproterozoic gap, we would expect to see a better correlation between SEDEX deposits and passive margins in the rock record.

4 The fertility of Phanerozoic passive continental margins

A "reflux brine" model (Fig. 4) was suggested for the genesis of the giant Red Dog deposit (Leach et al. 2004). In this model, brines are produced in a seawater evaporative environment within shelf carbonates sequences. These brines infiltrate into the underlying basement rocks, extract heat and metals, and discharge into the reduced sediments in a passive margin basin. An important feature of this model is that generation of the brine occurs in high evaporation climatic regions. The principal arid zones for modern Earth are located about 30° N and S of the equator (Warren 1989).

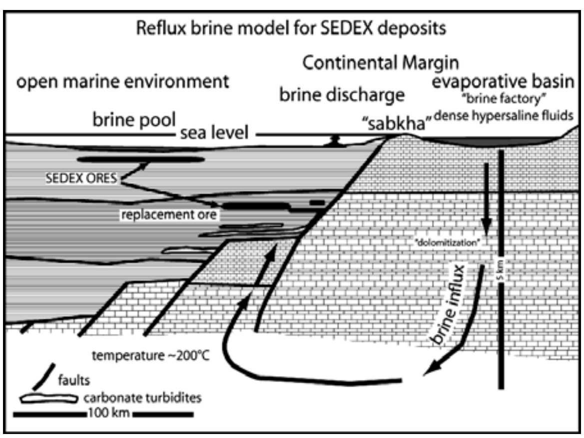

Figure 4: Reflux brine model for the formation of SEDEX ores in continental passive margin basin.

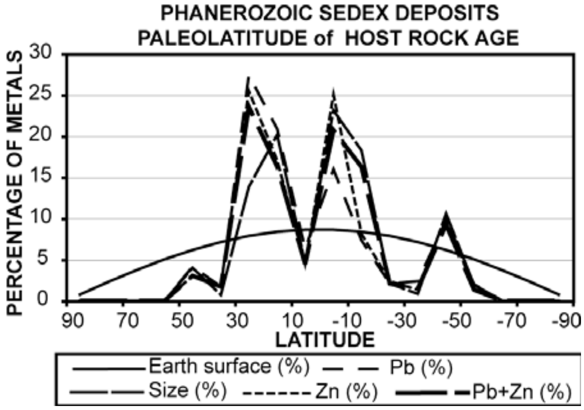

Figure 5: Total metal content of SEDEX deposits (expressed as a percentage of the total of all Phanerozoic deposits) summarized by paleo-latitude at time of deposit formation. Area% defines the surface area of the Earth and the theoretical random distribution of SEDEX deposits.

To test if the brine reflux model can be applied to other Phanerozoic SEDEX deposits, the distribution of the paleolatitudes of the deposits at the time of mineralization can be determined. This is accomplished by an analysis of the distribution of SEDEX deposits in a GIS (Geographical Information System) plate-tectonics database. The approach uses GIS to query results from plate-tectonic reconstructions (Scotese 1999) and quantify both spatial and temporal patterns. Figure 5 summaries the percentage of metal content of all Phanerozoic SEDEX deposits vs. paloelatitudes for ore deposition. The Earth surface area, defined as percentage of the total surface area of the Earth defines the expected distribution of SEDEX deposits (assuming distribution is random).

Considering the uncertainties in plate reconstructions, age of ore deposition and the paleolatitudes of global arid belts, the metal distributions remarkably mirror present day latitudes of high evaporative zones. This observation may provide one aspect of why some passive margins are fertile whereas others are barren of SEDEX. Passive margins basins that do not evolve in high evaporative areas of the Earth have significantly less potential to have been exposed to ore-forming brines.

References

Barley ME, Groves DI (1992) Supercontinent cycles and the distribution of metal deposits through time. Geol 20: 291-294

Bradley, DC, Rowley, DB (2004) Lifespans of passive margins and Atlantic-type ocean crust since 2500 Ma: Penrose Conference on Secular Variation in Tectonics and Allied Fields, Geol Soc of Am, St. George, Utah, Oct. 22-28, 2004 (abst) 7-8

Collerson KD, Kamber BS (2000) Evolution of the continents and the atmosphere inferred from Th-U-Nb systematics of the depleted mantle. Science 283: 1519-1522

Farquhar J, Bao H-M, Thiemens M (2000) Atmospheric influence of the Earth's earliest sulfur cycle. Science 289: 756-758

Goodfellow W (2004) Geology, genesis and exploration of SEDEX deposits, with emphasis on the Selwyn Basin, Canada. In: Deb M, Goodfellow WD (eds) Sediment hosted Lead-Zinc sulphide deposits; Attributes and models of some major deposits in India, Australia and Canada. Narosa Publishing House: 24-99

Huston DL, Logan GA (2004) Barite, BIFs and bugs: Evidence for the evolution of the Earth's early hydrosphere. Earth and Planetary Science Letters 220: 41-55

Huston DL, Stevens B, Southgate P, Muhling P, Wyborn L (in review) Australian Zn-Pb-Ag mineral systems: a review and analysis

Hutchinson RW (1992) Mineral deposits and metallogeny: Indicators of Earth's evolution. In: Schidlowski, M, (ed) Early organic evolution: implications for mineral and energy resources. Springer-Verlag Berlin Heidenberg: 521-544

Kusky TM, Hudleston PJ (1999) Growth and demise of an Archean carbonate platform, Steep Rock Lake, Ontario, Canada. Can Jour of Earth Sci. 36: 565-584

Large RR, Bull SW, McGoldrick PJ, Derrick G, Carr G Walters S (2005) Stratiform and stratabound Zn-Pb-Ag deposits of the Proterozoic sedimentary basins of northern Australia. In: Henquist J, Thompson J, Richards JG (eds) SEG 100th Anniversary Special Publication (in press)

Leach DL, Marsh E, Emsbo P, Rombach C, Kelley K, Anthony M (2004) Nature of the hydrothermal fluids at the shale-hosted Red Dog zinc-lead-silver deposits, Brooks Range, Alaska. Econ Geol 99: 1449-1480

Leach DL, Sangster DF, Kelley KD, Large RR, Garven G, Allen CR, Gutzmer J, Walters S (2005) Sediment-hosted lead-zinc deposits: a global perspective. In: Henquist J, Thompson J, Richards JG (eds) SEG 100th Anniversary Special Publication (in press)

Meert JG, Mukherjee D (2004) Supercontinents through time: status of the issues: Penrose Conference on Secular Variation in Tectonics and Allied Fields. Geol Soc of Amer, St. George, Utah, Oct. 22-28, 2004. 36-37

Pollack HN (1997) Thermal characteristics of the Archean. In: M.J. De Wit and L.D. Ashwal, editors: Greenstone Belts, Clarendon Press, Oxford: 223-232

Rye R, Holland HD (1998) Paleosols and the evolution of atmospheric oxygen; a critical review. Amer Jour Sci. 298: 621-672

Sangster D (1990) Mississippi Valley-type and sedex lead-zinc deposits; a comparative examination: Transactions, Inst Mining Metal Section B, 99: B21-B42

Sengor AMC, Natal'in BA (2001) Rifts of the world: Geol Soc America Special Paper 352, 389-482

Scotese CR (1999) The Global Plate Tectonic Model, unpubl. report

Tinker J, de Wit M, Grotzinger J (2002) Seismic stratigraphic constraints on Neoarchean-Paleoproterozoic evolution of the western margin of the Kaapvaal Craton, South Africa. So African Jour Geol. 105: 107-134

Titley SR (1993) Relationship of stratabound ores with tectonic cycles of the Phanerozoic and Proterozoic: Precam Res. 61: 295-322

Warren JK (1989) Evaporite sedimentology: Importance in hydrocarbon accumulation. Englewood Clifs, Prentice Hall. 285