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Notes

Temporal relations between mineral deposits and global tectonic cycles

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Abstract: Mineral deposits are heterogeneously distributed in both space and time, with variations reflecting tectonic setting, evolving environmental conditions, as in the atmosphere and hydrosphere, 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-hosted 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, such as Ni–Cu–PGE deposits, 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 that 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 on the location of individual deposits. Equally important and perhaps less well understood are the broad-scale processes associated with the development of continental lithosphere and their control on mineral deposit type and distribution. It has long been recognized that the distribution of deposit types is related to tectonic setting, for example, gold in orogenic settings and clastic-dominated Pb–Zn ores in extensional settings (Mitchell & Garson 1981; 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. Ore deposits 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 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 & Groves 1992; Titley 1993; Groves *et al.* 2005*b*; Kerrich *et al.* 2005; Groves & Bierlein 2007; Bierlein *et al.* 2009; Goldfarb *et al.* 2010). Barley & Groves (1992) suggested that this uneven distribution is related to three major factors: (a) evolution of the hydrosphere–atmosphere; (b) secular changes in global heat flow; and (c) long-term tectonic trends. The first two factors relate to specific deposit types. For example, the temporal distribution of 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 Barley and Groves (1992; see also Groves *et al.* 2005*b*; Groves & Bierlein 2007) to formation

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during the cyclic aggregation and breakup of supercontinents. Our aim is to show that temporal variations in mineral deposit distribution not only are a primary signature of generation in specific tectonic settings but 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; Cawood *et al.* 2013).

Numerous and ever expanding data compilations, facilitated by the development of microanalytical techniques, on the age of crystallization of igneous rocks show a marked episodic distribution (Condie 1998, 2000, 2004, 2005; Rino *et al.* 2004; Groves *et al.* 2005*b*; Hawkesworth & Kemp 2006; Kemp *et al.* 2006; Campbell & Allen 2008; Condie *et al.* 2009*a*; Condie & Aster 2010; Iizuka *et al.* 2010; Voice *et al.* 2011). Campbell & 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 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 (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 ages of ancient passive margins and anomalies in the $^{87}Sr/^{86}Sr$ ratio also vary with time, correlating in part with the supercontinent cycle (Fig. 1). Passive margins show major frequency peaks in the late Archean, late Palaeoproterozoic and late Neoproterozoic to early Palaeozoic, 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 & 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 number of rock units and events with respect to the supercontinent cycles and noted that carbonatites and greenstone-belt deformation events also show an age distribution related to supercontinent cycles. The Sr isotope ratio in seawater 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 (Cawood *et al.* 2013; Hawkesworth *et al.* 2013). Rather it is a measure of the relative amount of continental v. 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 reflects the processes responsible for the generation of continental crust. For example, Condie (1998, 2000, 2004) proposed that this episodic pattern reflects juvenile addition to the continental crust through mantle plume activity (cf. Stein & 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 & Behn 2008; Condie *et al.* 2009*b*). 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 breakup (Stern & Scholl 2010).

The overall calc-alkaline andesitic composition of continental crust (Taylor 1967; Taylor & McLennan 1985; Rudnick 1995; Rudnick & Gao 2003; Davidson & Arculus 2006), along with evidence that plate tectonics have been active for extensive periods of Earth history (Cawood *et al.* 2006; Kerrich & Polat 2006; Condie & Kröner 2008; Shirey & Richardson 2011; Dhuime *et al.* 2012), suggests magmatic arcs should be the major site of

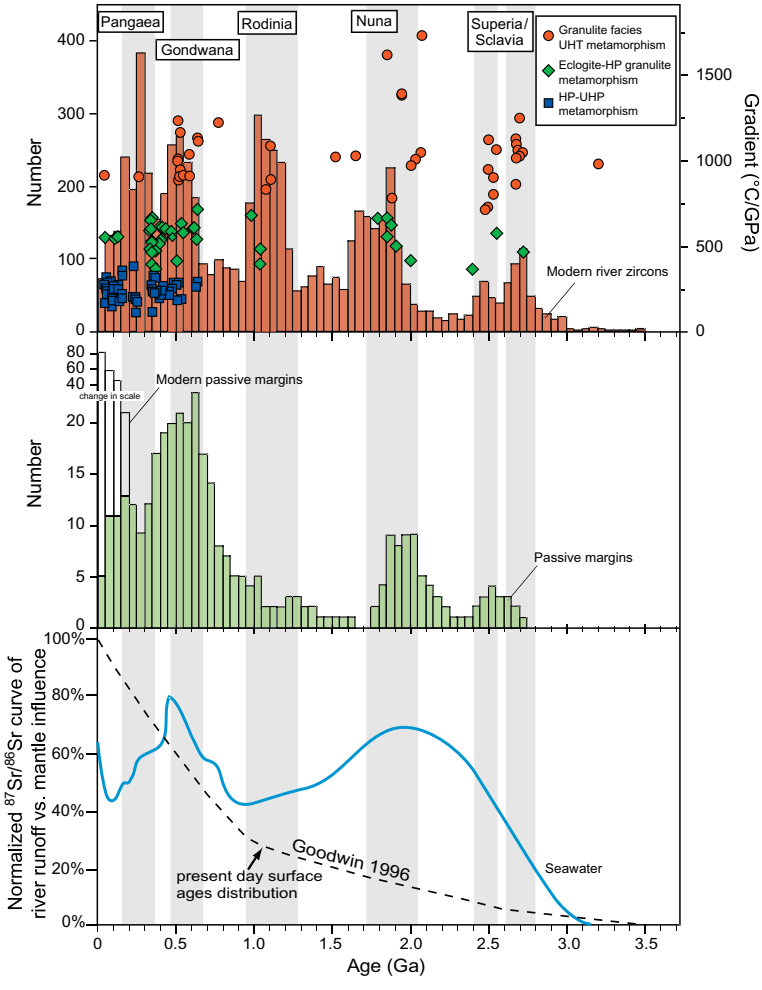

Fig. 1. (**a**) Histogram of *c.* 7000 detrital zircon analyses shows several peaks in their U–Pb crystallization ages (Campbell & Allen 2008) that correspond to the ages of supercontinents. Also shown is the apparent thermal gradient v. age of peak metamorphism for the three main types of granulite 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.

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

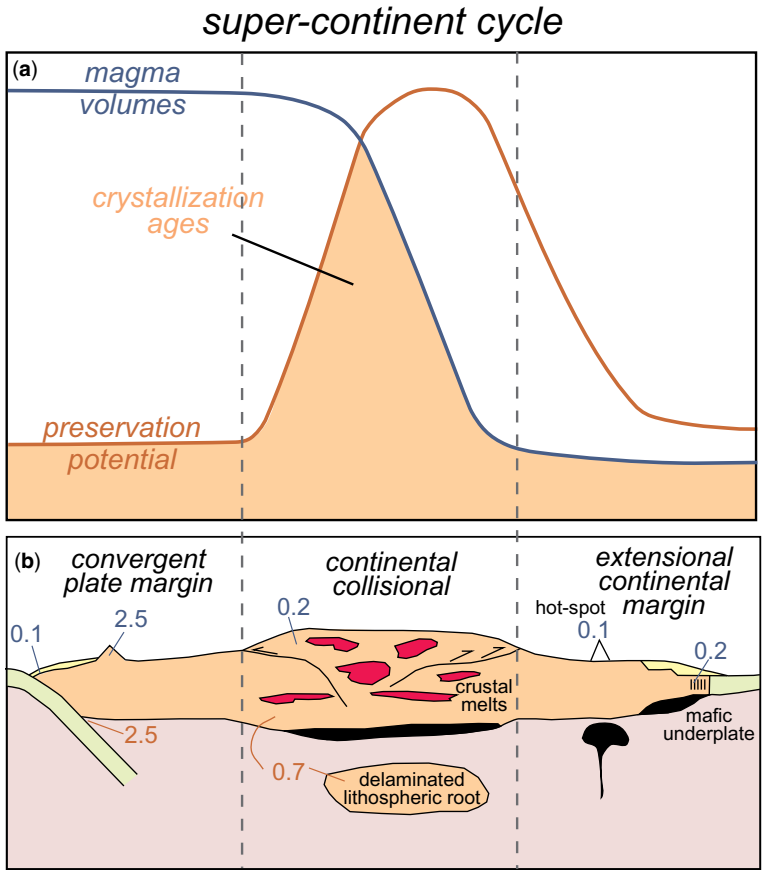

Fig. 2. (**a**) Conceptual model for the volumes of magma generated (blue line), and their probable preservation potential (red lines) during the stages of convergence, assembly and breakup of a supercontinent (Hawkesworth *et al.* 2009). The mean duration of a supercontinent cycle, based on the rock record, is around 500 Ma with a range of 700–200 Ma. Values for crustal addition and removal, associated with the vertical scale of the diagram, are up to around 3–5 $km^3\ a^{-1}$ (Scholl & von Huene 2007; Clift *et al.* 2009; Scholl & von Huene 2009; Stern 2011). The preservation potential in the first stage (convergent) is greater at margins where the subduction zone retreats oceanwards to form extensional basins than at margins where the subduction zone advances toward the continent. Thus, peaks in the crystallization 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).

potential of rocks in convergent and breakup settings is poor, whereas the preservation potential of collisional settings is high. Peaks in crystallization 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.* (2013) 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. Similarly, the overall episodic nature of the rock record, including the correlation with the supercontinent cycle of ages of high-grade metamorphic rocks, the age distribution of passive margins, the temporal distribution of variations in Sr isotopic ratios, carbonatites and greenstone deformation events, is consistent with a preservation-induced bias, and difficult to explain through temporal variations in the generation of each of these events and rock types.

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 & Groves 1992; Groves *et al.* 2005*a*; Kerrich *et al.* 2005). In unravelling this relationship it is important to differentiate deposits that have gone through a complete supercontinent cycle from those that have not, 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 depth of formation of a deposit will impact on its long-term survival within the rock record. High-level deposits have a poor long-term survival record, especially in active tectonic environments that 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 & Kesler 2007).

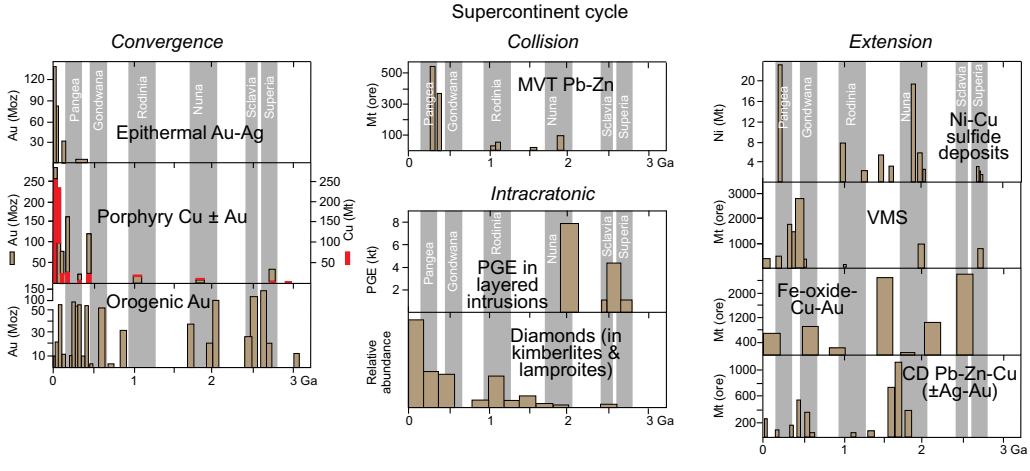

Fig. 3. Diagram showing the temporal distribution of deposit types ascribed to broad geodynamic settings in terms of the supercontinent cycle. Temporal distributions are based on Groves *et al.* (2005*b*) and references therein. Intracratonic deposit types lie in the interior of continents and generally form after a previous pulse of collisional assembly.

Subduction erosion (Scholl *et al.* 1980; von Huene & 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 breakup 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 Palaeozoic), 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 Cenozoic Caribbean and Scotia arc systems. In contrast to the Pacific, Palaeozoic 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. volcanic-hosted massive sulfide (VMS) deposits). 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 and thus their distribution is much more likely to be independent of the supercontinent cycle. Any preservation bias shown by such deposits is probably fortuitous and related to the inherent stability of cratons and their thick subcontinental 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 (Fig. 3; e.g. Barley & Groves 1992; Groves *et al.* 2005*b*; Groves *et al.* 2005*a*; 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–Mo ± 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 & Wyman 1990; Groves *et al.* 1998).

The preservation potential of convergent plate margin deposits is variable and not only reflects 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 & Kesler 2007; Wilkinson *et al.* 2009; Gombosi & Wilkinson 2012). As a consequence, epithermal Ag–Au and porphyry Cu deposits older than Mesozoic are rare.

Mississippi Valley type (MVT) 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 & 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 and Ouachita orogens). Fluids and associated MVT mineralization migrate away from zones of thickening and exhumation, thus facilitating preservation in regions external to the main orogen.

Uranium (U) deposits form in a variety of settings in part controlled by secular evolution of Earth processes (Cuney 2010) and include significant deposits in collision-related settings (Ruzicka 1996; Kerrich *et al.* 2005). Such deposits are well developed in Proterozoic belts in Canada, Gabon and northern Australia in association with the Nuna supercontinent cycle.

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. Sn–W granites are associated with melting of over-thickened crust in association with input of mantle melts during a

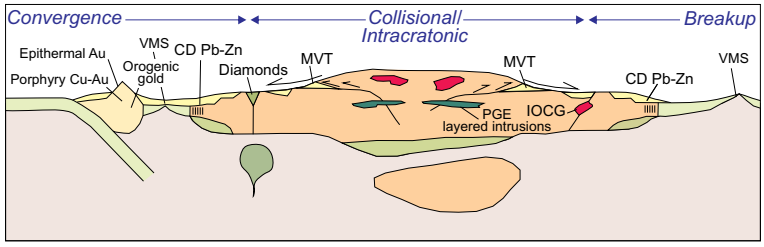

Fig. 4. Schematic cross-section of convergent, collisional and extensional plate boundaries associated with supercontinent cycle showing distribution of main deposit types. *Abbreviations*: VMS, volcanic massive sulphide; CD Pb–Zn, clastic-dominated lead zinc; IOCG, iron oxide–copper–gold; PGE, platinum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

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; Gurney *et al.* 2005, 2010; Naldrett 2010). Intra-continental deposits reflect the interaction between a pre-existing cratonic substrate, which hosts the deposit, with asthenospheric and subcontinental lithospheric mantle (SCLM)-derived melts. Major PGE, chromite and vanadiferous and titaniferous magnetite deposits in layered intrusions tend to occur towards the centre of Archean cratons. Groves *et al.* (2005*a*) postulated that thick 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 temperature and high pressure at the base of thick SCLM favour the growth of diamonds, 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 & 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 in either mid-ocean ridge or supra-subduction zone environments (Huston *et al.* 2010). They are incorporated into the continental record through accretion events associated with periods of ocean closure and continental assembly/terrane accretion and hence correspond with cycles of supercontinent assembly. Their overall temporal distribution is similar to orogenic gold deposits with peaks in the Neoarchaean and late Palaeoproterozoic and a more continuous distribution in the Phanerozoic but with significant peaks in the early and mid-Palaeozoic corresponding with assembly of Gondwana and Pangea (Groves *et al.* 2005*a*; Huston *et al.* 2010). This temporal association with orogenic gold reflects their common formation in back-arc basin settings and the higher preservation potential of this association in the long-term rock record than mid-ocean ridge environments. Neoproterozoic and younger oceanic crust is preserved on land in ophiolite complexes and, in addition to VMS deposits, which are in the upper levels of the crustal section, podiform chromite might also be present in its upper mantle sections. Ophiolites show age peaks at around *c.* 800–750 Ma, corresponding with initial 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 and 100–90 Ma that formed during closure of the Tethys and final assembly of Pangea (Dilek 2003). Cawood & 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.

Iron formations, whose distribution is also controlled by evolving atmospheric and thermal conditions, developed on basin platforms including passive continental margins (Superior-type) and in association with greenstone-belt volcanic activity, the latter often linked to VMS deposits (Algoma-type; Bekker *et al.* 2010). Peaks in iron formation deposition at 2.7 and 1.9 Ga have been related to inferred peaks in mantle plume activity (Isley & Abbott 1999) but also correspond to end-Archaean and end-Palaeoproterozoic supercontinent assembly (e.g. Fig. 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 appear to be 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 (1.7–1.4 Ga) in eastern Australia (Broken Hill–Mount Isa) and western North America (Sullivan). 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 is 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 & Korsch 2008; Gibson *et al.* 2008; Cawood *et al.* 2012), 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 are 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.* 2005*a*, 2010; Kerrich *et al.* 2005;). The development of IOCG deposits in intracontinental settings and the relationship with mantle derived magmatism means that their temporal distribution is not directly related to the supercontinent cycle. However, the global temporal distribution of anorogenic magmatism is focused in the late Palaeoproterozoic and Mesoproterozoic overlapping with the Rodinian supercontinent.

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 deposit 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.* 2005*a*; Huston *et al.* 2010). 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 & 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 orogenic 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 (Fig. 1; Goodwin 1996). De Wit & Thiart (2005) highlight secular variation in metallogenic potential with Archean cratons more richly endowed in some types of 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 (also termed Columbia) to assembly of Gondwana (*c.* 1.7–0.7 Ga), seems anomalous in the general distribution of rock types, geological events and mineral deposits (Fig. 5). 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.* 2013). 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; Parnell *et al.* 2012) and associated titanium deposits (Meyer 1988) (Fig. 5). 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 1.7–0.9 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, Palaeoproterozoic and Phanerozoic (Figs 1 & 3). The absence

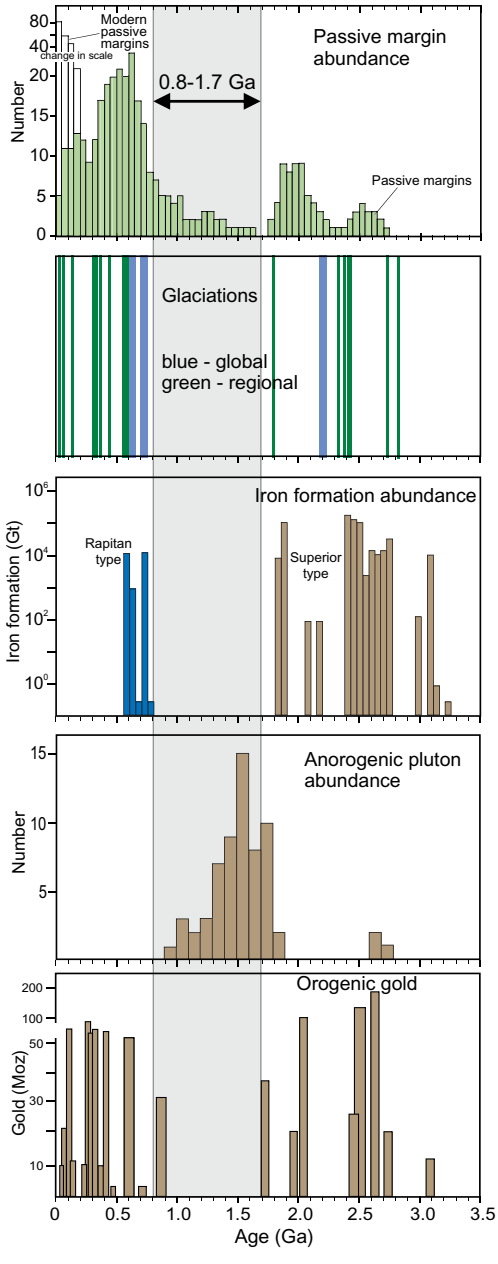

Fig. 5. Temporal distributions of passive margins (Bradley 2008), glaciations (Hoffman 2009), iron formations (Bekker *et al.* 2010), anorogenic plutons (Parnell *et al.* 2012) and orogenic gold (Goldfarb *et al.* 2001; Groves *et al.* 2005*b*). The period 1.7–0.8 Ga, which is marked by a paucity of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

of gold deposits in this period, despite the presence of accretionary orogens, has been related to lack of preservation owing to exhumation of the end-Mesoproterozoic orogens and only high-grade basement remains (Goldfarb *et al.* 2001; Groves *et al.* 2005*b*). Huston *et al.* (2010) suggest that the corresponding paucity of VMS deposits during this period reflects an overall advancing rather than a retreating accretionary orogen setting, such that the overriding plate did not go into extension to enable development of a back-arc basins and associated deposits. However, deposits which form in an overall extensional environment, whether in intracontinental or continental margin settings, such as IOCG and CD Pb–Zn, are well developed during the Rodinia cycle at around the end Palaeoproterozoic 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 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 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 to 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 & 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 & Behn 2008; Bekker *et al.* 2010). However, the presence of long-lived late Palaeoproterozoic 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 the record is 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 to 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 young mean ages (e.g. epithermal gold, Wilkinson & 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 orogenic gold deposits, which form in accretionary environments during on-going convergent plate interaction, correlating with the timing of supercontinent assembly, most notably in the Neoarchaean, late Palaeoproterozoic 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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References

Ashwal, L. D. 1993. *Anorthosites*.Springer, Berlin.

Barley, M. E. & Groves, D. I. 1992. Supercontinent cycle and the distribution of metal deposits through time. *Geology*, **20**, 291–294.

Bekker, A., Slack, J. F., Planavsky, N., Krapež, B., Hofmann, A., Konhauser, K. O. & Rouxel, O. J. 2010. Iron formation: the sedimentary product of a complex interplay among mantle, tectonic, oceanic, and biospheric process. *Economic Geology*, **105**, 467–508.

Bierlein, F. P., Groves, D. I. & Cawood, P. A. 2009. Metallogeny of accretionary orogens – the connection between lithospheric processes and metal endowment. *Ore Geology Reviews*, **36**, 282–292.

Bradley, D. C. 2008. Passive margins through earth history. *Earth-Science Reviews*, **91**, 1–26.

Bradley, D. C. 2011. Secular trends in the geologic record and the supercontinent cycle. *Earth-Science Reviews*, **108**, 16–33.

Bradley, D. C. & Leach, D. L. 2003. Tectonic controls on Mississippi Valley-type lead zinc mineralization in orogenic forelands. *Mineralium Deposita*, **38**, 652–667.

Brown, M. 2007. Metamorphic conditions in orogenic belts: a record of secular change. *International Geology Review*, **49**, 193–234.

Campbell, I. H. & Allen, C. M. 2008. Formation of supercontinents linked to increases in atmospheric oxygen. *Nature Geoscience*, **1**, 554–558.

Cawood, P. A. 2005. Terra Australis Orogen: Rodinia breakup and development of the Pacific and Iapetus margins of Gondwana during the Neoproterozoic and Paleozoic. *Earth-Science Reviews*, **69**, 249–279.

Cawood, P. A. & Buchan, C. 2007. Linking accretionary orogenesis with supercontinent assembly. *Earth-Science Reviews*, **82**, 217–256.

Cawood, P. A. & Korsch, R. J. 2008. Assembling Australia: Proterozoic building of a continent. *Precambrian Research*, **166**, 1–35.

Cawood, P. A. & Suhr, G. 1992. Generation and obduction of ophiolites: constraints from the Bay of Islands Complex, western Newfoundland. *Tectonics*, **11**, 884–897. http://dx.doi.org/10.1029/92TC00471

Cawood, P. A., Kröner, A. & Pisarevsky, S. 2006. Precambrian plate tectonics: criteria and evidence. *GSA Today*, **16**, 4–11.

Cawood, P. A., Kröner, A., Collins, W. J., Kusky, T. M., Mooney, W. D. & Windley, B. F. 2009. Accretionary Orogens through Earth History. *In*: Cawood, P. A. & Kröner, A. (eds) *Earth Accretionary Systems in Space and Time*. Geological Society, London, Special Publications, **318**, 1–36.

Cawood, P. A., Hawkesworth, C. J. & Dhuime, B. 2012. Detrital zircon record and tectonic setting. *Geology*, **40**, 875–878.

Cawood, P. A., Hawkesworth, C. J. & Dhuime, B. 2013. *The Continental Record and the Generation of Continental Crust*. Geological Society of America, Boulder, CO, Bulletins.

Clark, A. H., Farrar, E. *et al.* 1990. Geologic and geochronologic constraints on the metallogenic evolution of the Andes of southeastern Peru. *Economic Geology*, **85**, 1520–1583.

Clift, P. D., Vannucchi, P. & Morgan, J. P. 2009. Crustal redistribution, crust–mantle recycling and Phanerozoic evolution of the continental crust. *Earth-Science Reviews*, **97**, 80–104.

Condie, K. C. 1998. Episodic continental growth and supercontinents: a mantle avalanche connection? *Earth and Planetary Science Letters*, **163**, 97–108.

Condie, K. C. 2000. Episodic continental growth models: afterthoughts and extensions. *Tectonophysics*, **322**, 153–162.

Condie, K. C. 2004. Supercontinents and superplume events: distinguishing signals in the geologic record. *Physics of The Earth and Planetary Interiors*, **146**, 319–332.

Condie, K. C. 2005. *Earth as an Evolving Planetary System*. Amsterdam, Elsevier.

Condie, K. C. & Aster, R. C. 2010. Episodic zircon age spectra of orogenic granitoids: the supercontinent connection and continental growth. *Precambrian Research*, **180**, 227–236.

Condie, K. C. & Kröner, A. 2008. When did plate tectonics begin? Evidence from the geologic record. *In*: Condie, K. C. & Pease, V. (eds) *When Did Plate Tectonics Begin?* Geological Society of America, Boulder, CO, Memoirs, **440**, 281–295.

Condie, K. C., Belousova, E., Griffin, W. L. & Sircombe, K. N. 2009*a*. Granitoid events in space and time: constraints from igneous and detrital zircon age spectra. *Gondwana Research*, **15**, 228–242.

Condie, K. C., O'Neill, C. & Aster, R. C. 2009*b*. Evidence and implications for a widespread magmatic shutdown for 250 My on Earth. *Earth and Planetary Science Letters*, **282**, 294–298.

Condie, K. C., Bickford, M. E., Aster, R. C., Belousova, E. & Scholl, D. W. 2011. Episodic zircon ages, Hf isotopic composition, and the preservation rate of continental crust. *Geological Society of America Bulletin*, **123**, 951–957.

Cuney, M. 2010. Evolution of uranium fractionation processes through time: driving the secular variation of uranium deposit types. *Economic Geology*, **105**, 553–569.

Dalziel, I. W. D., Sharon, M. & Gahagan, L. M. 2000. Laurentia–kalahari collision and the assembly of Rodinia. *The Journal of Geology*, **108**, 499–513.

Davidson, J. P. & Arculus, R. J. 2006. The significance of Phanerozoic arc magmatism in generating continental crust. *In*: Brown, M. & Rushmer, T. (eds) *Evolution and Differentiation of the Continental Crust*. Cambridge University Press, Cambridge, 135–172.

de Wit, M. & Thiart, C. 2005. *Metallogenic Fingerprints of Archaean Cratons*. Geological Society, London, Special Publications, **248**, 59–70.

Dhuime, B., Hawkesworth, C. J., Cawood, P. A. & Storey, C. D. 2012. A change in the geodynamics of continental growth 3 billion years ago. *Science*, **335**, 1334–1336.

Dilek, Y. 2003. *Ophiolite Pulses, Mantle Plumes and Orogeny*. Geological Society, London, Special Publications, **218**, 9–19.

Gibson, G. M., Rubenach, M. J., Neumann, N. L., Southgate, P. N. & Hutton, L. J. 2008. Syn- and post-extensional tectonic activity in the Palaeoproterozoic sequences of Broken Hill and Mount Isa and its bearing on reconstructions of Rodinia. *Precambrian Research*, **166**, 350–369.

Goldfarb, R. J., Groves, D. I. & Gardoll, S. 2001. Orogenic gold and geologic time: a global synthesis. *Ore Geology Reviews*, **18**, 1–75.

Goldfarb, R. J., Bradley, D. & Leach, D. L. 2010. Secular variation in economic geology. *Economic Geology*, **105**, 459–465.

Gombosi, D. J. & Wilkinson, B. H. 2012. Global rates of geologic cycling: tectonic diffusion of Upper Crustal Lithosomes. *The Journal of Geology*, **120**, 121–133.

Goodwin, A. M. 1996. *Principles of Precambrian Geology*. Academic Press, London.

Groves, D. I. & Bierlein, F. P. 2007. Geodynamic settings of mineral deposit systems. *Journal of the Geological Society, London*, **164**, 19–30.

Groves, D. I., Goldfarb, R. J., Gebre-Mariam, M., Hagemann, S. G. & Robert, F. 1998. Orogenic gold deposits: a proposed classification in the context of their crustal distribution and relationship to other gold deposit types. *Ore Geology Reviews*, **13**, 7–27.

Groves, D. I., Vielreicher, R. M., Goldfarb, R. J. & Condie, K. C. 2005*a*. Controls on the heterogeneous distribution of mineral deposits through time. *In*: McDonald, I., Boyce, A. J., Butler, I. B., Herrington, R. J. & Polya, D. A. (eds) *Mineral Deposits and Earth Evolution*. Geological Society, London, Special Publications, **248**, 71–101.

Groves, D. I., Vielreicher, R. M., Goldfarb, R. J. & Condie, K. C. 2005*b*. Secular changes in global tectonic processes and their influence on the temporal distribution of gold-bearing mineral deposits. *Economic Geology*, **100**, 71–101.

Groves, D. I., Bierlein, F. P., Meinert, L. D. & Hitzman, M. W. 2010. Iron oxide copper–gold (IOCG) deposits through Earth history: implications for origin, lithospheric setting, and distinction from other epigenetic iron oxide deposits. *Economic Geology*, **105**, 641–654.

Gurney, J. J., Helmstaedt, H. H., Le Roux, A. P., Nowicki, T. E., Richardson, S. H. & Westerland, K. J. 2005. Diamonds: crustal distribution and formation processes in time and space and an integrated deposit model. *Economic Geology*, **100**, 143–178.

Gurney, J. J., Helmstaedt, H. H., Richardson, S. H. & Shirey, S. B. 2010. Diamonds through time. *Economic Geology*, **105**, 689–712.

Hawkesworth, C. J. & Kemp, A. I. S. 2006. Evolution of continental crust. *Nature*, **443**, 811–817.

Hawkesworth, C., Cawood, P., Kemp, T., Storey, C. & Dhuime, B. 2009. A matter of preservation. *Science*, **323**, 49–50.

Hawkesworth, C., Dhuime, B., Pietranik, A., Cawood, P., Kemp, T. & Storey, C. 2010. The generation and evolution of the continental crust. *Journal of the Geological Society*, **167**, 229–248.

Hawkesworth, C., Cawood, P. & Dhuime, B. 2013. Continental growth and the crustal record. *Tectonics*, in press.

Hoffman, P. F. 2009. Pan-glacial – a third state in the climate system. *Geology Today*, **25**, 100–107.

Holmes, A. 1965. *Principles of Physical Geology*. Nelson, London.

Huston, D. L., Pehrsson, S., Eglington, B. M. & Zaw, K. 2010. The geology and metallogeny of volcanic-hosted massive sulfide deposits: variations through geologic time and with tectonic setting. *Economic Geology*, **105**, 571–591.

HUTTON, J. 1788. Theory of the earth; or an investigation of the laws observable in the composition, dissolution, and restoration of land upon the globe. *Transactions of the Royal Society of Edinburgh*, **1**, 209–304.

IIZUKA, T., KOMIYA, T., RINO, S., MARUYAMA, S. & HIRATA, T. 2010. Detrital zircon evidence for Hf isotopic evolution of granitoid crust and continental growth. *Geochimica et Cosmochimica Acta*, **74**, 2450–2472.

ISLEY, A. E. & ABBOTT, D. H. 1999. Plume-related mafic volcanism and the deposition of banded iron formation. *Journal of Geophysical Research*, **104**, 15 461–15 477.

KARLSTROM, K. E., AHALL, K.-I., HARLAN, S. S., WILLIAMS, M. L., MCLELLAND, J. & GEISSMAN, J. W. 2001. Long-lived (1.8–1.0 Ga) convergent orogen in southern Laurentia, its extensions to Australia and Baltica, and implications for refining Rodinia. *Precambrian Research*, **111**, 5–30.

KEMP, A. I. S., HAWKESWORTH, C. J., PATERSON, B. A. & KINNY, P. D. 2006. Episodic growth of the Gondwana supercontinent from hafnium and oxygen isotopes in zircon. *Nature*, **439**, 580–583.

KEMP, A. I. S., SHIMURA, T., HAWKESWORTH, C. J. EIMF 2007. Linking granulites, silicic magmatism, and crustal growth in arcs: ion microprobe (zircon) U–Pb ages from the Hidaka metamorphic belt, Japan. *Geology*, **35**, 807–810.

KERRICH, R. & POLAT, A. 2006. Archean greenstone–tonalite duality: thermochemical mantle convection models or plate tectonics in the early Earth global dynamics? *Tectonophysics*, **415**, 141–165.

KERRICH, R. & WYMAN, D. 1990. Geodynamic setting of mesothermal gold deposits: an association with accretionary tectonic regimes. *Geology*, **18**, 882–885.

KERRICH, R., GOLDFARB, R. & RICHARDS, J. P. 2005. Metallogenic provinces in an evolving geodynamic framework. *Economic Geology*, **100**, 1097–1136.

LEACH, D. L., BRADLEY, D. C., HOUSTON, D., PISAREVSKY, S. A., TAYLOR, R. D. & GARDOLL, S. J. 2010. Sediment-hosted lead-zinc deposits in earth history. *Economic Geology*, **105**, 593–625.

LINDGREN, W. 1909. Metallogenetic epochs. *Economic Geology*, **4**, 409–420.

MEYER, C. 1988. Ore deposits as guides to geologic history of the earth. *Annual Review of Earth and Planetary Sciences*, **16**, 147–171.

MITCHELL, A. H. G. & GARSON, M. S. 1981. *Mineral Deposits and Global Tectonic Settings*. Academic Press, New York.

NALDRETT, A. J. 2010. Secular variation of magmatic sulfide deposits and their source magmas. *Economic Geology*, **105**, 669–688.

O'NEILL, C., LENARDIC, A., MORESI, L., TORSVIK, T. H. & LEE, C. T. A. 2007. Episodic Precambrian subduction. *Earth and Planetary Science Letters*, **262**, 552–562.

OLIVER, J. 1986. Fluids expelled tectonically from orogenic belts: their role in hydrocarbon migration and other geologic phenomena. *Geology*, **14**, 99–102.

PARNELL, J., HOLE, M., BOYCE, A. J., SPINKS, S. & BOWDEN, S. 2012. Heavy metal, sex and granites: crustal differentiation and bioavailability in the mid-Proterozoic. *Geology*, **40**, 751–754.

PROKOPH, A., SHIELDS, G. A. & VEIZER, J. 2008. Compilation and time-series analysis of a marine carbonate $\delta^{18}O$, $\delta^{13}C$, $^{87}Sr/^{86}Sr$ and $\delta^{34}S$ database through Earth history. *Earth-Science Reviews*, **87**, 113–133.

RASMUSSEN, B., FLETCHER, I. R., BEKKER, A., MUHLING, J. R., GREGORY, C. J. & THORNE, A. M. 2012. Deposition of 1.88-billion-year-old iron formations as a consequence of rapid crustal growth. *Nature*, **484**, 498–501.

RAUP, D. M. 1972. Taxonomic diversity during the Phanerozoic. *Science*, **177**, 1065–1071.

RINO, S., KOMIYA, T., WINDLEY, B. F., KATAYAMA, I., MOTOKI, A. & HIRATA, T. 2004. Major episodic increases of continental crustal growth determined from zircon ages of river sands; implications for mantle overturns in the Early Precambrian. *Physics of the Earth and Planetary Interiors*, **146**, 369–394.

RUDNICK, R. L. 1995. Making continental crust. *Nature*, **378**, 571–578.

RUDNICK, R. L. & GAO, S. 2003. Composition of the continental crust. *In*: RUDNICK, R. L. (ed.) *Treatise on Geochemistry. The Crust*. Elsevier, Amsterdam, **3**, 64.

RUZICKA, V. 1996. *Unconformity-associated Uranium*. Geological Survey of Canada, Ottawa, Geology of Canada, **8**, 197–210.

SCHOLL, D. W. & VON HUENE, R. 2007. Exploring the implications for continental basement tectonics if estimated rates of crustal removal (recycling) at Cenozoic subduction zones are applied to Phanerozoic and Precambrian convergent ocean margins. *In*: HATCHER, R. D., JR, CARLSON, M. P., MCBRIDE, J. H. & CATALÁN, J. M. (eds) *4-D Framework of Continental Crust*. Geological Society of America, Boulder, CO, Memoirs, **200**, 9–32.

SCHOLL, D. W. & VON HUENE, R. 2009. Implications of estimated magmatic additions and recycling losses at the subduction zones of accretionary (non-collisional) and collisional (suturing) orogens. *In*: CAWOOD, P. A. & KRÖNER, A. (eds) *Earth Accretionary Systems in Space and Time*. Geological Society, London, Special Publications, **318**, 105–125.

SCHOLL, D. W., VON HUENE, R., VALLIER, T. L. & HOWELL, D. G. 1980. Sedimentary masses and concepts about tectonic processes at underthrust ocean margins. *Geology*, **8**, 564–568.

SEEDORFF, E., DILLES, J. H. *ET AL.* 2005. Porphyry deposits: characteristics and origin of hypogene features. *Economic Geology*, **100**, 251–298.

SHIELDS, G. A. 2007. A normalised seawater strontium isotope curve: possible implications for Neoproterozoic–Cambrian weathering rates and the further oxygenation of the Earth. *eEarth*, **2**, 35–42.

SHIREY, S. B. & RICHARDSON, S. H. 2011. Start of the Wilson Cycle at 3 Ga shown by diamonds from subcontinental mantle. *Science*, **333**, 434–436.

SILVER, P. G. & BEHN, M. D. 2008. Intermittent plate tectonics? *Science*, **319**, 85–88.

SLACK, J. F. & CANNON, W. F. 2009. Extraterrestrial demise of banded iron formations 1.85 billion years ago. *Geology*, **37**, 1011–1014.

SMITH, A. B. & MCGOWAN, A. J. 2007. The shape of the Phanerozoic marine Palaeodiversity curve: how much

can be predicted from the sedimentary rock record of Western Europe? *Palaeontology*, **50**, 765–774.

STEIN, M. & HOFMANN, A. W. 1993. Mantle plumes and episodic crustal growth. *Nature*, **372**, 63–68.

STERN, C. R. 2011. Subduction erosion: rates, mechanisms, and its role in arc magmatism and the evolution of the continental crust and mantle. *Gondwana Research*, **20**, 284–308.

STERN, R. J. & SCHOLL, D. W. 2010. Yin and Yang of continental crust creation and destruction by plate tectonic processes. *International Geology Review*, **52**, 1–31.

TAYLOR, S. R. 1967. The origin and growth of continents. *Tectonophysics*, **4**, 17–34.

TAYLOR, S. R. & MCLENNAN, S. M. 1985. *The Continental Crust: Its Composition and Evolution*. Blackwell Scientific, Oxford.

TITLEY, S. R. 1993. Relationship of stratabound ores with tectonic cycles of the Phanerozoic and Proterozoic. *Precambrian Research*, **61**, 295–322.

TURNEAURE, F. S. 1955. Metallogenic provinces and epochs. *Economic Geology*, **50**, 38–98.

VOICE, P. J., KOWALEWSKI, M. & ERIKSSON, K. A. 2011. Quantifying the timing and rate of crustal evolution: global compilation of radiometrically dated detrital zircon grains. *The Journal of Geology*, **119**, 109–126.

VON HUENE, R. & SCHOLL, D. W. 1991. Observations at convergent margins concerning sediment subduction, subduction erosion, and the growth of continental crust. *Reviews of Geophysics*, **29**, 279–316.

WILKINSON, B. H. & KESLER, S. E. 2007. Tectonism and exhumation in convergent margin orogens: insights from ore deposits. *The Journal of Geology*, **115**, 611–627.

WILKINSON, B. H., MCELROY, B. J., KESLER, S. E., PETERS, S. E. & ROTHMAN, E. D. 2009. Global geologic maps are tectonic speedometers–rates of rock cycling from area-age frequencies. *Geological Society of America Bulletin*, **121**, 760–779.