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Bicentennial Review

Geodynamic settings of mineral deposit systems

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Abstract: Mineral deposits represent extraordinary metal concentrations that form by magmatic, magmatic–hydrothermal or hydrothermal processes in geodynamic environments typified by anomalously high thermal and/or mechanical energy near plate boundaries. As they require the conjunction of specific environmental conditions to form, particular mineral deposit types tend to occupy specific geodynamic niches. The temporal distributions of mineral deposit types reflect both formational and preservational processes. In the Archaean and Palaeoproterozoic, these were linked because of preservation in continental crust connected to thick buoyant subcontinental lithospheric mantle (SCLM), but were decoupled by the Neoproterozoic and Phanerozoic as a result of evolution to thinner, increasingly dense SCLM. The transition marks a change from mantle plume-influenced plate tectonics to modern-style plate tectonics, with broadly coincident environmental changes and a major impact on the nature and abundance of preserved mineral deposit types. As mineral deposits represent an integral part of tectonic process, they are essential indicators of that process and geodynamic settings, and should be incorporated into any holistic tectonic terrane analysis. Their distribution also provides a particularly critical test on ancient continental reconstructions derived from palaeomagnetic data. Conversely, such reconstructions provide a first-order targeting tool for the conceptual exploration required to discover new mineral provinces and deposits under cover.

Economically viable mineral-deposit (ore) systems are heterogeneously, but not randomly, distributed in time and space (e.g. Meyer 1988; Barley & Groves 1992). Their distribution is intimately related to the evolution of the Earth, particularly to its progressive cooling and geodynamic evolution from plume-influenced tectonics to modern plate tectonics (e.g. Groves *et al*. 2005*b*; Kerrich *et al*. 2005), with consequences for balance between formational and preservational processes (e.g. Groves *et al*. 2005*a*). Because mineral deposit systems require a very specific conjunction of processes to produce the exceptional metal enrichments over background terrestrial concentrations that result in ore deposits, they can form only under certain conditions in particular tectonic environments. Thus, certain mineral-deposit types are diagnostic of specific tectonic settings and can be used not only to help define these settings, in conjunction with more conventional tectonic and petrogenetic evidence, but also to help constrain the geodynamic evolution of the Earth and its environmental (atmospheric, hydrospheric, biospheric) consequences (e.g. Sawkins 1984; Titley 1993; Kesler 1997; Condie 2005).

In view of the above, a logical first-order grouping of mineral deposit types is in terms of their geodynamic setting. This is most conveniently viewed in the context of a plate-tectonic framework, with reference to the influences of mantle plume impacts where appropriate. In turn, the most logical way in which to describe these plate-tectonic settings is in terms of the supercontinent cycle (Fig. 1), which controls the dominant geodynamic environments on the Earth at any particular time during its evolution and is a first-order control on the temporal distribution of its mineral deposit types (e.g. Groves *et al*. 2005*b*; Kerrich *et al*. 2005). This paper first considers deposit types related to intracratonic extension, which is most likely to occur after supercontinent assembly, through those related to continental break-up and to divergent plate margins, to those that formed at convergent margins, which are most likely to occur during amalgamation of continents to form supercontinents. There is clearly insufficient space in this brief, but wide-ranging, review to discuss the geodynamic setting of all mineral deposit types, although the major primary (hypogene) examples are covered. Secondary (supergene) deposits, produced by weathering of metal-enriched rocks (e.g. bauxites, Ni laterites: Freysinnet *et al*. 2005) or pre-existing mineral deposits (e.g. supergene Cu over porphyry deposits: Sillitoe 2005), are not discussed. There is also insufficient space to quote all primary references to particular deposit types or their tectonic settings. Hence, more recent reviews that themselves contain exhaustive reference lists are quoted in the text. For comprehensive up-to-date descriptions of the deposit styles and their genesis, the reader is referred to the *Economic Geology 100th Anniversary Volume* (Hedenquist *et al*. 2005)

Uncertainties in geodynamic settings of some mineral deposit types

Although most mineral deposit types can reliably be allocated to specific geodynamic settings based on Mesozoic to Recent examples where tectonic evolution of hosting terranes is well understood (e.g. porphyry and epithermal, volcanogenic massive sulphide (VMS), orogenic gold) or they have an obvious magmatic association and/or obvious tectonic setting (e.g. Ni–Cu, platinum group elements (PGE), diamonds), there are a number of problems with tectonic classification of other deposits.

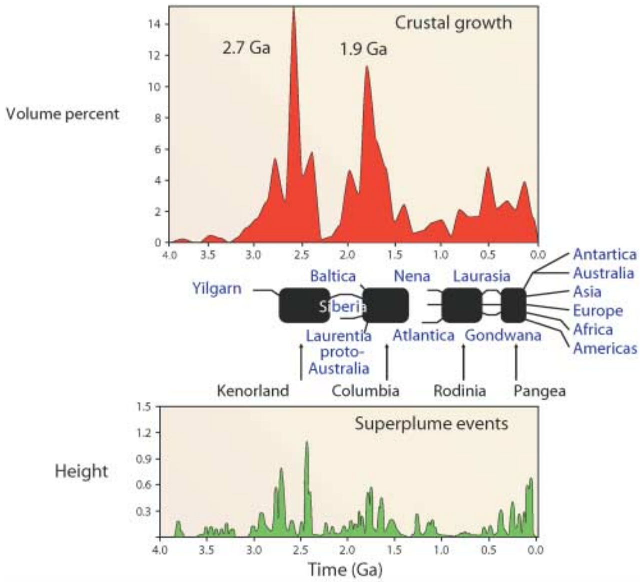

Fig. 1. Critical elements of the supercontinent cycle. (**a**) Frequency distribution of growth of continental crust. Modified from Condie (2000). (**b**) Major elements of the supercontinent cycle. Modified from Kerrich *et al*. (2005). (**c**) Distribution of mantle plume events. Modified from Abbott & Isley (2002).

For some deposits, particularly those in extensional terranes well inboard of subduction zones in margins of grossly convergent tectonics, it is difficult to decide whether to classify them according to their extensional settings or broader-scale convergent geodynamic settings. Such deposits include the sediment-hosted exhalative (SEDEX) and Mississippi Valley-type (MVT) Zn–Pb deposits (e.g. Leach *et al*. 2005), and Carlin-type gold deposits (e.g. Cline *et al*. 2005). For other deposits (e.g. sediment-hosted Cu–Co deposits of the Zambian Copperbelt; Selley *et al*. 2005: Witwatersrand Au–U deposits; Frimmel *et al*. 2005; Law & Phillips 2005) the problem lies in controversy on absolute timing of the deposits, which leads to uncertainties in ascribing the deposit types to their depositional settings or settings related to basin inversion. In yet other examples, there are debates as to the classification of specific deposits within genetic groups (e.g. orogenic v. intrusion-related Au deposits: Goldfarb *et al*. 2005), which also affect the certainty of allocation of geodynamic setting to each group.

These uncertainties are discussed, where appropriate, below, and the relevant deposit types are at least mentioned in the alternative setting where controversy or uncertainty exist.

Mineral deposits related to intracratonic magmatism

A number of deposit types are related to anomalous mantle magmatism in continental crustal settings above thick subcontinental lithospheric mantle (SCLM) in intracratonic settings, probably during initial extension related to the failed break-up of supercontinents. These include PGE deposits in layered intrusions, diamond deposits in alkaline pipes and iron–oxide Cu–Au (IOCG) and related deposits related to alkaline to A-type granite intrusions. These are shown, together with Ni–Cu sulphide deposits, in Figure 2.

Deposits related to mantle basic magmatism

The classic deposit types of this style are the PGE, chromite and vanadiferous and titaniferous magnetite deposits in large layered mafic to ultramafic intrusions. These form discrete, commonly continuous layers at predictable positions within the layered intrusions (lower chromite and PGE; upper V–Ti magnetite), with minor discordant ore bodies. All of these clearly relate to segregation of magmatic components, although precise controlling mechanisms remain unclear (Cawthorn *et al*. 2005). Half of the global resources of these commodities lies in the Bushveld Complex of South Africa, with significant resources in the Stillwater Complex, USA and the Great Dyke, Zimbabwe. These giant deposits tend to lie towards the centre of Archaean cratons (Fig. 2) whereas smaller deposits such as the Pana and Pennikat deposits of Kola and Finland, respectively, tend to lie closer to craton margins. It is postulated that thick buoyant Archaean SCLM is required to support and preserve the large volumes of dense basic magma required for producing the giant deposits; hence their central cratonic position (e.g. Groves *et al*. 2005*b*). The basic magmas form in hotter than normal parts of the mantle (e.g. Arndt *et al*. 2005), probably as a result of uprise of mantle plumes beneath Archaean SCLM. Mass balance considerations summarized by Cawthorn *et al*. (2005) indicate that parent magmas must be highly enriched in ore elements, particularly PGE, relative to normal magmas to produce the high tonnages and high concentrations of metals in the mineralized layers or reefs. Mechanisms to produce this enrichment in the parent magma are, however, hotly debated (e.g. Arndt *et al*. 2005). The deposits are largely Neoarchaean to Palaeoproterozoic because they require both thick buoyant SCLM to form and be preserved in combination with significant erosion to expose mineralized segments of intrusions that are several kilometres thick.

Deposits related to deep alkaline magmatism

The classic deposits of this type are diamonds, which have been brought to the Earth's surface by mantle-derived magmas and redistributed into alluvial deposits by sedimentary processes. They are sited mainly in Precambrian (largely Archaean) cratons (Fig. 2) where the relatively low-T and high-P conditions near the base of the underlying thick SCLM favoured diamond growth mainly in metasomatized garnet hartzburgite or eclogite, as summarized by Gurney *et al*. (2005). It is likely that the uprise of mantle plumes beneath this SCLM triggered melting of refractory mantle metasomatized by fluids derived from the plumes, or melting of previously metasomatized lithosphere, to produce magmas with a mixed signature of refractory mantle and incompatible elements derived from metasomatized mantle. Diamonds were brought to the surface by the rapid uprise of alkaline kimberlite magmas throughout the craton or lamproite magmas towards its margin (e.g. Argyle pipe, Western Australia: Jaques *et al*. 1984). Diamond deposits have formed since the inception of widespread thick SCLM in the Neoarchaean (*c*. 2.8 Ga) but become more abundant in younger rocks as a result of the susceptibility of their host igneous rocks to weathering combined with diamond enrichments in near-surface breccia pipes or diatremes.

Deposits related to melting of metasomatized SCLM

The iron-oxide Cu–Au (IOCG) group of deposits (Hitzman *et al*. 1992) is a disparate group of deposits that are rich in iron oxides, including essentially sulphur-free P, F and REE-bearing deposits.

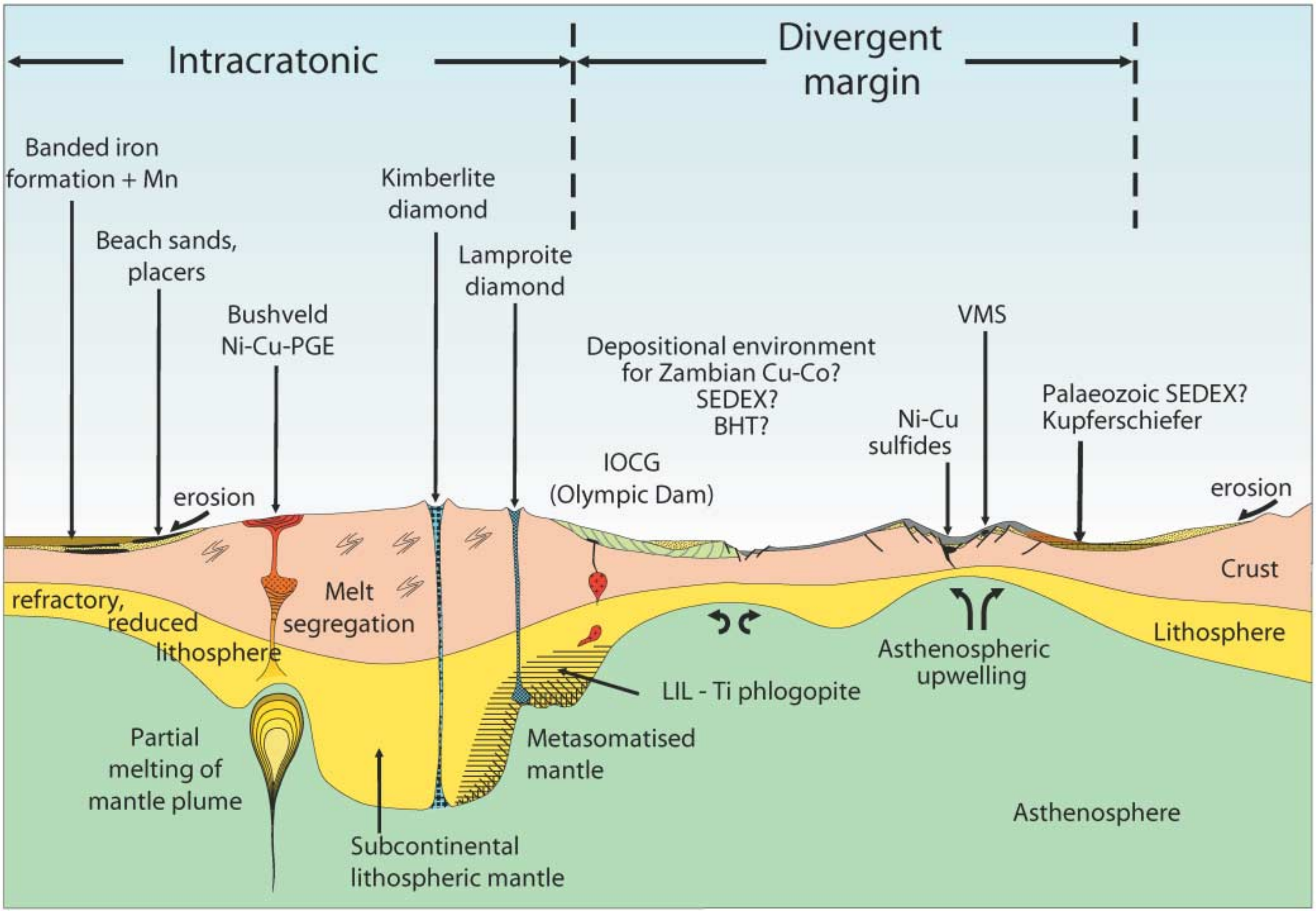

Fig. 2. Schematic diagram showing both major mineral deposit types formed in continental crust above SCLM, normally Archaean in age (adapted from Groves *et al*. 1987), and those formed in passive continental margins and oceanic spreading ridges in divergent margin tectonic settings. Thickness of crust and SCLM not to scale.

The inclusion of so many different deposit styles in this group, even in the latest review by Williams *et al*. (2005), means that their tectonic setting becomes obscure. If only the Precambrian world-class to giant deposits that actually produce Cu and Au are considered, the situation becomes much clearer (e.g. Groves *et al*. 2005*b*). They are all sited within about 100 km of the margins of Archaean cratons (e.g. Carajas, Brazil; Olympic Dam, Australia; Palabora, South Africa) or close to the boundary between Archaean and Proterozoic lithosphere (Fig. 2). The giant Kiruna Fe–P deposits have a similar lithospheric setting. They are all related spatially and temporally to widespread anorogenic alkaline or A-type granitic igneous events in an intracratonic setting in lithosphere that is several hundred million years older than the metallogenetic event. These associations strongly suggest that iron-oxide Cu–Au deposits are related to plume-induced partial melting of SCLM previously metasomatized during subduction or other tectonic processes along cratonic margins, and hence the importance of tectonic setting. The oldest examples broadly coincide temporally with the oldest PGE and diamond deposits but, like diamonds, they extend beyond the Mesoproteozoic limits of the PGE deposits as a result of their emplacement at higher crustal levels and their common near-vertical (as compared with near-horizontal) geometries. The youngest world-class deposits ascribed to this class, the *c*. 115 Ma Candelaria deposits (e.g. Mathur *et al*. 2002), are also spatially and temporally related to subalkaline to alkaline granites but in a tectonic setting dominated by transpression and basin inversion in a long-lived arc-parallel fault system related to subduction in the coastal batholith of Chile, outboard of Precambrian lithosphere.

Mineral deposits related to intracontinental rifting or continental break-up

Deposits on rifted cratonic margins

Magmatic Ni–Cu ± PGE sulphide deposits in mafic–ultramafic intrusions (e.g. Naldrett 1997; Arndt *et al*. 2005; Barnes & Lightfoot 2005) are the type example of this deposit setting. They show a classic temporal distribution (e.g. Groves *et al*. 2005*b*) related to rifting of Archaean or younger SCLM in the Palaeoproterozoic, Mesoproterozoic, Neoproterozoic and Mesozoic, probably related to mantle plume events and following supercontinent amalgamation, but preceding extensive rift volcanism or ocean creation. They represent Ni–Cu sulphide segregation and enrichment from high-MgO magmas of varying petrogenetic affinity (e.g. Barnes & Lightfoot 2005), commonly involving magma mixing, that formed smaller intrusive bodies than those hosting giant PGE deposits within the cratons. Their tectonic setting and timing allows the formation of complex intrusions rather than more simple sills, enhancing the potential

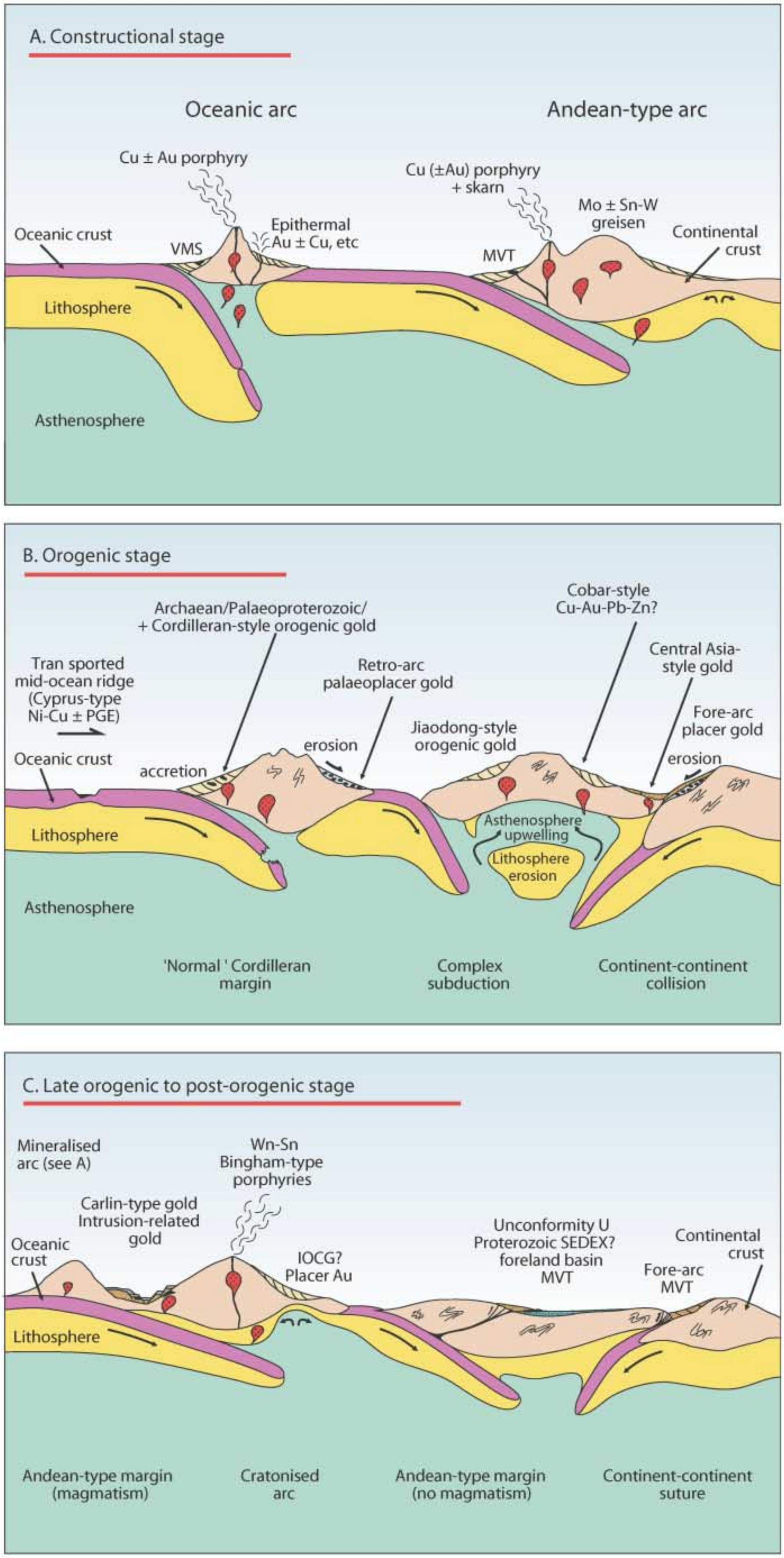

Fig. 3. Schematic diagram showing the wide range of deposit types formed in convergent margin settings. The deposit types are divided into those of the constructional, orogenic and late- to post-orogenic stages. Derived from several sources including Groves *et al*. (1998) and Leach *et al*. (2005). Arrows on subducting slabs represent vector of motion of crust in response to subvertically sinking oceanic lithosphere.

to trap and enrich immiscible sulphides. The Ni–Cu sulphide deposits form adjacent to, and commonly outboard of, Precambrian lithospheric margins (e.g. Voisey's Bay, Jinchuan, Noril'sk: see Fig. 2). Sudbury represents an unique example where a meteorite impact in an appropriate tectonic setting led to one of the largest accumulations of Ni–Cu sulphides globally. Archaean Ni–Cu sulphide deposits are of different type, largely relating to highly magnesian komatiitic volcanism in a hotter early Earth (e.g. Lesher 1989; Lesher & Keays 2002).

Other deposits formed near continental margins as a result of mantle plume impingement on rifted Archaean SCLM include the Fe–Ti oxide deposits related to anorthoritic magmatism. These are restricted in time to the break-up and dispersal of the Mesoproterozoic supercontinent, Columbia, when mantle plumes are interpreted to have caused widespread decompressional melting and large volumes of basaltic magmas that produced thick anorthoritic crust on extended post Archaean SCLM (e.g. Kerrich *et al*. 2005).

Deposits in intracratonic rift settings

A number of sediment-hosted mineral deposits occur in sedimentary basins that developed in intracratonic rift settings, albeit connected in some cases to oceanic basins. These include the giant stratabound Cu–Co deposits of the Zambian Copperbelt, the giant Proterozoic SEDEX Pb–Zn deposits of Northern Australia and the giant Broken Hill-type (BHT) Pb–Zn–Ag deposits of Australia and South Africa. However, there is debate as to the timing of some deposits, and the probability that the settings of others represent a distal expression of convergent margin tectonics. They are described below under the heading 'Sediment-hosted deposits of non-diagnostic or variable geodynamic setting'.

Mineral ore deposits related to divergent margin tectonics

Mineral deposits formed in divergent margins during supercontinent break-up include a variety of essentially sediment-hosted syngenetic and epigenetic deposits in passive continental margins and deposits associated with oceanic spreading ridges. The latter may be tectonically emplaced and preserved during subsequent ocean closure and basin inversion. These tectonic environments and deposits are shown in Figure 2.

Syngenetic deposits of passive continental margins

Syngenetic sediment-hosted deposits that form on passive continental margins include beach sand deposits, such as those in along-shore sedimentary 'traps' that typify both the eastern and western continental margins of Australia, and banded iron formation (BIF) and manganese deposits, both of which may be enriched to low-P hematitic ores (e.g. Hamersley, Australia; Carajas, Brazil) by subsequent hydrothermal (e.g. Barley *et al*. 1999) and/or supergene processes. The most economically important BIF formed at *c*. 2.65–1.85 Ga when there was a convergence of a large supply of aqueous iron from sea-floor hydrothermal systems, probably related to mantle plumes (Isley & Abbott 1999), large continental shelves for deposition of the rhythmically banded iron formations with minimal clastic input, and at least partially anoxic oceans (e.g. Clout & Simonson 2005). Precambrian manganese deposits show a similar temporal pattern to BIF as most of the deposits are related to enrichments of manganiferous BIF with manganese carbonate layers (e.g. Kalahari deposits, South Africa: Astrup & Tsikos 1998). Later manganese deposits are also deposited on passive continental margins, with ores classed as black shale-hosted or oncolytic–oolitic deposits such as Nikopol, Ukraine (Schaefer *et al*. 2001). The younger iron deposits are also oolitic; for example, the Clinton-type deposits of the USA and minette-type ores of Europe (e.g. Melon 1962).

Deposits formed during ocean spreading

Mineral deposits that formed at spreading centres or in primitive backarcs are rare because of their poor preservational potential. However, such deposits do occur in slices of ophiolite obducted onto continental crust during ocean closure, and hence appear in convergent margin settings in their final tectonic position. They include the mafic type (Franklin *et al*. 2005) of volcanogenic massive sulphide (VMS: see further discussion below) deposits, such as those of the Mesozoic Troodos of Cyprus and the Semail Complex of Oman, which formed by hydrothermal circulation of modified seawater on the sea floor. Other deposit styles include structurally modified, originally magmatic podiform chromite deposits (e.g. Edwards *et al*. 2000) that occur in obducted Palaeozoic and Mesozoic mantle or crust–mantle transition zones of oceanic lithosphere; for example, in Eurasia and Cyprus, Turkey and Oman, as summarized by Kerrich *et al*. (2005). Precambrian examples of both deposit styles are rare.

Mineral deposit related to convergent margin tectonics

By far the greatest variety of mineral deposit types is associated with convergent margin settings, largely because of the complexity of tectonic environments within these settings (Fig. 3). This, in turn, leads to a wide variety of magma types, metal source regions and hydrothermal fluid compositions and P–T conditions that control mineral deposit formation under different geodynamic regimes.

Arc-related magmatic–hydrothermal and hydrothermal mineral deposits

The classic deposit styles of continental arc, and more rarely intra-oceanic arc, environments are porphyry Cu–Au–Mo deposits (e.g. Seedorff *et al*. 2005), which are typified by those of the Andes, North American Cordillera, Altaids and SW Pacific. The majority of deposits are Mesozoic to Cenozoic in age because of susceptibility to erosion in rapidly uplifting arcs, generally above thin, negatively buoyant SCLM (e.g. Groves *et al*. 2005*b*), although Precambrian examples with essentially similar features are known (e.g. Barley 1982).

Porphyry deposits arguably show the clearest relationship to subduction processes of all, being related to dehydration of the subducting oceanic slab, and related high fluid flux into the overlying mantle wedge, which resulted in its metasomatism, and generation of evolved high-level granitic magmas from the hydrous, metal-enriched basaltic magmas produced by melting of this metasomatized mantle (e.g. Kerrich *et al*. 2005). These high-level ($<$3 km depth), normally porphyritic intrusions exsolve hot, boiling saline ore fluids that fracture the intrusion and its roof rocks and deposit copper sulphides in this permeable carapace over 50–500 ka (e.g. Seedorff *et al*. 2005). Deposits in more primitive intra-oceanic arcs (e.g. SW Pacific) tend to be more gold rich compared with those in more continental settings (e.g. North American Cordillera), which may be enriched in Mo, or even Sn (Bolivia) or W (New Brunswick, Canada) in rare cases.

Epithermal high-sulphidation Cu–Au–Ag deposits appear to represent the upper portions of porphyry systems in some cases.

Low-sulphidation epithermal Au–Ag deposits form at even shallower crustal levels (<1.5 km) and lower temperatures (<300 °C) than porphyry–high sulphidation epithermal systems and have an even more restricted time range, most being Tertiary or younger (Simmons *et al*. 2005), although they have a similar geographical position mostly around the Pacific Rim and in the Mediterranean region. The deposits form in a variety of host rocks in volcanic regions with anomalously high thermal gradients from mixed magmatic and meteoric fluids that boil or mix close to the surface, creating physical and chemical gradients that induce metal precipitation below the water table (e.g. Simmons *et al*. 2005).

Backarc-related submarine mineral deposits

VMS deposits of Cu–Zn–Pb (± Au–Ag–Ba) are forming at present on mid-ocean ridges from hot plumes (>300 °C) of modified seawater, possibly with some magmatic input, termed 'black smokers', but the vast majority of this mid-ocean ridge lithosphere is subducted by negative buoyancy. Hence, Archaean to Cenozoic VMS deposits that are preserved in the geological record are more likely to be from convergent margin settings (e.g. Franklin *et al*. 2005; Hannington *et al*. 2005). The preserved deposits formed during arc-related rifting, mostly in backarc, but also in fore-arc, settings associated with slab rollback during subduction of old, cold oceanic crust, the impact of mantle plumes, or extension related to change in plate geometry during oblique convergence. These processes, which caused thinning of the SCLM, provided the extensional structural architecture and high thermal gradients required to sustain the long-lived and high-temperature submarine hydrothermal systems that formed the VMS deposits (Franklin *et al*. 2005).

Some gold-rich and pipe-like deposits, such as Mt. Lyell in Tasmania, which occurs in an extensive VMS province (e.g. Solomon & Groves 1994), may represent the root systems of VMS deposits in the conduits that channelled hydrothermal fluids to the near-surface or surface depositional sites of the VMS deposits. The gold deposits of Lihir Island in the SW Pacific may be shallower, essentially submarine, epithermal equivalents formed above fluid-metasomatized sub-arc mantle (e.g. McInnes *et al*. 2001).

Magmatic–hydrothermal mineral deposits in far backarc settings or deformed continental margins

Several deposit styles are sited in far backarc settings, normally within deformed sedimentary sequences on the margins of cratons adjacent to thick Precambrian SCLM.

Many Phanerozoic Sn–W deposits are associated with fractionated S-type granites in rather unusual tectonic settings that Kerrich *et al*. (2005) described as continent–continent orogens (e.g. Alpine–Himalayas; Appalachian–Caledonian) that close an internal ocean. These are commonly the only economic deposit style because there is limited juvenile crust formed and/or preserved in such orogens. For other Mesozoic to Tertiary deposits, the tectonic environment is more clearly defined as a far backarc setting as shown, for example, by the tungsten skarns of the Yukon and the Sn–W deposits of the Tasman orogen of Australia (e.g. Solomon & Groves 1994). Tin deposits also occur on the continental margin of accretionary orogens such as those of Bolivia in the Andes.

Phanerozoic reduced intrusion-related gold deposits are a recently recognized deposit type (e.g. Thompson *et al*. 1999) that occur in districts formerly known for their Sn–W deposits. They therefore have a similar tectonic setting to those Sn–W deposits in far backarc or continental margins of convergent margin settings. They are intrusion-centred deposits that, in the type Tintina Province of Alaska and Yukon, range from skarns through granitoid-hosted sheeted vein systems such as Fort Knox to gold-rich shear veins and distal base-metal and silver deposits. The deposits postdate the major compressional phase in the hosting orogen, being related to the onset of extension related to shallow subduction and/or mantle plume impingement close to the cratonic margin. Highly unusual mixed mantle–crustal magmas, derived from melting of metasomatized SCLM, are the proposed magmatic source of H_2O–CO_2 ± CH_4 ore fluids (e.g. Hart *et al*. 2004). The anomalous tectonic setting appears to be the key factor controlling the coincidence of fertile reduced magmas and reactive host sequences critical to the formation of this mineral deposit class.

Tertiary Carlin-type sediment-hosted gold deposits in the giant Carlin District of Nevada (e.g. Cline *et al*. 2005) occupy a very similar tectonic position to the intrusion-related gold systems of the Tintina Province, occurring in deformed shelf sedimentary rocks adjacent to the North American cratonic margin during the onset of extension. The deposits lie on linear trends that appear to be broadly anticlinal or horst zones developed over deep reactivated basement faults marginal to the craton during compressional deformation involving thrusting, which emplaced impermeable siliciclastic sequences over gold- and sulphur-rich shelf sequences (e.g. Emsbo *et al*. 2003) to provide impermeable seals for the hydrothermal systems. Although their origin is highly debated (Cline *et al*. 2005), the deposits of the Carlin District occur in a metallogenic province that includes undoubted magmatic–hydrothermal skarn, porphyry and disseminated gold deposits, and there is growing evidence for spatial relationship to broadly coeval granitic plutons and dykes that are largely below the present level of erosion (e.g. Johnston & Ressel 2004). Interestingly, the anomalous giant Bingham porphyry system to the east in Utah (e.g. Cunningham *et al*. 2004) is of indistinguishable age, has disseminated gold deposits similar to those of the Carlin District, and was generated by magmas of mixed mantle–crust parentage (e.g. Waite *et al*. 1997) very similar to those that generated the Yukon intrusion-related gold deposits described above. Again, geodynamic setting appears to be a critical factor in generating these anomalous and giant ore systems.

The anomalously gold-rich epithermal deposits of Cripple Creek, Colorado also best fit into this geodynamic setting, representing volcanic and intrusive activity during extension within the overall convergent-margin setting of the North American Cordillera (e.g. Jensen & Barton 2000). Similar alkalic gold-rich epithermal deposits are related to extension in backarcs in anomalous tectonic settings around the Pacific at Emperor, Fiji, Ladolam, Bismarck Archipelago and Porgera, Papua New Guinea. The gold-rich nature of these hydrothermal systems is probably due to low degrees of partial melting of incompatible-element (including Au) enriched, metasomatized mantle to produce the source alkaline magmas (e.g. McInnes *et al*. 2001) in backarc settings (e.g. Moss *et al*. 2001)

Orogenic gold and base metal deposits

The mineral deposits described above were formed from ore fluids driven by high thermal gradients related to local igneous intrusions or volcanic activity, either during the constructional stage of arc to backarc evolution or during backarc to continental margin rifting.

On the other hand, Archaean to Tertiary orogenic gold deposits (Groves *et al*. 1998) formed late in the major compressional–transpressional stages of deformation of fore-arcs to backarcs in convergent margin settings (e.g. Goldfarb *et al*. 2001, 2005). Unlike the largely magmatic–hydrothermal mineral deposits, which formed normally at crustal depths less than 3 km (intrusion-related gold systems are exceptions at depths up to 6 km?), orogenic gold formed at all crustal depths to at least 15 km, and probably 20 km, and hence have a superior preservational record to all but the VMS deposits that were accreted into the terranes in which the orogenic gold deposits were forming (e.g. Groves *et al*. 2005*a*). They represent orogen-wide fluxes of deep-sourced auriferous fluids, almost certainly in response to changes in far-field stresses caused by anomalous plate geometries (e.g. Wyman *et al*. 1999). Giant gold provinces and deposits are generally sited in geodynamic settings involving lithospheric thinning just prior to, or synchronous with, the gold event (e.g. Bierlein *et al*. 2006), rather than adjacent to thick SCLM as for several of the other gold-rich systems described above. The source of ore fluids is still widely debated, with conflicting isotopic signatures being the product of the extensive crustal pathways followed by advecting hydrothermal fluids (e.g. Mccuaig & Kerrich 1998; Groves *et al*. 2003). Local magmatic sources can be ruled out in most provinces, and the only reasonable sources of ore fluid are metamorphic reactions in the deeper parts of the supracrustal sequences hosting gold or in even deeper crust, or, alternatively, from devolatilization of the mantle wedge above the subducting slab or of the slab itself (e.g. Kerrich *et al*. 2000; Groves *et al*. 2003; Goldfarb *et al*. 2005).

Some base-metal deposits show similarities in their setting, timing, structural control and lack of any obvious genetic relationship to granitic intrusions or orogenic gold deposits, and may be broadly related, with contrasting metal contents related to contrasting hosting sequences and/or underlying crust. Such deposits are exemplified by the Cobar District of NSW, Australia, where structurally controlled Pb–Zn, Cu and Au deposits coexist in metasedimentary sequences (e.g. Solomon & Groves 1994).

Mineral deposits in foreland basins

Economic mineral deposits in foreland basins can be broadly divided into two groups: (1) placer and palaeoplacer gold; (2) sediment-hosted hydrothermal deposits. The former are concentrated within the active orogen or form along the mountain front where the detrital gold is constantly transported, deposited and reworked, and not dispersed within large quantities of rapidly deposited immature sediments (e.g. Craw *et al*. 2006). The latter form by convergence-induced, but distal, fluid circulation, and include the MVT Pb–Zn–Ba deposits and unconformity-related U deposits, as discussed below.

Most of the giant placer gold deposits (e.g. California, Alaska) that started the global gold rushes of the 19th century were deposited in Mesozoic to Recent convergent margins around the Pacific Rim where tectonic uplift, and related changes to drainage base levels, ensured effective erosion and sedimentary concentration of gold eroded from orogenic gold deposits in adjacent orogenic belts (e.g. Henley & Adams 1979; Goldfarb *et al*. 1998). Most deposits were mined in river systems or on beaches but some were preserved as palaeoplacers beneath volcanic rocks (e.g. Victoria, Australia).

Palaeoplacer gold deposits older than Tertiary are rare, yet the giant Neoarchaean Witwatersrand deposits represent the largest gold province globally. Although a hydrothermal model has been proposed (summarized by Law & Phillips 2005), the bulk of the evidence argues for a palaeoplacer origin (e.g. Frimmel *et al*. 2005). For example, detailed detrital zircon studies by Kositcin & Krapez (2004) clearly demonstrate that the hosting Central Rand Group was deposited in a retro-arc foreland basin (see Burke *et al*. 1986; Coward *et al*. 1995) on continental crust and thick SCLM that had developed during cratonization some 200–300 Ma earlier, not during orogenesis on thin SCLM prior to cratonization as for all Archaean orogenic gold provinces, even though they formed at broadly the same time (e.g. Goldfarb *et al*. 2005). Both gold and associated rounded pyrites have pre-sedimentation ages, consistent with a placer origin (Frimmel *et al*. 2005), the deposits contain detrital uraninite, and they are capped by basaltic sequences as in most Tertiary palaeoplacers. The morphologically similar Palaeoproterozoic conglomerate-hosted deposits at Tarkwa, Ghana, also deposited in a foreland basin, have detrital magnetite instead of detrital pyrite, and a hydrothermal origin is untenable. The occurrence of these giant gold palaeoplacers in the early Precambrian is probably due to the existence of extreme climatic conditions (e.g. CO_2-rich atmosphere from degassing of mantle plumes; Isley & Abbott 1999), which would have aided chemical weathering and super-effective sorting of heavy minerals in braided stream systems in the absence of any vegetation or soil-binders, combined with exceptional preservation in crust above Precambrian SCLM, as developed further below (Groves *et al*. 2005*b*).

Although some MVT deposits (e.g. Lennard Shelf, Western Australia) are arguably related to extensional tectonics (e.g. Brannon *et al*. 1996), the majority formed in foreland basins related to convergent margins (Leach *et al*. 2005). They represent the classic non-magmatic mineral deposit type formed in a distal environment by basin-wide fluid flow induced by compressional orogeny in distinct convergent margins (e.g. Garven 1985; Bethke & Marshak 1990). The strata-bound to discordant deposits are hosted in relatively shallow-water, platform sedimentary sequences of the continental shelf, commonly including limestone reefs, at low latitudes, and controlled in part by basement highs, extensional faults and sedimentary facies changes. However, radiometric and palaeomagnetic ages of most deposits place their formation firmly during contractional events of global scale. The most important period was during the assembly of Pangaea in the Devonian to Permian, with important deposits also forming from the Cretaceous to Tertiary related to Cordilleran orogeny in North America and closure of the Mediterranean in North Africa and Eurasia (Leach *et al*. 2005).

The restriction of the larger MVT deposits to the Phanerozoic almost certainly relates to the emergence of coralline limestone reefs from the Devonian onwards, with consequent greater porosity and permeability of potential depositional sites than in older dolomitic equivalents.

A significant proportion of the global uranium resource is hosted in Palaeoproterozoic siliciclastic sequences proximal to unconformities in foreland basins in North America, Australia and western Africa: the so-called unconformity-associated uranium deposits (e.g. Solomon & Groves 1994; Ruzicka 1996). Their origin is linked to supercontinent assembly at *c*. 1.8–1.7 Ga, which generated thick terrestrial to marine sedimentary sequences in foreland basins that developed subsequently into intracratonic basins during supercontinent asssembly. These basins were mineralized about 100–200 Ma later by advecting basinal fluids through reduction by basement rocks below the unconformity. Protracted fluid flow was tectonically induced and generated several pulses on mineralization, including the first major uranium mineralization event (see summary by Kerrich *et al*. 2005).

It is noteworthy that the giant SEDEX Pb–Zn deposits of Northern Australia (Large *et al*. 2005) occur in equivalent tectonic settings and sedimentary basins to the giant unconformity-associated uranium deposits at Jabiluka, Ranger and Narbelek, and formed at approximately the same time. These SEDEX deposits are discussed below.

Sediment-hosted deposits of non-diagnostic or variable geodynamic setting

The stratiform to strata-bound sediment-hosted deposits with variable proportions of Pb, Zn and Cu, such as those of the Zambian Copperbelt and Kupferschiefer (e.g. Hitzman *et al*. 2005) and the so-called SEDEX deposits (e.g. Leach *et al*. 2005), are difficult to classify in terms of geodynamic setting at the time of their formation. Although there is general agreement that they formed in intracratonic rift basins during crustal extension, there is considerable controversy concerning their broader-scale tectonic setting and the driving force for hydrothermal fluid flow at the time of mineralization. For example, many of the deposits could be considered to form during far-field compression in originally extensional basins in far backarc settings related to convergent-margin geodynamic settings.

The hosting sequence of some important sediment-hosted stratabound copper deposits, such as those of the Zambian Copperbelt, almost certainly formed in an intracratonic rift setting (e.g. Tembo *et al*. 1999) although a passive margin setting has also been suggested (e.g. Binda 1995). Kerrich *et al*. (2005) related their occurrence to the initial dispersal of Rodinia at *c*. 800 Ma. Although there is general agreement for the Neoproterozoic Zambian Copperbelt that (1) the source of metals was underlying oxidized red beds, (2) the source of sulphur was evaporites in the hosting sequence and/or petroleum, and (3) mineralization was multi-stage (e.g. Hitzman *et al*. 2005), there is considerable debate concerning whether the economic deposits formed mainly during diagenesis (e.g. Selley *et al*. 2005) or during inversion of the intracratonic basins during later orogeny (e.g. McGowan *et al*. 2006). The Permian Kupferschiefer in Europe also appears to have been a large intracontinental basin floored in part by red beds, and containing evaporites and petroleum, with multi-stage copper and anomalous PGE–gold mineralization of debated timing (e.g. Hitzman *et al*. 2005).

SEDEX deposits (e.g. Lydon 1996; Leach *et al*. 2005) are stratiform to stratabound massive Zn–Pb ± Cu deposits that formed during sedimentation or early diagenesis from basinal brines circulating in host sedimentary successions. They illustrate well the problems of categorization of the geodynamic setting of some mineral deposits. The Proterozoic examples of Northern Australia (e.g. Large *et al*. 2005) appear to have formed in intracontinental failed rifts that were, however, linked to ocean basins (Leach *et al*. 2005). These giant Proterozoic deposits (e.g. Mt. Isa, McArthur River, Century) formed at *c*. 1650–1600 Ma, following shortly after the final assembly of Proto-Australia at *c*. 1780–1700 Ma (e.g. Betts *et al*. 2002), as part of the global supercontinent Columbia which was assembled via collisions between Laurentia, Baltica and Siberia at *c*. 1850–1700 Ma (e.g. Condie 2000). Groves *et al*. (2005*b*) argued that this was the first supercontinent assembly of major crustal fragments, providing a foundation for the extensive sedimentary rift basins in which the SEDEX deposits could form in response to episodic extension related to tectonism at the margins of the cratonic blocks. Reactivation of deep extensional faults, close to the sutures along which the old cratonic fragments were assembled, appears critical for the generation of SEDEX deposits in the rift basins. If tectonic models presented by Large *et al*. (2005) are correct, the Proterozoic SEDEX deposits formed in such rift basins during far backarc extension in a convergent margin setting and hence in a similar geodynamic setting to the Sn–W, intrusion-related gold and Carlin-type deposits described above.

Palaeozoic SEDEX deposits (e.g. Sullivan, Red Dog) occur in rifted continental margins, and hence could also be included in the category of deposits related to divergent margins. In terms of their hosting sedimentary basins and genesis, however, Palaeozoic SEDEX deposits appear broadly similar to their Proterozoic analogues. Their position on a late Devonian continental reconstruction (Lydon 1996) suggests that they are related in some way to the assembly of Pangaea, and may also owe their origin to distal convergent tectonics, as suggested for Proterozoic SEDEX deposits.

Broken Hill-type (BHT) deposits show similarities to SEDEX deposits (Leach *et al*. 2005) although they have much higher Ag and significantly higher Pb contents than the former (e.g. Walters 1998). In Australia, BHT deposits at Broken Hill and Cannington are broadly coeval with SEDEX deposits at Mt. Isa and McArthur River, but are hosted in quartzofeldspathic sedimentary sequences rather than sequences rich in reduced dolomitic siltstones and shales that host SEDEX deposits (Large *et al*. 2005). The occurrence of bimodal volcanic sequences together with the amphibolite to granulite metamorphic grades that characterize these deposits, in the absence of evidence for significant crustal thickening to produce these metamorphic conditions, suggest that more extreme crustal and lithospheric thinning was involved than in normal SEDEX basins. The isolation of the giant deposits in districts with only minor associated deposits, combined with their low S, but high P and REE contents, and high precious-metal (Ag) enrichment, are suggestive of an alkaline affinity in concert with the evidence for extreme extension of the basin. However, confirmatory evidence remains elusive.

In spite of 80 years of mining and research, the genesis of the copper orebody in the giant Pb–Zn–Cu deposit at Mt. Isa remains equally controversial (e.g Perkins 1990; Solomon & Groves 1994). The interdigitation of the Cu and Pb–Zn (± Ag) orebodies was originally interpreted as reflecting a biogenic control on the entire ore system. Structural, fluid and geochronological studies more recently have led to a change from a syngenetic chemical concept to that of an epigenetic, massive metasomatic replacement system developed during or just post-dating the peak of the Mesoproterozoic Isan Orogeny at *c*. 1500 Ma. In this respect, the Mt. Isa copper deposit is probably more akin to the class of orogenic gold and base-metal deposits discussed above.

The balance between formational and preservational processes

The temporal distribution of mineral deposits relates to the balance between formation under specific conditions in particular dynamic settings and the preservation of the deposit once formed. The latter depends on two main factors: the crustal depth at which the deposits formed and the age and nature of the SCLM underlying the crustal environment of deposit formation (e.g. Groves *et al*. 2005*b*). The former is clearly displayed in the temporal patterns of deposit types that formed close to the Earth's surface, such as porphyry Cu–Au–Mo and epithermal Au–Ag deposits, which are rare in terranes older than Mesozoic and Tertiary, respectively; placer gold deposits, which are rare beyond the Tertiary; and diamond deposits, which are most common in the Palaeozoic to Tertiary. However, whereas porphyry and epithermal deposits are exceptionally rare beyond the Mesozoic, the giant palaeoplacers of the Witwatersrand and Tarkwa were formed and preserved in the Archaean to Palaeoproterozoic and significant primary diamond deposits occur back to the Palaeoproterozoic

As discussed in some detail by Groves *et al*. (2005*b*) and Kerrich *et al*. (2005), such contrasting temporal patterns relate not only to the tectonic environment and depth of deposit formation but also to the age of SCLM beneath the mineral district at the time of formation or incorporation of the deposit into the crust. As a result of progressive cooling of the Earth, and decreasing mantle plume activity, thick buoyant Archaean SCLM gave way to somewhat thinner Palaeoproterozoic SCLM, and to much thinner, negatively buoyant SCLM in the Phanerozoic (e.g. Poudjom Djomani *et al*. 2001; Griffin *et al*. 2003). Archaean SCLM would therefore normally be buoyant relative to asthenosphere and it could not be delaminated by gravitational processes, but only by rifting and replacement by more fertile asthenosphere. Thus, mineral deposit types (e.g. PGE in layered intrusions, diamonds, Au palaeoplacers), that formed in or on Archaean cratons or even Palaeoproterozoic cratons, particularly in their centres, have high preservational potential. Even deposits that form close to craton margins (e.g. Ni–Cu sulphides, iron-oxide Cu–Au, SEDEX Pb–Zn) are likely to be preserved. Mineral deposit types that formed in the Archaean or Palaeoproterozoic during the final stages of orogenesis immediately prior to cratonization (e.g. orogenic Au), or were incorporated into orogenic belts at this stage (e.g. VMS), will also be preferentially preserved. However, deposits formed from the Mesoproterozoic onwards in or adjacent to orogenic belts have lower preservational potential because of the gravitationally unstable, negatively buoyant SCLM. Such deposits are less likely to be preserved in older belts because of progressive uplift and erosion, and to show classical preservational patterns as, for example, shown by porphyry Cu–Au–Mo deposits, which commonly occur in arcs that have exceptionally high uplift rates (over 0.5 km Ma^{-1}) as discussed by Garwin *et al*. (2005). Even deposit types that formed throughout geological time from the Mesoarchaean (*c*. 3.5–3.2 Ga) to the Quaternary (e.g. orogenic Au, VMS) have temporal patterns with a distinct lack of large deposits between about 1.6 and 0.6 Ga, at least in large part due to the inversion of buoyancy of SCLM over this period (e.g. Goldfarb *et al*. 2001; Groves *et al*. 2005*b*). This probably reflects the period during which mantle plume-influenced plate tectonics evolved to modern-style plate tectonics as plume activity waned.

Mineral deposits and the supercontinent cycle

As many, if not most mineral deposit types form in specific intracratonic, divergent margin or convergent margin geodynamic settings, the temporal distribution of groups of those deposit types should broadly reflect the supercontinent cycle (e.g. Rogers & Santosh 2004), which produced supercontinents at *c*. 2.7–2.2 Ga (Kenorland), *c*. 1.7–1.4 Ga (Columbia) and *c*. 1.0–0.6 Ga (Rodinia), and the latest, Pangaea, which broke up at *c*. 180 Ma (e.g. Condie 2004; see Fig. 1).

Figure 4 displays the grouping of deposit types discussed above within the framework of the supercontinent cycle. There is undoubted diachroneity in accretionary and collisional events during continent convergence and both failed and oceanic rifting during continent divergence. Within these constraints, the deposit groups ascribed to different geodynamic settings do have grossly different temporal patterns, with those ascribed to convergent or divergent margin settings broadly correlating with supercontinent assembly and dispersal events, respectively. Interestingly, the deposit types whose geodynamic setting are controversial correlate better with assembly (generally slightly later) rather than with dispersal events. Few deposits appear to form during periods of supercontinent stability, with most deposit types related to magmatism in intracratonic settings related to either late convergence, perhaps owing to shallower subduction affecting far backarc settings or mantle plume impingement during initial dispersal.

The temporal patterns of most deposit types are thus broadly compatible with the supercontinent cycle, and most deposits

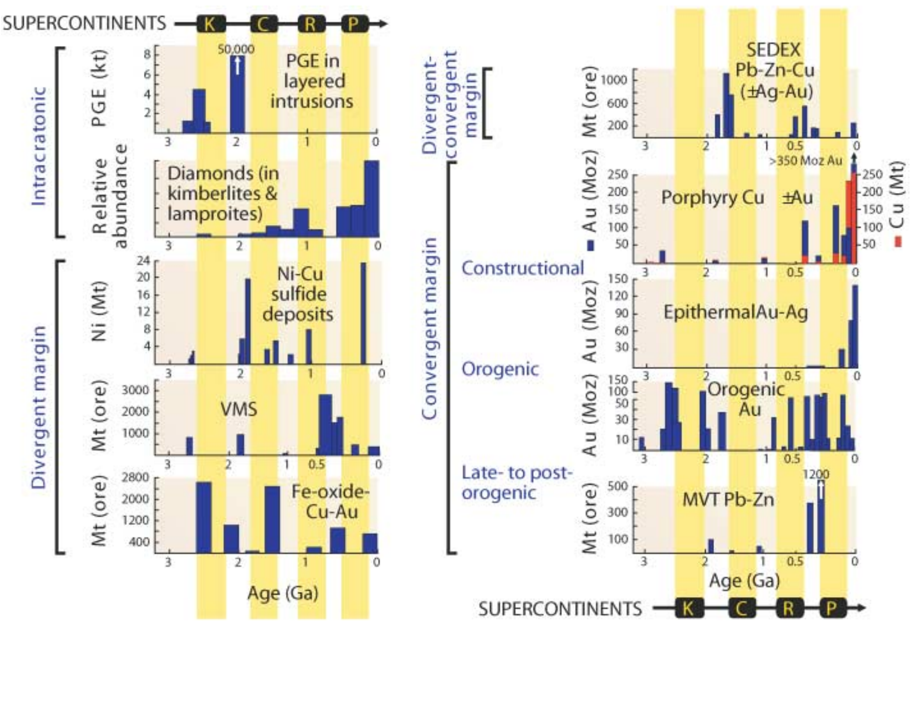

Fig. 4. Diagram showing the temporal distribution of deposit types ascribed to broad geodynamic settings in terms of the supercontinent cycle, as summarized from Figure 1. Temporal distributions are from Groves *et al*. (2005*b*) and references therein. K, Kenorland; C, Columbia; R, Rodinia; P. Pangaea.

form (e.g. iron-oxide Cu–Au, Ni–Cu sulphide, porphyry Cu–Au–Mo, epithermal Au–Ag, orogenic Au, SEDEX Pb–Zn), or are incorporated into the crust (VMS, podiform Co), within a few hundred kilometres of craton margins. Thus, well-dated mineral deposits can provide an important constraint on the veracity of supercontinent reconstructions because they should lie adjacent to proposed sutures or on the margins of external oceans in such reconstructions. Excellent examples are provided for SEDEX Pb–Zn, iron-oxide Cu–Au and anorthosite-associated Fe–Ti–V deposits in a reconstruction of Columbia by Kerrich *et al*. (2005; fig. 8) and for Palaeozoic orogenic gold deposits in a reconstruction of Gondwana and Laurentia by Goldfarb *et al*. (2005; fig. 5). Conversely, accurate supercontinent reconstructions can indicate the potential for as yet undiscovered mineral provinces in the extensions of metallogenic provinces subsequently dispersed during supercontinent break-up, and are hence important aids in first-order conceptual exploration targeting.

Synthesis: geodynamic importance of mineral deposits

Economic mineral deposits are exceptional concentrations of metals that are at least one to five orders of magnitude enriched over background terrestrial abundances (Skinner 1989). Their formation therefore requires an exceptional conjunction of processes to concentrate the metals, in magmatic, magmatic–hydrothermal or hydrothermal systems that are powered by exceptional thermal-energy and/or tectonic-stress drivers. These drivers are essentially lithospheric to crustal-scale energy generated by convergent to extensional forces related to the cyclic assembly and dispersal of continental lithosphere. The responses to these drivers vary from the generation of belts of metal-enriched magmas, through development of orogen-wide fluxes of heat and advecting fluid, to the initiation of basinal fluid flow in distal basins. The mineral deposit types that form from these variable high-energy processes occupy specific geodynamic niches, and hence can be a critical indicator of these niches in ancient terranes. As such, they should be used, together with other critical parameters such as magma petrogenesis, basin fill and architecture, and metamorphic and deformational style, in reconstruction of the tectonic environments and evolution of ancient terranes. Examples of such integration include that by Goldfarb *et al*. (1997) for the Cordilleran tectonics and metallogeny of Alaska, and by Bierlein *et al*. (2002) for the metallogeny of the Phanerozoic Lachlan Orogen of eastern Australia.

The temporal distribution of the mineral deposit types also assists in understanding of the progressive changes in tectonic processes related to a cooling Earth. For example, the excellent preservation of giant orogenic gold, VMS and palaeoplacer provinces in Archaean and Palaeoproterozoic terranes (e.g. Goldfarb *et al*. 2001), yet their essential absence in Mesoproterozoic terranes, which preserve an almost unique record of giant intracratonic SEDEX and BHT deposits and anorthorite-associated Fe–Ti–V deposits, points to a change in tectonic process at this time. On the basis of this evidence, in combination with evidence from crustal growth rates (e.g. Condie 2000), the temporal distribution of mantle plume events (e.g. Abbott & Isley 2002), and progressive change in density and thickness of SCLM (e.g. Griffin *et al*. 2003), Groves *et al*. (2005*a*, *b*) and Kerrich *et al*. (2005), among others, have argued that the Mesoproterozoic represents the transition from mantle-plume-influenced (or dominated) plate tectonics to modern-style plate tectonics. As a result of the changing buoyancy of the SCLM, formational and preservational processes were linked in the Archaean–Palaeoproterozoic Earth but decoupled thereafter (e.g. Groves *et al*. 2005*a*).

Mineral deposits also provide important constraints on the debate concerning whether the atmosphere–hydrosphere was rapidly oxidized (e.g. Ohmoto *et al*. 2001) or more progressively oxidized (e.g. Holland 1999). The presence of detrital pyrite and uraninite in the Neoarchaean Witwatersrand conglomerates and the greatest development of BIF between *c*. 2.3 and 2.4 Ga have, in particular, been used to support the latter hypothesis. It is also noteworthy that sediment-hosted mineral deposit types of metals that have multiple oxidation states (e.g. Fe, Mn, U) vary throughout time, with specific deposit types having restricted temporal distributions (Groves *et al*. 2005*b*, fig. 9). This contrasts markedly with the distributions of deposit styles largely unaffected by redox state, in which similar styles appear throughout Earth history. The redox-related mineral deposits thus support a model of progressive atmospheric and hydrospheric evolution from the Precambrian to Phanerozoic. However, episodic changes in redox state of the oceans as a result of mantle plume impingement also produced mineral deposits more characteristic of the early Precambrian at specific intervals in the Phanerozoic (e.g. Titley 1993).

The conclusion is that mineral deposit types are generally sensitive indicators of geodynamic environments and other environmental factors and should be included in any holistic tectonic analysis of ancient terranes.

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