Temporal relations between mineral deposits and global tectonic cycles: implications for prospectivity

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Abstract: Mineral deposits are heterogeneously distributed in both space and time, with variations reflecting tectonic setting, evolving environmental conditions, such as atmosphere-hydrosphere conditions, and secular changes in the Earth's thermal history. The distribution of deposit types whose settings are tied to plate margin processes (e.g., orogenic gold, volcanic-hoisted massive sulphide, Mississippi valley type Pb-Zn deposits) correlates well with the supercontinent cycle, whereas deposits related to intra-cratonic settings and mantle driven igneous events, lack a clear association. The episodic distribution of deposits tied to the supercontinent cycle is accentuated by selective preservation and biasing of rock units and events during supercontinent assembly, a process which encases the deposit within the assembled supercontinent and isolates it from subsequent removal and recycling at plate margins.

The regional framework of mineral deposits and mineral provinces provides fundamental information essential for successful long term exploration and discovery. Critical data that can be gleaned from regional studies include stratigraphic, structural and tectonic controls and geophysical, geochemical and isotopic data; all of which constrain the setting, extent and age of a mineral province and focus exploration for the location of individual deposits. Equally important and perhaps less well understood are the broad-scale processes associated with the development of continental crust and their control on mineral deposit type and distribution. It has long been recognized that distribution of deposit types is related to tectonic setting; for example, gold in orogenic settings and clastic-dominated Pb-Zn ores in extensional settings (Goldfarb et al., 2001; Leach et al., 2010, and references therein). The temporal and spatial distribution of deposits is related to features specific to the generation of each of these tectonic environments. In this contribution, we discuss the controls on the preservation of the rock archive and how that impinges on the distribution of mineral deposit types. Magmas, and their associated ores, generated in different tectonic settings have different likelihoods of survival, and the supercontinent cycle imparts a preservational bias that is an intrinsic characteristic of the age distribution of many mineral deposits, and on the proportions of mineral deposits from different tectonic settings preserved in the rock record.

Temporal relations between mineral deposits and global tectonic cycles

Mineral deposits are heterogeneously distributed in both space and time (Lindgren, 1909; Turneaure, 1955; Meyer, 1988; Barley and Groves, 1992; Titley, 1993; Groves et al., 2005b; Kerrich et al., 2005; Groves and Bierlein, 2007; Bierlein et al., 2009; Goldfarb et al., 2010). Barley and Groves (1992) suggested this uneven distribution was related to three major factors: 1) the evolution of the hydrosphere-atmosphere; 2) secular changes in global heat flow; 3) long term tectonic trends. The first two factors relate to specific deposit types. For example, the temporal distribution of banded iron formations and clastic-dominated (CD) Pb-Zn deposits reflects, at least in part, global evolution of oxidation-reduction conditions in the atmosphere and hydrosphere, whereas the Earth's evolving heat flow influenced the distribution of komatiite-associated nickel deposits. Long term tectonic trends in mineral deposit distributions were related by Barely and Groves (1992; see also Groves et al., 2005b; Groves and Bierlein, 2007) to formation during the cyclic aggregation and breakup of supercontinents. Our aim is to show that temporal variations in mineral deposit distribution are not a primary signature of generation in specific tectonic settings but they also reflect selective preservation enhanced by specific phases of the supercontinent cycle.

Episodic Rock Record

The rock record is the archive of Earth history. The oceanic record only extends back some 200 Ma whereas the continental record of rocks and rock fragments extends back to 4.4 Ga, within 150 Ma of the age of the Earth, and guides our understanding of processes and events that have controlled our planet's evolution. The record is episodic with a heterogeneous distribution, in both space and time, of rock units and events; for example ages of igneous crystallization, metamorphism, continental margins, mineralization, and seawater and atmospheric proxies are distributed about a series of peaks and troughs (Fig. 1).

Numerous and ever expanding data compilations, facilitated by the development of micro-analytical techniques, on the age of crystallization of igneous rocks show a marked episodic distribution (Condie, 1998; Condie, 2000, 2004; Rino et al., 2004; Condie, 2005; Groves et al., 2005b; Hawkesworth and Kemp, 2006; Kemp et al., 2006; Campbell and Allen, 2008; Condie et al., 2009a; Condie and Aster, 2010; Iizuka et al., 2010; Voice et al., 2011). Campbell and Allen (2008), amongst others, on the basis of the analysis of global detrital zircon data (Fig. 1) emphasized the link between peaks in the distribution of the uranium-lead (U-Pb) crystallization ages of the mineral zircon (which reflect the ages of the parent igneous rocks) and the development of supercontinents.

The distribution of the ages of high grade metamorphic rocks are grouped in clusters similar to the peaks of igneous crystallization ages that correspond with periods of supercontinent assembly (Fig. 1; Brown, 2007). The implication is that granulite-facies metamorphism is linked to the processes of crust generation (cf., Kemp et al., 2007) and/or the peaks of the ages of crust generation and granulite metamorphism are both a function of the unevenness of the continental record. The distribution of ancient passive margins and anomalies in the $^{87}Sr/^{86}Sr$ ratio are also heterogeneous, correlating in part with the supercontinent cycle (Fig. 1). Passive margins show major frequency peaks in the late Archean, late Paleoproterozoic and late Neoproterozoic to early Paleozoic, which correspond with times of supercontinent aggregation (Bradley, 2008). The proportion of modern passive margins is somewhat different, correlating with the breakup of Pangea and the resultant increase in margin area (Bradley, 2008). Smith and McGowan (2007) noted that the Phanerozoic diversity of marine fossils is affected by the supercontinent cycle with marine rocks dominating during rifting phases of supercontinents. Bradley (2011) has recently compiled temporal trends in a variety of rock units and events with respect to the supercontinent cycles and noted that carbonatites and greenstone-belt deformation events also show a distribution related to supercontinent cycles. The Sr isotope ratio in sea water shows positive excursion corresponding with the Gondwana and Nuna supercontinents, but it is different from some of the other proxies in that it is unlikely to have been influenced by preservation bias in the geological record. Rather it is a measure of the relative amount of continental versus mantle input (Fig. 1), and the age of the continental material, with positive anomalies taken to be indicative of uplift and erosion of continental basement during continental collision (e.g., Prokoph et al., 2008).

Generational Archive or Preservational Bias in Rock Record

The punctuated nature of the record (Fig. 1) remains difficult to explain and although we have long known that the geologic record in incomplete (e.g., Hutton, 1788; Holmes, 1965; Raup, 1972), the general consensus has been that the heterogeneous distribution of ages and events reflect the processes responsible for the generation of continental crust. For example, Condie (1998; 2000, 2004) proposed that this episodic pattern reflected juvenile addition to the continental crust through mantle plume activity (cf. Stein and Hofmann, 1993). Others have suggested that it reflects intermittent plate tectonics with bursts of, for example, igneous crystallization ages reflecting subduction zone activity separated by longer quiescence phases of no subduction (O'Neill et al., 2007; Silver and Behn, 2008; Condie et al., 2009b). More recently, peaks of ages have been interpreted to reflect periods of increased magmatic activity associated with increases in the volumes of subduction-related magmas during continental break-up (Stern and Scholl, 2009).

The overall calc-alkaline andesitic composition of continental crust (Taylor, 1967; Taylor and McLennan, 1985; Rudnick, 1995; Rudnick and Gao, 2003; Davidson and Arculus, 2006), along with evidence that plate tectonics has been active for extensive periods of Earth history (Cawood et al., 2006; Condie and Kröner, 2008; Shirey and Richardson, 2011) suggests magmatic arcs should be the major site of continental growth (Taylor and

McLennan, 1985; Davidson and Arculus, 2006). Importantly however, global compilations of addition and removal of continental crust (Fig. 2) suggest that not only are convergent plate margins the major sites of growth but also of continental loss, and that overall at the present day there is no net addition of crust (Scholl and von Huene, 2007; Clift et al., 2009; Scholl and von Huene, 2009; Stern, 2011).

Hawkesworth et al. (2009; 2010; see also Condie et al., 2011) have argued that peaks in age data may not represent episodic growth but instead reflect the greater preservation potential of igneous and sedimentary rocks formed in collisional belts, and are therefore biased by the construction of supercontinents. They outline a model whereby the observed rock record of igneous crystallization ages is the integration of the volumes of magma generated during the three phases of the supercontinent cycle (subduction, collision and breakup), and their likely preservation potential within each of these phases (Fig. 2): magma volumes are high in subduction settings but low during continental collision and breakup. In contrast, the preservation potential of rocks in convergent and breakup settings is poor, whereas the preservation potential of collisional settings is high. Peaks in crystallisation ages that are preserved would then reflect the integration of the magma volumes generated during supercontinent evolution with their preservation potential (shaded area under the curves in Fig. 2). The resultant peak corresponds to the collisional phase of the supercontinent cycle even though this is not a major phase of crustal generation (compare with Fig. 1). Thus the supercontinent cycle will inherently bias the rock record both through selective isolation of material in continental cores during supercontinent assembly and through removal and recycling of material formed during stages of extension and convergence.

One test of such models is how the estimated volumes of zircon that crystallized in magmas generated at different tectonic settings at different stages in the supercontinent cycle compare with the observed distribution of zircon crystallization ages. Cawood et al (submitted) used estimated volumes of magma generated in different settings to argue that the volumes of zircon generated in subduction-related magmas in the subduction phase of the supercontinent assembly are almost an order of magnitude greater than those generated in the collision phase. This is clearly in marked contrast to the observed distribution of the zircon crystallization ages in which most zircons have ages similar to that of supercontinent assembly (Fig. 1). This highlights that the preservation potential of magmas generated in different settings is markedly different, and that preservation bias is an important aspect of the observed geological record.

Implications of preservational bias to mineral exploration: differentiating modern and ancient deposits

Our interpretation that the episodic nature of the global rock record incorporates a supercontinent cycle induced preservation bias (Fig. 2) has considerable implications for understanding the spatial and temporal distribution of mineral deposits. The first order control on the heterogeneous distribution of mineral deposits would then reflect the balance between the volumes of rocks (and mineral deposits) generated during the three stages of supercontinent evolution (convergence, collision and breakup) and the respective preservation potential of each of these stages.

Figure 3 highlights the heterogeneous temporal distribution of mineral deposits and shows their relationship to the supercontinent cycle (e.g., Barley and Groves, 1992; Groves et al., 2005a). In unravelling this relationship it is important to differentiate deposits that have gone through a complete supercontinent cycle from those that haven’t, and the location of deposits with respect to plate margin processes. Deposits that have yet to go through a supercontinent cycle may be as old as Neoproterozoic. The distribution of such deposits varies both spatially and temporally, and it is controlled by the interplay of processes of generation within specific tectonic settings together with the effects of exhumation, which will be most pronounced in active tectonic environments at plate margins. In detail the issue of preservation may be considered on two scales: the first is that of the supercontinent cycle, as discussed above, and the second is that of the different tectonic settings. Thus, with respect to the latter, the level of emplacement of a deposit will impact on their long term survival within the rock record, with high level deposits having a poor long term survival record, especially in active tectonic environments which are likely to be undergoing active exhumation, and hence preservation is poor irrespective of whether they have been through a supercontinent cycle (e.g. epithermal Au-Ag, Wilkinson and Kesler, 2007). Subduction erosion (Scholl et al., 1980; von Huene and Scholl, 1991; Stern, 2011) may further impact on the long-term survival of material, especially in the regions of the frontal arc. Mineral deposits distributed around the Pacific and Atlantic oceans were generated during the break-up of the Rodinian and Pangean supercontinents respectively, and these oceans are yet to close. For the Pacific, a succession of passive margin deposits, related to Rodinia breakup (Neoproterozoic to Paleozoic), and convergent margin deposits, related to subduction initiation (late Neoproterozoic to the present), developed around its margins. Thus, rock units and associated mineral deposits around the Pacific are yet to be incorporated into a supercontinent, and only then can their ultimate preservation potential be assessed. For the Atlantic Ocean, continental breakup occurred in the Mesozoic and subduction is spatially limited to the Tertiary Caribbean and Scotia arcs. In contrast to the Pacific, Paleozoic successions bordering the Atlantic (e.g. Appalachian-Caledonian orogen) have already been through a supercontinent cycle.

The relationship between mineral deposit type and tectonic setting determines the applicability of preservation bias impacting on the distribution of deposits. Supercontinent cycle induced preservation bias is a function of plate margin processes and thus its effect is most pronounced on deposits formed at or near plate boundaries (e.g. orogenic gold) or deposits incorporated into the long term rock record by accretion at plate margins (e.g. VMS). Deposits that develop in intracontinental settings, especially within cratons, need not show any temporal link to the supercontinent cycle. These reflect the influence of deep Earth (mantle) processes on pre-existing continental lithosphere that thus their distribution is independent of the supercontinent cycle. Any preservation bias shown by such deposits is likely fortuitous and related to the inherent stability of cratons and their thick sub-continental mantle lithosphere.

Supercontinent cycle and mineral deposits

The three major phases of the supercontinent cycle, convergence, collision and extension, are each associated with characteristic deposit types (e.g., Barley and Groves, 1992; Groves et al., 2005b; Groves et al., 2005a; Kerrich et al., 2005).

Convergent plate margins are sites of major continental growth and are fertile settings for the formation of mineral deposits (Bierlein et al., 2009). They are preserved in the rock record as accretionary orogens, especially at retreating convergent margins (Cawood et al., 2009). Major deposit types include epithermal Au-Ag and porphyry Cu±Au, which form in magmatic arc settings (Seedorff et al., 2005), and orogenic gold, which forms late in the history of the convergent margin associated with orogenic events (Kerrich and Wyman, 1990; Groves et al., 1998).

Preservation potential of convergent plate margin deposits is variable and reflects not just proposed bias associated with the supercontinent cycle (Figs 1, 3) but is also a function of level of emplacement, which impacts on the propensity for erosion and removal of the deposit and hence its subsequent preservation. Epithermal Ag-Au, porphyry Cu and orogenic Au deposits, which form at average depths of 0.5, 1.9 and 10 km, show age modes of 2, 11 and 199 Ma, respectively (Wilkinson and Kesler, 2007; Wilkinson et al., 2009; Gombosi and

Wilkinson, 2012). As a consequence epithermal Ag-Au and porphyry Cu deposits older than Mesozoic are rare.

Mississippi Valley type Pb-Zn deposits are a characteristic deposit of collisional settings. MVT deposits are generally hosted in platform carbonates that typically originated in passive margin settings (Leach et al., 2010), with fluid-driven mineralization developed during crustal thickening and deformation (Oliver, 1986) in collisional and accretionary orogens (Bradley and Leach, 2003). They only became abundant after the second oxygenation event in the Neoproterozoic and reached their maximum abundance during assembly of Pangea in the Devonian and Carboniferous (Leach et al., 2010). We would argue that preservation of such deposits is further enhanced by their isolation within the enveloping sheath of the assembled supercontinent (for example the MVT deposits in their type area which lies within, and inboard of, the collisional Appalachian orogen). Fluids and associated MVT mineralization migrate away from zone of thickening and exhumation, thus facilitating preservation in regions external to the main orogen.

Uranium (U) deposits also form in collision-related settings in association with unconformities in foreland basins (Ruzicka, 1996; Kerrich et al., 2005). They are well developed in Paleoproterozoic belts in Canada and northern Australia associated with the Nuna supercontinent cycle but also occur in the Mesoproterozoic and Neoproterozoic supercontinent cycles associated with the Grenville and Damara orogenic pulses.

Deposits of tin (Sn) and tungsten (W) occur in granites in collisional and some accretionary orogens, all largely of Phanerozoic age. These include those in the Appalachian-Caledonian orogen (e.g. Nova Scotia, Cornwell), the Tethyan orogen (Thailand), the Terra Australis Orogen (eastern Australia), and the Andean orogen (refs). Sn-W granites are associated with melting of over-thickened crust in association with input of mantle melts during a pulse of orogenic extension (Clark et al., 1990; Kerrich et al., 2005).

Deposit types in intra-continental settings include platinum group elements (PGE) in layered intrusions and diamonds in kimberlites and lamproites (Figs. 3, 4). Intra-continental deposits reflect the interaction between a pre-existing cratonic substrate, which hosts the deposit, with a mantle derived magmatic source. Major PGE, chromite and vanadiferous and titaniferous magnetite deposits in layered intrusions tend to occur towards the centre of Archean cratons. Groves et al (2005a) postulated that thick subcontinental lithospheric mantle (SCLM) is required to support and preserve large volumes of dense mafic magma associated with such deposits. Diamond deposits are also focused in Precambrian cratons where low-T and high P at the base of thick SCLM favour diamond growth which are transported to the surface when alkaline intrusions interact with, and punch through, the lithosphere (Gurney et al., 2005). The stable nature of cratons with thick SCLM ensures a high preservation potential (Groves and Bierlein, 2007).

Principal deposit types associated with extension environments include VMS, Ni-Cu sulphide, Fe-oxide-Cu-Au and CD Pb-Zn deposits. VMS deposits form in oceanic lithosphere at either mid-ocean ridge or supra-subduction zone environments. They are incorporated into the continental record through accretion events associated with periods of ocean closure and continental assembly. Their overall temporal distribution is similar to orogenic gold deposits with peaks in the late Archaean and late Palaeoproterozoic and a more continuous distribution in the Phanerozoic (Groves et al., 2005a). Neoproterozoic and younger oceanic crust is preserved on land in ophiolite complexes and in addition to VMS deposits, which lie in the upper levels of the crustal section, they may also contain podiform chromite in their upper mantle sections. Ophiolites show age peaks at around ca. 800–750 Ma, corresponding with assembly of Gondwana, at 500–440 Ma, related to closure of the Iapetus Ocean and formation of the Appalachian-Caledonides orogen during the earliest stages of formation of Pangea, and at 160–150 Ma and 100–90 Ma that formed during closure of the Tethys and final assembly of Pangea (Dilek, 2003). Cawood and Suhr (1992) argued that the short age lag between generation and subsequent preservation of ophiolites (and any associated mineralization) was related to extension in trapped oceanic lithosphere during the earliest phases of collision, and accounts for their episodic age distribution.

Banded iron formations (BIF), whose distribution is also controlled by evolving atmospheric conditions, developed on basin platforms including passive continental margins. Peaks in BIF deposition at 2.7 Ga and 1.9 Ga have been related to inferred peaks in mantle plume activity (Isley and Abbott, 1999) but also correspond with end Archaean and end Palaeoproterozoic supercontinent assembly (e.g., Figs. 1). Rasmussen et al. (2012) argue that iron formation is a consequence of rapid crustal growth. We consider these time periods to be ones of apparent rather than real rapid growth (Fig. 2), reflecting supercontinent cycle preservation bias (cf., Hawkesworth et al., 2009), and that actual rates of continental growth were relatively uniform through time (e.g., Dhuime et al., 2012). CD Pb-Zn deposits occur in extensional settings, including rift and passive margins, back-arc basins and intracratonic rifts (Leach et al., 2010). The major pulse of mineralization of this type is recorded at the end of the Palaeoproterozoic to early Mesoproterozoic (1.7-1.5 Ga) in eastern Australia (Broken Hill-Mount Isa). This time frame corresponds with breakup of Nuna and the start of the Rodinian cycle and thus does not readily fit with the preservation bias model outlined above. The environment for these deposits are ascribed to intracontinental sags (Leach et al., 2010), which may account for their preservation, but recent tectonic models for Australia as well as detrital zircon provenance data suggest a passive margin setting bounding a back arc basin or marginal sea (Cawood and Korsch, 2008; Gibson et al., 2008; Cawood et al., in press), in which case subsequent ocean closure would be required to isolate and protect these deposits.

Fe-oxide Cu-Au (IOCG) occupy a variety of extensional settings within pre-existing cratons and tied to pulses of anorogenic alkaline or A-type magmatism close to the margins of the cratons or to lithospheric boundaries within the cratons (Groves et al., 2005a; Kerrich et al., 2005; Groves et al., 2010). The development of IOCG deposits in intra-continental settings and relationship with mantle derived magmatism means that their temporal distribution is not directly related to the supercontinent cycle.

Prospectivity and Endowment

The variety of mineral deposit types and the variables controlling their spatial and temporal distribution ensure that no single, or simple, factor can be used to predict mineral prospectivity. However as outlined above supercontinent induced preservation bias is an additional factor that impacts on the long term distribution of deposits, notably those tied to plate margin processes. This is most clearly demonstrated by orogenic gold deposits (Figs. 1, 3) with Precambrian deposits showing an episodic distribution that correlates well with the timing of supercontinent assembly whereas Phanerozoic deposits display a more continuous distribution (Goldfarb et al., 2001). VMS deposits show a similar distribution (Groves et al., 2005a). The more continuous distribution of these younger deposits is interpreted to reflect their prevalence around the circum Pacific which opened in the Neoproterozoic and is yet to close (Cawood, 2005; Cawood and Buchan, 2007) and hence is yet to go through a supercontinent cycle and the resultant preservation bias imposed on rock units and events (Fig. 2). Temporal variations in gold resources also establish that even the episodic pattern displayed by Precambrian deposits is not solely the result of preservation bias imposed on rock types and/or settings with a uniform endowment. Some 25% of gold resources occur in Archean deposits (Goldfarb et al., 2001), largely in the range 2.7-2.5 Ga, yet Archean crust constitutes less than 6% of the current continental crustal volume (Goodwin, 1996). De Wit and Thiart (2005) highlight secular variation in metallogenic potential with Archean cratons more richly endowed in mineral deposits than younger terrains, reflecting more efficient transfer of metallogenic elements from the mantle to the continental lithosphere.

Rodinia and the Boring Billion: the geologic and mineral deposit record

The Rodinia supercontinent cycle, which extends from breakup of Nuna to assembly of Gondwana (~1.7-0.7 Ga), seems anomalous in the general distribution of rock types, geological events and mineral deposits. U-Pb crystallization and metamorphic ages for this period show an episodic distribution similar to earlier and later supercontinent cycles (Fig. 1) but there is a paucity of passive margins (Bradley, 2008), and an absence of a significant Sr anomaly in the palaeoseawater record (Shields, 2007). The lack of passive margins and associated features can be related to Rodinian assembly through development of opposing subduction zones on either side of the closing ocean basin (double-sided subduction)(Dalziel et al., 2000)(Cawood et al, submitted). In addition, the Rodinian cycle corresponds with the complete absence of regional or global glaciations (Hoffman, 2009), an absence of iron formations from the geologic record (Bekker et al., 2010), and an abundance of massif-type anorthosites (Ashwal, 1993) and associated titanium deposits (Meyer, 1988). The Rodinian cycle approximates in time with the “Boring Billion”; that period of time when many mineral deposit types are absent from the rock record (Meyer, 1988; Goldfarb et al., 2001; Kerrich et al., 2005). For example, orogenic gold deposits for the period 1.7 Ga to 0.9 Ga account for far less than 1% of known production yet this period corresponds to the generation of almost 20% of the preserved crustal record indicating markedly diminished gold endowment relative to the Archaean, Paleoproterozoic, and Phanerozoic (Figs. 1, 3). The absence of gold deposits in this period, despite the presence of accretionary orogens has been related to lack of preservation due to exhumation of the end Mesoproterozoic orogens and only high-grade basement remains (Goldfarb et al., 2001; Groves et al., 2005b). However, deposits which form in an overall extensional environment, whether in intra-continental or continental margin settings, such as IOCG and CD Pb-Zn are well developed during the Rodinia cycle at around the end Paleoproterozoic to early Mesoproterozoic (notably in eastern and central Australia). Anorogenic granites, some with Sn deposits, are also widespread during this timeframe (Kerrich et al., 2005). As noted above, the timing of these major deposits corresponds with the breakup of Nuna breakup and not with a phase of supercontinent assembly, as the selective preservation model outlined in figure 2 might predict. Their occurrence in the rock record suggests either an intracratonic setting (cf. Leach et al 2010) or isolation from plate edge erosion during continental collisional assembly.

Drivers for the unique features of the Rodinian cycle are not well understood. They range from suggestions specific to individual deposit types to global processes but as yet none are convincing and much remains to be resolved as to reasons for the differences between this and other supercontinent cycles. For example, the lack of orogenic gold has been related an inferred higher grade and deeper level of exposure of Mesoproterozoic accretionary belts with only basement sequences now preserved (Goldfarb et al., 2001) but the overall character and preservation of the convergent related Yavapai, Mazatzal, and Granite-Rhyolite provinces and correlatives (Karlstrom et al., 2001) belies this proposal. Slack and Cannon (2009) have suggested that the demise of banded iron formations in the late Palaeoproterozoic is related to effects of the Sudbury impact on ocean chemistry through mixing of shallow and deep ocean waters. Others have proposed that subduction was episodic and the Mesoproterozoic was a phase of minimal or no subduction (Silver and Behn, 2008; Bekker et al., 2010). But the presence of long lived late Paleoproterozoic to Mesoproterozoic subduction zones that were ultimately instrumental in assembly of Rodinia does not support such a model.

Conclusions

The geologic record is incomplete. The record that is preserved shows an episodic distribution of rock units and events, including mineral deposits. The key issue is how representative is the record and how can it be interpreted to understand Earth processes. Many have argued that the episodic record represents discontinuous processes, including the formation of mineral deposits. Alternatively, we argue that the incompleteness of the record relates not only the surficial effects of erosion and the consequent removal and/or recycling of material but also systematic biasing of the preserved record through the periodic assembly and dispersal of continents within the supercontinent cycle. Surficial removal of material will be most pronounced at zones of uplift and hence focused in orogenic belts but also present at extending margins along rift shoulders. The implications for mineral deposits is that those generated in near surface environments in zones of active uplift have a young mean ages (e.g., epithermal gold, Wilkinson and Kesler, 2007). Supercontinent cycle induced preservation bias is also focused at plate margins and results in selective preservation of rock units and events associated with the assembly and collision of continental fragments. From a mineral deposit perspective this is consistent with the correlation of orogenic gold deposits, which form in accretionary environments during on-going convergent plate interaction, with the timing of supercontinent assembly, most notably in the late Archean, late Paleoproterozoic and Neoproterozoic. Temporal variation in mineral endowment, the causes for which are not well understood, mean that even those deposit types that form at plate margins may not be generated during each supercontinent cycle and hence cannot then be preferentially preserved during continental assembly. Thus, the distribution of rock units, events and mineral deposits during the Rodinian cycle (1.7-0.8 Ga) appears to be different from preceding and succeeding cycles. Mineral deposit types which do not form at plate margins, and hence are not directly involved with a supercontinent cycle, will not show a temporal distribution that correlates with pulses of continental assembly. For example PGE deposits related to the interaction of mantle upwelling with cratonic lithosphere.

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Figure Captions

Figure 1. (a): Histogram of ca. 7000 detrital zircon analyses shows several peaks in their U-Pb crystallisation ages (Campbell and Allen, 2008) that correspond to the ages of supercontinents. Also shown is the apparent thermal gradient versus age of peak metamorphism for the three main types of granulite facies metamorphic belts (Brown, 2007); (b) Histogram of the ages of ancient and modern passive margins (Bradley, 2008); (c) Normalized seawater $^{87}Sr/^{86}Sr$ curve (Shields, 2007). Low $^{87}Sr/^{86}Sr$ in Archean reflect lack of data. Present day surface age distribution from Goodwin (1996). Periods of supercontinents are highlighted in grey: Superia – 2.8-2.6 Ga, Sclavia – 2.55-2.40 Ga, Nuna – 2.1-1.7 Ga, Rodinia – 1.25-0.95 Ga, Gondwana – 0.65-0.45 Ga, and Pangea – 0.35-0.15 Ga.

Figure 2. (a) Conceptual model for the volumes of magma generated (blue line), and their likely preservation potential (red lines) during the stages of convergence, assembly, and break-up of a supercontinent (Hawkesworth et al., 2009). The preservation potential in the first stage (convergent) is greater at margins where the subduction zone retreats ocean ward to form extensional basins than at margins where the subduction zone advances toward the continent. Thus, peaks in the crystallisation ages that are preserved (shaded area) reflect the balance between the magma volumes generated in the three stages and their preservation potential. (b) A schematic cross-section of convergent, collisional and extensional plate boundaries associated with supercontinent cycle showing estimated amounts (in $km^3\ a^{-1}$) of continental addition (numbers in parentheses above Earth surface) and removal (numbers in brackets below surface). Data from Scholl & von Huene (2007, 2009).

Figure 3. Diagram showing the temporal distribution of deposit types ascribed to broad geodynamic settings in terms of the supercontinent cycle. Temporal distributions are based Groves et al. (2005b) and references therein.

Figure 4. Schematic cross-section of convergent, collisional and extensional plate boundaries associated with supercontinent cycle showing distribution of main deposit types. Abbreviations: VMS – volcanic massive sulphide; CD Pb-Zn – clastic-dominated lead zinc; IOCG – iron oxide copper gold; PGE – platinum group elements; MVT – Mississippi valley type; Cu-Au – copper gold.

Figure 5. Temporal distributions of passive margins (Bradley, 2008), glaciations (Hoffman, 2009), iron formations (Bekker et al., 2010), anorogenic plutons (Parnell et al., 2012), and orogenic gold (Goldfarb et al., 2001; Groves et al., 2005b). The period 1.7 – 0.8 Ga, which is marked by a paucity of a number of mineral deposit types, is highlighted.

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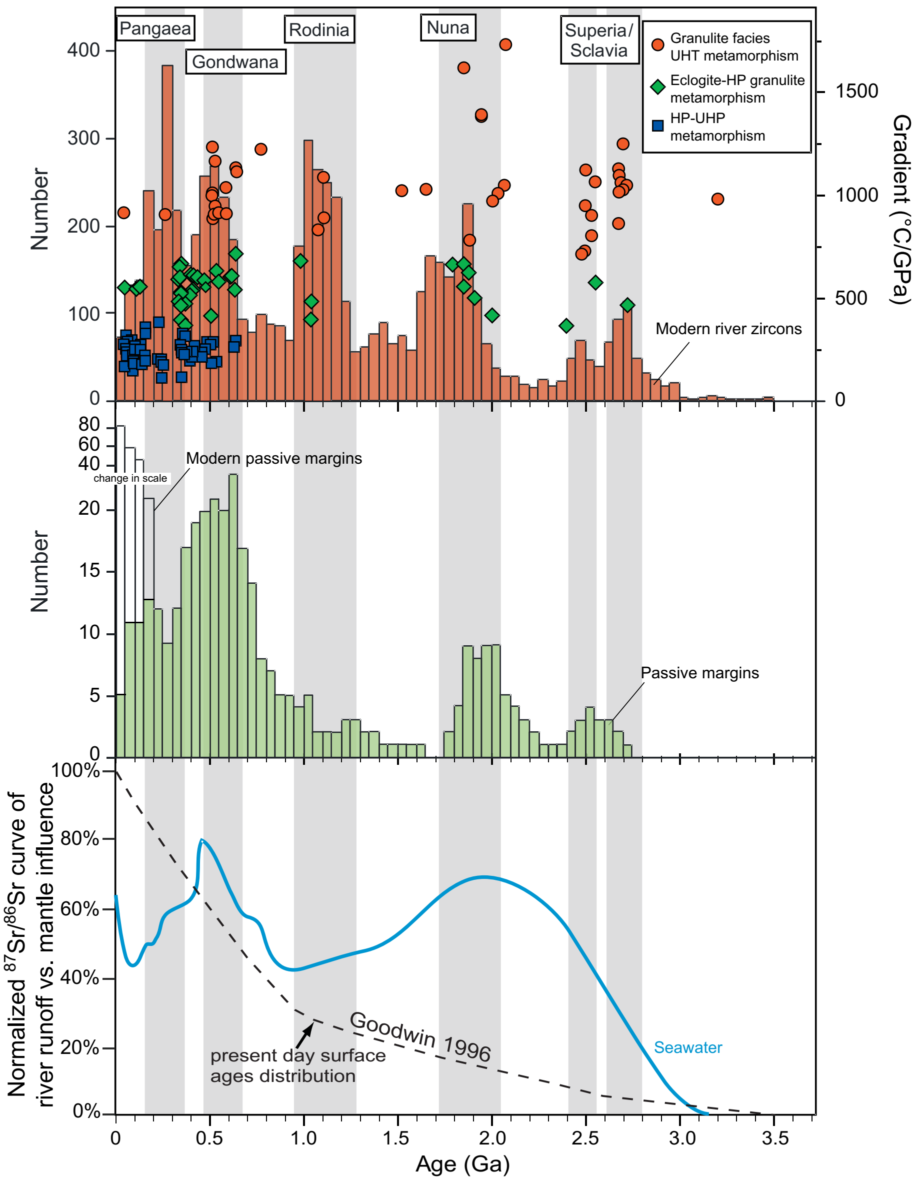
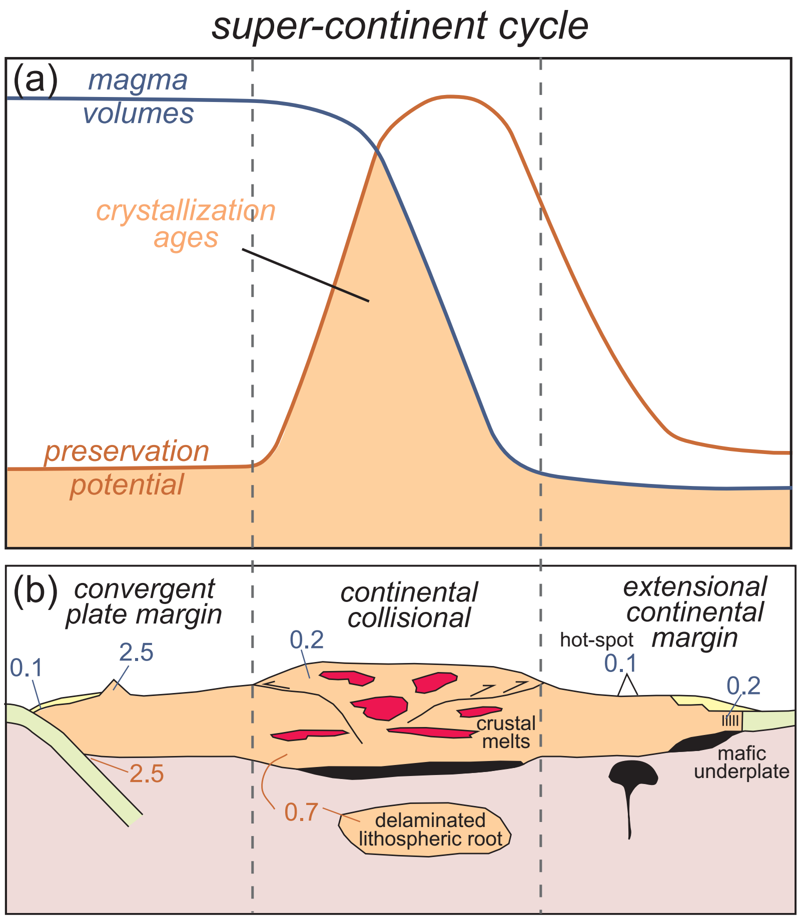
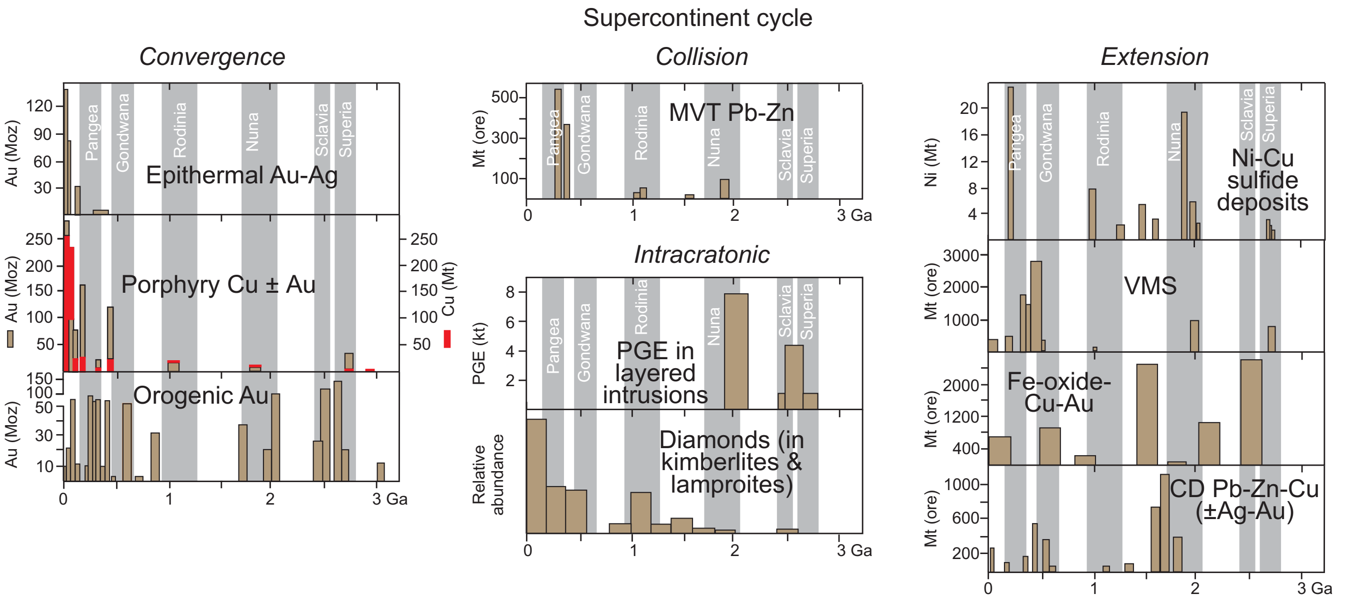
Cawood & Hawkesworth - Fig. 1



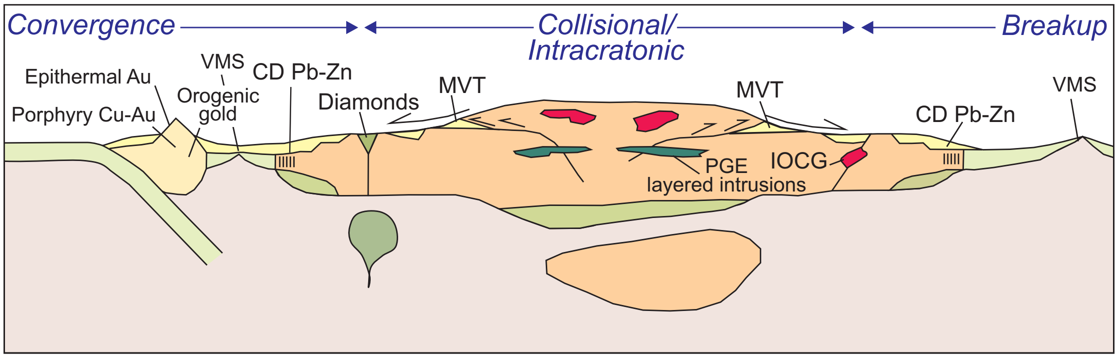
Cawood & Hawkesworth - Fig. 2



Cawood & Hawkesworth - Fig. 3



Cawood & Hawkesworth - Fig. 4



Cawood & Hawkesworth Fig. 5