

THE LITHOSPHERE, GEODYNAMICS AND METALLOGENY OF EARLY EARTH

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Relationship of ore deposits to plate tectonics

Ore systems are closely linked to processes resulting from plate tectonics and global dynamics (e.g. Mitchell & Garson 1981, Sawkins 1984, Windley 1995, Kerrich et al. 2005). A robust understanding of the genetic controls on ore deposit formation means that deposits themselves can be sensitive indicators of geologic process (e.g. Meyer 1988, Groves & Bierlein 2007). In this paper we explore the lithospheric and geodynamic controls on ore deposits in the early Earth prior to the Mesoproterozoic, and attempt to discover why there are so few significant deposits older than 3 Ga. Mantle plume activity related to a cooling Earth, the onset of plate tectonics, the evolution of the continental crust and sub-continental lithospheric mantle, the rise of atmospheric oxygen, and biological evolution are some of the factors that are likely to have influenced the genesis and preservation of deposits through time. The latter two are not considered further here.

Earliest evidence for plate tectonics and related ore deposits

Cooling of the Earth is primarily through the action of plate tectonics (linked with mantle convection) and the melting of mantle plumes to form large igneous provinces. Modelling of a hot early Earth suggests that plume dynamics may have been the dominant mode until at least the Neoproterozoic. Analysis of paleomagnetic, geochemical, tectonostratigraphic, isotopic and seismological evidence indicates that plate tectonics has operated since at least 3.2 Ga (Cawood et al. 2006, Dilek & Polat 2008), but possibly as early as the Hadean (summarized in Condie & Kroner 2008, Shirey et al. 2008). The earliest preserved crust that is indicative of probable plate tectonic processes is the Eoarchean 3.8 Ga Isua greenstone belt, Greenland (Dilek & Polat 2008). Both vertical forces related to gravitational equilibration of the crust, and horizontal forces related to plate tectonics, appear to have operated throughout the Paleo- to Neoproterozoic, with the former declining in significance with time and with cooling of the lower crust (e.g. Bedard 2003, Van Kranendonk et al. 2007). Plate tectonics has been dominant since at least the Late Neoproterozoic (Cawood et al. 2006), building cratons via accretionary and collisional processes (e.g. Kerrich & Polat 2006, Polat et al. 2005).

Rare well-preserved remnants of Paleo- and Mesoarchean upper crust indicate that mineralizing processes were active at this time. The 3.315 Ga Spinifex Ridge Porphyry Cu-Mo deposit and 3.24 Ga Sulphur Springs VHMS deposit, both in the Pilbara craton, are among the oldest preserved deposits of their type. Both formed

at a time when vertical tectonics was locally dominant (Van Kranendonk et al. 2007), and may not be direct genetic correlatives of similar deposits in post-Archean convergent margin environments elsewhere. The 2.95 Ga orogenic gold deposits in the Barberton Greenstone Belt appear to be associated with late orogenic lateral (plate) tectonics, similar to later deposits of this type (e.g. Goldfarb et al. 2005). Ca 2.92 Ga nickel sulphide deposits of the Yilgarn craton may be associated with a cratonic margin, similar to younger deposits of this type (Begg et al., submitted). The size of 2.89-2.82 Ga placer gold deposits of the peri-cratonic foreland Witwatersrand Basin, indicates that the Mesoarchean (and possibly earlier) processes were considerably more efficient at extracting and concentrating gold from the mantle than the later Earth (Frimmel 2008).

Abundant high-quality Neoproterozoic metal deposits are preserved. Witwatersrand gold aside, does the generally smaller size and relative paucity of older deposits indicate a change in Earth processes, or does it merely reflect poor preservation of the upper crust? Was there something fundamentally different about plate tectonic processes or metal source regions?

Growth of Sub-Continental Lithospheric Mantle (SCLM)

Integration of geophysical, geological, and geochemical data on the crust and lithospheric mantle has generated a map of lithospheric composition and architecture that suggests ca 70% of the existing SCLM may have an Archean parentage. Modelling of zircon Hf-isotope data from GEMOC's worldwide database concludes that a similar percentage (>60%) of continental crust had formed by the end of the Archean (Belousova et al., in prep). Of particular significance is the inference that most preserved Proterozoic crust overlies Archean SCLM that has been variably refertilised and metasomatised by mantle melts associated with convergent margin, post-collisional, and mantle plume processes (Begg et al. 2009a, Griffin et al. 2009). These interpretations suggest that consideration of lithospheric preservation and recycling is crucial to understanding Earth evolution. Pristine Archean SCLM comprises highly depleted (Fe-poor) dunite/harzburgite that most likely formed by high degree partial melting of large, hot mantle plumes (Griffin et al. 2009). Re-Os isotopic studies of sulphides from SCLM peridotites (e.g. Griffin et al. 2004) indicate that most of this Archean SCLM formed between 3-3.5 Ga ago (Griffin et al, this volume), a finding consistent with isotopic and trace element data from mafic-ultramafic crustal rocks (Shirey et al. 2008), and the record of PGE contents in komatiites (Maier et al. 2009). It is likely

therefore that the geodynamic environment during this period was dominated by particularly vigorous mantle plume activity and possibly major mantle overturns (e.g. Davies 1995).

In a recycling model, depleted, rigid, buoyant Archean SCLM survives the rifting and accretionary processes of supercontinent cycles, while the juvenile, fertile, dense SCLM typical of island arcs is removed. At least 20% of existing SCLM may be such fertile SCLM that has yet to be recycled. Although geochronological and isotopic (Hf, Nd) studies indicate that juvenile Proterozoic crust may be less extensive than previously believed, a recycling model must still account for significant amounts of juvenile Proterozoic crust. Accretionary events and rifting at margins may add or subtract variable thicknesses of crust via obduction or detachment, respectively. Also, crustal re-surfacing with juvenile mantle-derived products, and development of cover sequences, make detection of older crust difficult.

Interaction between Plate tectonics and SCLM

Formation of a buoyant, anhydrous (stiff) SCLM represents a milestone in Earth dynamics as it will have had a profound interaction with, and influence on, plate tectonics. Amalgams of lithospheric blocks form rigid cratons, dictating a minimum plate size, localizing subduction on their margins, and facilitating the transfer of stress during accretionary and collisional events. Lateral plate motions involving intra-continental rifting or subduction at a convergent margin represent opportunities to thin crust, and to dissect continents and cratons. In particular, subduction rollback facilitates the formation of backarc basins, which are first documented at 3.0 Ga and are widespread by 2.7 Ga (Condie & Kroner 2008). Fragmentation of brittle cratonic lithosphere may result in the development of intracratonic basins with high geothermal gradients. Far field stresses may reactivate old boundaries within the SCLM, or form new translithospheric faults. Significantly, the appearance of this cratonic SCLM enabled the formation of supercontinents, forcing a new organizing framework on a coupled plate tectonic-mantle convection system.

Linking the Lithosphere and Geodynamics to Ore Deposits in the Early Earth

A coupled whole-lithosphere and geodynamic approach can help us understand secular and spatial controls on metallogeny, within the larger framework and macro control of the supercontinent cycles. In the modern Earth, the polarity of subduction, disruption of subduction, and rate of convergence conspire to determine the metallogenic fertility of Cu and Au source regions in both the convecting mantle and SCLM (e.g. Solomon 1990, Richards 2009). This probably also applied to Archean plate tectonics. Many giant ore deposits of all ages are located on or near translithospheric faults, implying either a direct or indirect mantle role in their genesis. Examples of the former include deposits of magmatic Ni-Cu-PGE sulphides, porphyry Cu-Mo-Au, and Iron-Oxide-Copper-Gold. As well as enabling the passage of melts, translithospheric faults may exert an influence on crustal structure (fault arrays, basins, topographic

highs) and thermal architecture, and hence the location of deposits related to hydrothermal fluid systems (e.g. SEDEX Ag-Pb-Zn, polymetallic VHMS).

The collisional climaxes heralding supercontinents that lasted from ca 2.65-2.45 Ga and ca 1.85-1.65 Ga were characterized by peaks in mantle plume activity. In the Neoproterozoic, Banded Iron Formations (BIF) precipitated from the resultant Fe-rich seawater in narrow ocean basins. The variable thickness of SCLM resulted in plume melting being focused in areas of thin lithosphere at cratonic margins, forming giant magmatic Ni-Cu-PGE deposits of the Yilgarn (Neoproterozoic) and Superior (Paleoproterozoic) cratons (Begg et al. 2009b, Begg et al., submitted). Collision of arcs, cratons, and microcontinental fragments of depleted SCLM created a smorgasboard of opportunities for convergent margin-related ore deposits. The effects of delamination of denser (e.g. oceanic) lithosphere and crustal thickening at accretionary/collisional margins made magmatic arc-related deposits (epithermal gold, porphyry copper, VHMS base metal) the victims of uplift and erosion, explaining their paucity in the ancient record. In contrast, those backarcs protected from major crustal thickening by underlying or outboard microcontinents, preserve some of the syn-volcanic deposits (e.g. VHMS deposits of the southern Superior or nickel sulphide deposits of the Yilgarn and Zimbabwe cratons), and were prime locations for the generation and preservation of late-stage orogenic gold deposits (southern Abitibi and Eastern Goldfields provinces in the Archean; Birrimian Province in the Paleoproterozoic). Similarly, peri- or intra- cratonic settings will enhance the preservation potential of a range of other deposit types, including platform-hosted BIF (e.g. Sao Francisco and Pilbara cratons), sediment-hosted base metals (e.g. SEDEX of northern Australia, Broken Hill Ag-Pb-Zn of eastern Australia), Iron-Oxide-Copper-Gold of the Gawler craton, "stratiform" sediment-hosted Cu, and placer deposits of gold (Witwatersrand) and diamonds.

Conclusions

There is a strong case for early Archean, and possibly Hadean subduction. This must have provided an environment favourable for the formation of many convergent-margin-related ore deposits, but not the environment required to preserve them. A period of major mantle plume activity (possibly in response to earlier subduction) created thick, depleted, buoyant and stiff SCLM in the Paleo- to Mesoarchean, paving the way for craton formation. It also created a captive potential metal source region. Cratonic lithosphere, coupled with plate tectonics, provided suitable lithospheric and geodynamic settings for ore-forming processes and the preservation of the resultant deposits. These settings include: craton margins with their changes in lithospheric thickness and associated translithospheric faults; stable continental shelves; intracratonic basins; backarc basins. In particular, it is proposed that the creation of backarc basins involving fragmentation of cratonic lithosphere preferentially along pre-existing sutures, was a KEY development in metallogenic evolution, in terms of both enhanced metallogenic fertility AND high crustal-

preservation potential. Magmatic arcs on continental/cratonic margins are capable of forming many large ore deposits, but these deposits rarely survive the uplift and erosion attendant with accretion/collision-related crustal thickening.

The appearance of cratonic lithosphere dictated a re-organisation of plate tectonics, and likely resulted in the onset of the supercontinent cycle which is still with us today. Changing geodynamic conditions implicit through these cycles are a macro control on metallogenesis.

We have found that continents are dominantly (ca 70%) built on Archean SCLM. This implies that there may have been a great number more Archean ore deposits than are preserved. Archean and Paleoproterozoic ore deposits have only survived on cratons that:- a) have remained large entities on the order of 1000 km across; b) have mostly, if not exclusively, remained as lower plates during post-deposit plate interactions.

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