Earth-Science Reviews 245 (2023) 104551

Contents lists available at ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev

Convergent margin metallogenic cycles: A window to secular changes in Earth's tectonic evolution

David L. Huston [a,*], Michael P. Doublier [a], Bruce Eglington [b], Sally Pehrsson [c], Steve Piercey [d], Patrick Mercier-Langevin [e]

[a] Geoscience Australia, GPO Box 378, Canberra, ACT 2601, Australia
[b] Geological Sciences, University of Saskatchewan, 114 Science Place, Saskatoon, SK S7N 5E2, Canada
[c] Geological Survey of Canada, 601 Booth St, Ottawa, ON K1A 0E8, Canada
[d] Department of Earth Sciences, Memorial University of Newfoundland, Room 4063, Alexander Murray Building, 9 Arctic Avenue, St. John's, NL A1B 3X5, Canada
[e] Geological Survey of Canada, 490 rue de la Couronne, Québec (Québec) G1K 9A9, Canada

ARTICLE INFO

Keywords:
Convergent margins
Metallogenesis
Tectonic evolution
Convergent margin metallogenic cycle
Secular evolution

ABSTRACT

Compilation of age and endowment data for deposits that commonly occur on convergent margins (volcanic-hosted massive sulfide, porphyry copper, orogenic gold, granite-related rare metal and pegmatite deposits: over 1000 deposits from 21 mineral provinces) indicate that metallogenic patterns have changed over time. For much of Earth's history, metallogenesis along convergent margins is marked by a relatively systematic temporal progression of deposits succeeding one-another, which we refer to as the convergent margin metallogenic cycle (CMMC): volcanic-hosted massive sulfide (VHMS) and/or calc-alkalic porphyry copper → orogenic gold → alkalic porphyry copper, granite-related rare metals and/or pegmatite. Typically individual CMMCs last for 60–160 Myr, and the progression appears to be related to the convergent margin tectonic cycle. Prior to ca. 3000 Ma, however, CMMCs are not recognized. Rather, these old mineral provinces are characterized by long metallogenic histories (370–500 Myr) with no discernible pattern of deposit types. The Mesoarchean to Paleoproterozoic is characterized mostly by mineral provinces with relatively short (60–155 Myr) metallogenic histories and a single CMMC. Between 1950 Ma and 1700 Ma some convergent margin mineral provinces (e.g. Trans-Hudson and Svecofennian) are characterized by multiple CMMCs, with metallogenic histories that last up to 160 Myr. Between 1250 Ma and 750 Ma, longer-lived yet relatively poorly-constrained metallogenic histories (up to 320 Myr) appear, and after ca. 750 Ma, convergent margins are mostly long-lived (290–450 Myr) and are characterized by multiple CMMCs with complex metallogenic histories.

These four periods in the metallogenesis of convergent margins appear to reflect secular changes in tectonic processes. Prior to ca. 3200–3000 Ma, stagnant lid tectonics, which did not involve modern-style subduction, dominated, resulting in non-cyclical mineralization. After the initiation of some early form of subduction between ca. 3200 Ma and ca. 3000 Ma, the metallogenic style changed. The dominance of provinces from 3000 to 1700 Ma with a single CMMC, and a relatively short metallogenic history suggests that convergent margins were shorter-lived. This is consistent with models of shallow-break-off subduction whereby the subducting slab breaks off at shallow levels due to lower plate strength beginning in the later Archean. We suggest that between ca. 3000 and ca. 1700 Ma a propensity for slab break-off could shut down individual subduction systems and produce short-lived metallogenic histories with a single CMMC. The change to longer metallogenic histories and dominant multiple CMMCs begins with Rodinia assembly: the length and complexity of metallogenesis systematically increases thereafter. The lengthening of convergent margin metallogenesis resulted from more stable convergence as continuous ridge push and the stronger density contrasts of the subducting slab causing re-initiation of subduction outboard rather than complete termination of subduction when the convergent margin was perturbed. As consequence of these driving factors, the metallogenic history of young convergent margins involves multiple CMMCs and/or complex temporal interleaving of deposit types.

* Corresponding author.
E-mail address: david.huston@ga.gov.au (D.L. Huston).

https://doi.org/10.1016/j.earscirev.2023.104551
Received 23 June 2023; Received in revised form 17 August 2023; Accepted 29 August 2023
Available online 13 September 2023

1. Introduction

Shortly after the acceptance of the plate tectonics paradigm in the mid- to late-1960s (Wilson, 1966; Dewey and Burke, 1974), formation of several classes of mineral deposits, including porphyry copper (Sillitoe, 1972) and volcanic-hosted massive sulfide (VHMS: Hutchinson, 1973) deposits, were linked to the evolution of convergent margins. Sawkins (1972, 1990) presented an overview of the links between tectonics and metallogenesis and suggested that many classes of mineral deposits formed in specific tectonic settings, an inference confirmed by specific tectonic associations of currently forming and geologically young deposits. For example, Mesozoic and Cenozoic porphyry copper deposits occur along convergent margins generally associated with volcanic arcs (Sillitoe, 1972; Richards, 2001; Groves et al., 2022), and black smoker deposits, the modern equivalent of VHMS deposits, occur along mid-oceanic ridges or convergent margins in back-arc settings or rifted arcs

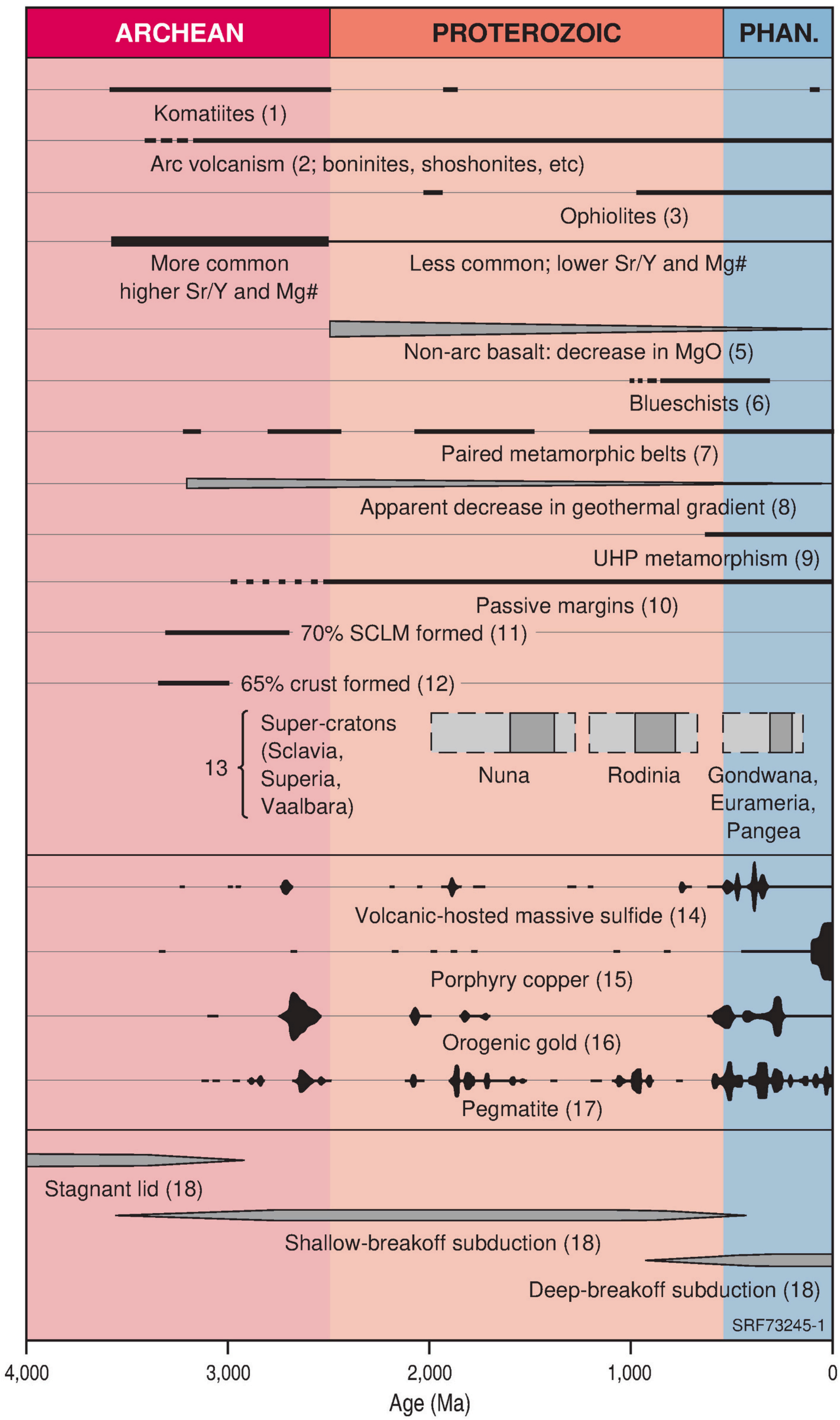

Fig. 1. Overview of secular trends in the geological record, including (1) the restriction of most komatiites prior to ca. 2500 Ma (Arndt et al., 2008); (2) the beginning of arc magmatism at ca. 3100 Ma (Smithies et al., 2004; Condie and Kröner, 2008); (3) the restriction of most ophiolites to after ca. 1000 (Stern, 2007); (4) changes in the abundance and compositon of tonalite-trondjemite-granodiorite suite magmatic rocks (Smithies and Champion, 2000); (5) the decrease in MgO of non-arc basalt (Herzberg et al., 2010); (6) the restriction of blueschist metamorphism to after ca. 700 Ma (Stern, 2007); (7) the temporal distribution of paired metamorphic belts (Brown, 2014); (8) the apparent decrease in geothermal gradients (Brown, 2014); (9) the restriction of ultra-high pressure (UHP) metamorphism to after ca. 700 Ma (Maruyama and Liou, 1998); (10) the development of passive margins after ca. 3000 Ma (Bradley, 2008); (11) the formation of sub-continental lithospheric mantle (SCLM) (Griffin et al., 2014); (12)) the formation of continental crust (Dhuime et al., 2012); (13) the formation and break-up of supercratons and supercontinents; (14) the temporal distribution of volcanic-hosted massive sulfide deposit (Huston et al., 2010); (15) the temporal distribution of porphyry copper deposits (Singer et al., 2008); (16) the distribution of orogenic gold deposits (Goldfarb et al., 2001); (17) the distribution of pegmatites (Tkachev, 2011); and (18) inferred changes in tectonic style (see text). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Hannington et al., 2005).

More recent work on Phanerozoic systems utilized the increasing amount of robust geochronological constraints on deposit formation, for example in the Tasman Element of Eastern Australia, that have been used to suggest that the formation of particular deposit types reflects different evolutionary stages of modern convergent margins (e.g. Collins and Richards, 2008; Huston et al., 2016). During subduction (i.e. stage 1), calc-alkalic magmatism is linked to the formation of calc-alkalic porphyry copper-gold deposits within the arc, whereas back-arc extension favors VHMS deposits. Subduction is then followed by orogenesis (stage 2), which reflects perturbation of subduction related to changes in the dip of subduction, accretion, the response of exotic blocks/seamounts/ridges arriving at the active margin, or continent collision. The development of structural architecture, along with metamorphism and deformation during this stage facilitate the formation of orogenic gold (sensu stricto: Groves et al., 2003) and other syn-orogenic deposit types. Lastly, post-orogenic extension (stage 3) favors the formation of rare-metal pegmatites, granite related W-Sn-Mo-Au deposits and alkalic porphyry copper-gold deposits. We refer to this systematic sequence of deposit formation as the **convergent margin metallogenic cycle** (CMMC).

This cyclicity implies that tectonic evolution and metallogenesis are inherently linked, and can be holistically viewed as a convergent margin tectono-metallogenic system (Huston et al., 2016). From an economic point of view, appreciation of this linkage is important, as it helps to define the exploration search space for particular deposit types within a province.

Convergent margins are a crucial component within the current tectonic mode operating on Earth, modern plate tectonics. In contemporary Earth convergent margins facilitate through subduction, the recycling of old, negatively buoyant and cold oceanic lithosphere back into the asthenosphere, a process that is largely driven by the slab pull of a (coherent) down-going oceanic plate (Conrad and Lithgow-Bertelloni, 2002). This results in downward dragging of isotherms and the overall cold subduction environment we observe in modern subductions zones (e.g. Gerya et al., 2002) as expressed by low geothermal gradients in lower plate settings (e.g. Penniston-Dorland et al., 2015; Brown and Johnson, 2018).

Secular changes within the geological record (Fig. 1), as well as insights from numerical modelling (e.g. Gerya, 2014, and references therein) suggest that the tectonic mode of Earth has likely changed over time. The most controversial debate in this context is the question of the timing of the onset of plate tectonics, with proposed times of initiation ranging from the Hadean to the Neoproterozoic (e.g. Palin et al., 2020 and references therein). As this question is intimately linked to the (first) development of (stable?) convergent margins, we present here a new avenue into this problem by investigating what constraints the metallogenic record may provide for the tectonic evolution of convergent margin systems. The aims of this contribution are to document convergent margin metallogenesis through time at global and province scales, and then assess if these data provide new insights into the secular tectonic evolution of Earth.

Building upon previous compilations (e.g. Myer, 1981; Lambert and Groves, 1981), our approach has now become possible because the amount of geochronological constraints on deposit formation has increased to a level sufficient to allow for global assessments at the metallogenic province level. To accomplish this we document the ages of deposits typically associated with young convergent margins – porphyry copper, VHMS, orogenic gold and granite-related rare metal (pegmatite and granite-related Sn-W-Mo deposits) – from metallogenic provinces of different ages from around the globe. We have also included some komatiite-associated and intrusion-hosted nickel sulfide deposits where they are spatially and temporally associated with the aforementioned convergent-margin-related deposits. The provinces were chosen as they are among the best mineralized and/or geologically the best understood, with good quality geochronological constraints on deposit formation. We first explore our dataset at the global scale, investigating the distribution patterns in regards to temporal trends, including the formation of supercontinents, but also the effect of preservation. We then investigate the temporal distribution of deposit formation within individual metallogenic provinces, emphasising whether and how far the CMMC can be tracked back through time. Finally, we demonstrate systematic changes in the metallogenic pattern that provide new constraints on the tectonic evolution of Earth, and the onset of sustainable convergent margins.

1.1. Secular changes in tectonic processes

Accumulating evidence suggests that uniformitarianism does not apply to tectonic processes, and that tectonic processes have changed significantly through Earth's history. The underlying driver to these changes is the progressive cooling of Earth's interior, related to a decrease in radioactive heat production due to the decay of radioactive elements (Van Schmus, 1995). Multiple lines of evidence support this inference (e.g. occurance of komatiites; Fig. 1). During the Hadean, Earth was probably hot enough to form a magma ocean (Abe, 1997; Hosono et al., 2019), and most thermal evolution models suggest that the mantle was 150–250 °C hotter than at present during the Meso-Nearchean (3200–2500 Ma: Abbott et al., 1994; Herzberg et al., 2010; van Hunen and Moyen, 2012). In response to this secular cooling, the mechanism of heat loss and, therefore, geodynamic processes changed (Stern, 2007; van Hunen and van der Berg, 2008), and these changes are mirrored by secular trends in the geological record (Fig. 1).

Many of these changes occurred early in Earth's history, including the transition at ca. 4400 Ma from a magma ocean to an unstable "hot" stagnant-lid (Brown, 2014; Johnson et al., 2014; O'Neill et al., 2016; Bédard, 2018) or "plutonic squishy lid" tectonic mode (Rozel et al., 2017) with intense plume magmatism and possible episodic mantle overturn events (Griffin et al., 2014). A (non-plutonic) squishy lid mode, where lithosphere movement is driven by mantle convection, can also be viable (Lenardic, 2018). The stagnant- or squishy-lid mode is thought to have transitioned into some early form of plate tectonics under an active lid mode, i.e. a regime where subduction is driven by the negative bouyancy of the lithosphere (Lenardic, 2018), by ca. 3200–3000 Ma (Fig. 1; e.g. Percival et al., 2006; Pease et al., 2008; Cawood et al., 2018, 2022).

On modern Earth, plate tectonics as an active lid mode is driven by negative buoyancy of oceanic lithosphere relative to ambient mantle due to cooling and stiffening of oceanic mantle lithosphere (Forsyth and Uyeda, 1975; Conrad and Lithgow-Bertelloni, 2002) as it moves away from oceanic ridges. This negative buoyancy causes "slab pull" and recycles oceanic lithosphere back into the mantle via subduction (e.g. Lallemand et al., 2005).

Higher Archean mantle temperatures may have produced profound differences in parameters controlling convergent margin and subduction zone dynamics, including thicker, more buoyant oceanic crust and mantle and an increase in the age when oceanic lithosphere becomes neutrally buoyant due to cooling (20–30 Myr presently) (Davies, 1992; Turcotte and Schubert, 2002; Van Thienen et al., 2004; Korenaga, 2006; van Hunen and van der Berg, 2008; van Hunen and Moyen, 2012). Thermomechanical models inferred three tectonic regimes controlled by mantle temperature (Sizova et al., 2010). The earliest "non-subduction" regime, where horizontal movements are accommodated by internal strain, transitions into a "pre-subduction" regime, where convergence causes shallow underthrusting without formation of a mantle wedge, when mantle temperatures decreased to 200–250 °C above modern temperatures. At mantle temperatures 175–160 °C hotter than modern temperatures transition to a "modern subduction" regime, where one-sided subduction was possible, occurs. It is at this transition that features characteristic of subduction, such as boninites and shoshonites (Dostal and Mueller, 1992; Wyman et al., 1999; Smithies et al., 2004), Barrovian metamorphism (Piette-Lauziére et al., 2019), and seawater signatures of carbon and sulfur in diamonds, kimberlites and granites, respectively, appeared (Weiss et al., 2015; Caruso et al., 2022).

The temporal distribution of blueschists and high to ultra-high pressure (HP-UHP) metamorphic terranes have also been used to infer the timing of the onset of subduction. Stern (2007) found that global blueschist terranes are restricted to ages younger than ca. 700 Ma, and Maruyama and Liou (1998) found that ultra-high-pressure metamorphic rocks are restricted to ages younger than ca. 540 Ma. The temporal distributions of these rocks, which are interpreted to be indicative of modern-style, cold subduction, have been used to argue that this style of

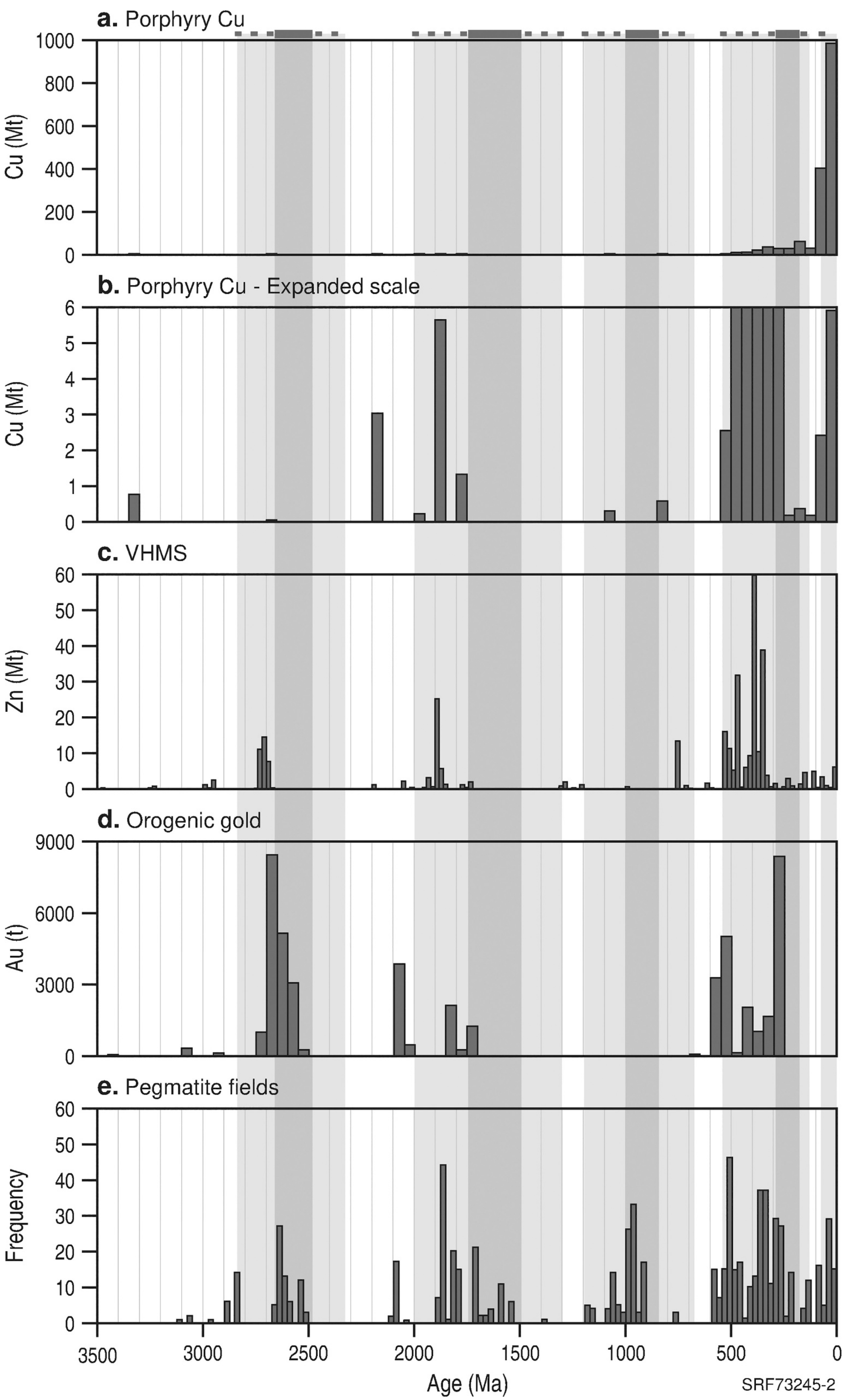

Fig. 2. Secular variations in the abundance of (A) and (B) porphyry copper deposits (B expands A; constructed using updated data from Singer et al., 2008), (C) volcanic-hosted massive sulfide deposits (constructed using data of Huston et al., 2022), (D) orogenic gold deposits (constructed using updated data of Goldfarb et al., 2001), and (E) pegmatite deposits (constructed using data of Tkachev, 2011). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

tectonics initiated in the latest Neoproterozoic. More recent compilations, however, indicate complexities. Although Palin and Santosh (2021) confirmed the Stern (2007) distribution of blueschists, they found that HP-UHP rocks are recognized back to the Mesoarchean, although these rocks are by far most abundant in the latest Neoproterozoic and Phanerozoic.

There are at least four ways to interpret these patterns: (1) initiation of subduction during the Neoproterozoic (e.g. Stern, 2007), (2) a progressive change in subduction style from the Mesoarchean to the Mesoproterozoic with a step change to modern-style cold subduction in the Neoproterozoic (e.g. Palin and Santosh, 2021), (3) subtle changes in metamorphic processes (e.g. a hotter mantle and lithosphere would favour formation of greenschists over blueschists earlier in Earth's history), irrespective of subduction style, or (4) a bias by post-formational destruction (e.g. re-equilibration of blueschists to higher temperature metamorphic assemblages, or erosion). With present data, it is not possible to resolve these different mechanisms; it may be that more than one of these mechanisms may be important, and different datasets are required for resolution.

In contrast to modern subduction systems, which invoke subduction of the down-going slab deep into the mantle, thermo-mechanical models suggest that Archean subduction may have been characterized by shallow slab breakoff, in which slab-weakness causes the slab to break-off or drip-off at a relatively shallow depth in the mantle. This mechanism is thought to effectively remove slab pull, leading to shorter-lived, episodic subduction ("proto-subduction": van Hunen and van der Berg, 2008; Moyen and van Hunen, 2012; van Hunen and Moyen, 2012; Fisher and Gerya, 2016). Alternatively, the thermal conditions might have favoured processes such as subcretion (Bédard et al., 2013; Bédard, 2018) that also would have been short-lived.

Conceptually, shallow slab breakoff subduction may have been active throughout much of the Proterozoic (e.g. van Hunen and Allen, 2011), although the rock record does not distinguish such processes (see above). Thermo-mechanical modelling by Sizova et al. (2014) suggested shallow slab breakoff subduction occurs until ambient upper mantle cools to temperatures of 80–100 °C above modern conditions (corresponding to the Neoproterozoic), after which slab coherence is maintained and deep "cold" subduction can be sustained.

As an input into the discussion on the evolution of tectonic style through time, we present a new dataset on the metallogenesis of convergent margins based on the assumption that mineral deposits formed along these margins reflect tectonic processes operating at the time of mineralization. This dataset is completely independent of other datasets and provides a new perspective on controversies regarding the secular evolution of convergent margins.

2. Temporal variations in the global distribution of deposits

Although it has been known for several decades that the distribution of many deposit types have changed through time (Laznicka, 1972; Myer, 1981; Lambert and Groves, 1981), as the number of well dated mineral deposits has grown, these distributions have been refined. Fig. 2, which is based on updated compilations from Singer et al. (2008), Huston et al. (2022), Goldfarb et al. (2001) and Tkachev (2011), shows the distribution of porphyry copper (Figs. 2A-B), VHMS (Fig. 2C), orogenic gold (Fig. 2D) and pegmatite (Fig. 2E) deposits through time. These distribution patterns are controlled by a number of factors, including, most importantly, formation rates, but also preservation, burial and unroofing rates.

2.1. The effects of preservation

As highlighted by previous workers (Groves and Bierlein, 2007), compilations such as those presented in Fig. 2 are inherently biased as they can only show preserved, accessible deposits. A range of tectonic processes influence both which deposits are preferentially removed from the geological record and which preferentially remain deeply buried (Kesler and Wilkinson, 2006; Cawood and Hawkesworth, 2013).

Surficial weathering and erosion, although most prevalent during orogenesis, also occur during stable periods in tectonic cycles and preferentially remove deposits formed at high levels in the crust. These processes most strongly influence the temporal distribution of porphyry copper and epithermal deposits (Kesler and Wilkinson, 2006) relative to other deposit classes (Goldfarb et al., 2001; Franklin et al., 2005; Huston et al., 2010; Tkachev, 2011). Preserved porphyry copper deposits (Fig. 2A) are almost exclusively a Phanerozoic phenomenon, with the vast majority having Mesozoic and Cenozoic ages.

The highly restricted temporal distribution of porphyry copper deposits is the result of the tectonic environment in which they form, which facilitated both their formation and destruction. Most Mesozoic and Cenozoic porphyry copper deposits formed along volcanic arcs (Sillitoe, 1972), highly elevated topographic features that are prone to erosion. As a consequence, porphyry copper deposits have a lower likelihood of preservation in older rocks, and their observed distribution does not accurately reflect their formation history. The true record of formation is most likely reflected by limited data for Precambrian deposits, which suggests a scattering of small deposits back through most of geological time, with indistinct peaks associated with supercontinent assembly, particularly Nuna (Fig. 2B). Porphyry copper deposit formation began as early as ca. 3320 Ma with the oldest known deposit being Spinifex Ridge in the Pilbara Craton, Western Australia (Cummins and Cairns, 2017).

The question of preservation is also relevant for VHMS deposits (Fig. 2C), which becomes obvious when considering the different tectonic settings these deposits form in. Black smokers – the modern analogues to VHMS deposits – commonly form along mid-oceanic ridges (Hannington et al., 2005). Little true oceanic crust is preserved older than the Mesozoic (Granot, 2016): oceanic crust is generally subducted and lost from the geological record, and most ophiolites, which were originally considered to be obducted oceanic crust, are now thought to represent crust formed in a back-arc or other extensional settings. Hence, the black smokers currently forming on mid-oceanic ridges (Hannington et al., 2005) are very unlikely to pass into the geological record.

This contrasts with back-arc basins and rifted arcs, which also host black smoker deposits (Hannington et al., 2005) and are topographically depressed features that are likely to be buried and, therefore, are less susceptible to subsequent erosion. These basins are also likely to be accreted onto convergent margins. Deposits formed in this environment, therefore, are much more likely to be preserved in the geological record. If the deposits are not rapidly covered, seafloor oxidation can destroy the deposits (Edwards et al., 2003), and if the deposits are not rapidly accreted or obducted onto continental crust, they can also be lost through subduction (Cawood and Hawkesworth, 2013). Hence, the observed temporal distribution most likely reflects the distribution of peri-continental deposits and does not include deposits formed on mid-oceanic rifts or those formed above oceanic subduction zones remote from continental crust. Overall, the distribution of preserved VHMS deposits suggests a close association with supercontinent assembly, although there is an apparent lack of deposits associated with Rodinia assembly (Huston et al., 2010).

2.2. The effects of burial and unroofing

The observed distribution of some deposits, however, may be influenced by the original depth these deposits formed at and the possibility that they have not yet been unroofed and exposed at or near the surface. Both orogenic gold (1.0–5.0 kbar: Groves, 1993) and pegmatite deposits (2.0–7.5 kbar: Černý and Ercit, 2005) form at deeper crustal levels than porphyry copper and VHMS deposits but also over a larger range of crustal depths. Hence, the observed distribution of these two deposit classes is dependent upon the extent of unroofing of deeper crustal levels. Although this effect is difficult to assess, the distribution patterns of these deposit classes are largely consistent (except during Rodinia assembly), and it is likely that the observed secular temporal distribution patterns are reflective of the original formation patterns.

2.3. Periodicity in the deposit record

Recognising potential biases from both preservation and burial, the patterns for VHMS, orogenic gold and pegmatite deposits have striking similarities. With the exception of Rodinia, all three deposit classes peak during periods of supercraton/supercontinent assembly. Rodinia assembly, however, is characterized only by a peak in the pegmatite distribution, suggesting that Rodinia assembly somehow differed from the assembly of the other major super continents.

2.3.1. Secular progression of deposit classes

In addition to the association of VHMS, orogenic gold and pegmatite deposits with supercraton/continent assembly, there also appears to be a progression of deposit types during periods of assembly (dark gray areas in Fig. 2). For example between 2750 Ma and 2500 Ma, there is a progression from VHMS (2750–2700 Ma) through orogenic gold (2700–2550 Ma) to pegmatite (2650–2500 Ma) deposits. Although not as clear cut, similar patterns are present from ca. 1900 Ma to ca. 1700 Ma, when Nuna was being assembled, and from ca. 400 Ma to ca. 200 Ma during final Pangea assembly: Fig. 2). However, these patterns are not straightforward. An examination of the age trends of these deposits on the scale of individual provinces is required to robustly demonstrate a progression in deposit types with timing during convergent margin activity.

3. Methods and approach

We have compiled the ages and, where possible, metal endowment based on production and JORC and NI43–101 resources, of mineral deposits for a large range of metallogenic provinces, focussing on deposits types mostly formed on convergent margins. All age data presented in our compilation have undergone a rigourous quality assessment, where only ages that provide direct constraints on a particular deposit are included. We have not included any form of inferred ages based on relationships outside the deposit, for example by extrapolating ages based on regional correlations. We have also been quite careful to select robust geochronological methods, avoiding geochronometers that are succeptible to resetting. These data are presented in Table E1, and summaries for each province are provided below. Table E1 also provides explanatory notes and references for the compiled deposits. Fig. 3 synthesizes the distribution of deposit types through time for all provinces considered. Fig. 4 illustrates the global distribution of the deposits considered. Appendix E1 describes the geological evolution and metallogenesis of the mineral provinces considered in this study.

We have collected data for seven general groups of deposits: (1) calc-alkline porphyry copper, (2) volcanic-hosted massive sulfide, (3) komatiite-related and intrusion-hosted nickel, (4) orogenic gold, (5) alkalic porphyry copper, (6) granite-related rare metal, and (7) pegmatite deposits. The granite-related rare metal deposits include a reasonable diverse group of deposit types, including porphyry molybdenum and skarn and carbonate-replacement Sn—W deposits, among others.

In young (Phanerozoic) metallogenic provinces, these seven deposit types form generally, but not exclusively, along convergent margins. For example, as discussed above, VHMS deposits can form both on convergent margins and divergent settings, although those formed along divergent mid-oceanic ridges are generally lost from the geologic record as they are subducted. In addition, it is possible that VHMS or similar deposits can form in other enrivonments that are likely to be preserved. For example, the Mount Read Volcanics in Tasmania, which host the Rosebery and Hellyer deposits, formed in a post-collisional environment (Crawford and Berry, 1992), and Stern et al. (2021) infer that some Jurassic deposits in Iran may have formed in an intracratonic rift. These settings, however, are unusual and not typical for ancient VHMS deposits in general, and we have compiled data for VHMS deposits and used the data in our analysis.

Although many (most) orthomagmatic Ni-Cu-PGE deposits form as a consequence of mantle plume activity (Begg et al., 2010), we have included some of these deposits, particularly komatiite-associated and related intrusion-related Ni-Cu-PGE deposits as in several provinces (Pilbara, Eastern Goldfields, Abitite-Wawa, Scecofennian, Trans-Hudson, Pine Creek-Lamboo and Tasmania) these deposit types form between VHMS and orogenic gold deposits in the same province. **This is not to imply that orthomagmatic deposits such as Sudbury, Bushveld and others formed in a convergent tectonic environment.**

4. Results and discussion – metallogenic trends

Although the global distributions of porphyry copper, VHMS, orogenic gold and pegmatite deposits (Fig. 2) highlight the relationship between supercontinent formation and metallogenesis, they also hint at a sequence of deposit formation consistent with CMMC (i.e. the sequence VHMS, orogenic gold, pegmatites) associated with the assembly of most supercratons and supercontinents. Metallogenic histories at the province level yield complementary insights which are crucial to understand tectonic processes. The metallogenic histories of all provinces discussed above are synthesized in Fig. 3. Although not part of the metallogenic inventory of modern convergent margins, KANS and intrusion-related Ni-Cu-PGE deposits are also included because the formation of these deposits coincides in space and time with other deposits that form along convergent margins. Even though we do not understand the reason behind this coincidence, this observation is consistent in our data set. In the discussion below, we first describe general trends emerging from province level metallogenic data, then explore the implications of our dataset, focussing on the distribution and characteristics of convergent margin metallogenic provinces through time, and finally consider implications of the results to secular tectonic processes, concentrating on subduction dynamics.

4.1. Diversity of deposits types

Most convergent margin metallogenic provinces of similar age have a similar assemblage of ore deposit types, which may be taken to suggest commonality of processes that vary through time. Exceptions to this observation may at least in some cases relate to the fact that a particular type of deposit hasn't been discovered yet, does not have reliable age constraints or has not been preserved. Moreover, the diversity in deposit types changes with time. Although Eo- to Mesoarchean provinces have a wide range of deposit types, Meso- to Neoarchean Provinces are more restricted. These latter provinces usually contain VHMS, orthomagmatic Ni—Cu deposits, orogenic gold, and rare metal pegmatite deposits; other deposit types are uncommon or not present. Provinces become more diverse from the late Paleoproterozoic onwards, when calc-alkalic porphyry copper deposits become more common. The Phanerozoic has the most diverse deposit assemblages, with some types of deposits, such as alkalic porphyry copper deposits, mostly known from this time interval.

Although some of these trends may be partly explained by the preservation potential of particular deposit types, other trends more likely reflect true changes in deposit formation through time. For example, non-pegmatite-related granite-related W-Sn-Mo-Au deposits are rare in the Archean, but are often present in younger provinces, and alkalic porphyry copper deposits are only known from Phanerozoic provinces, despite having a possibly higher preservation potential than calc-alkalic porphyry copper deposits.

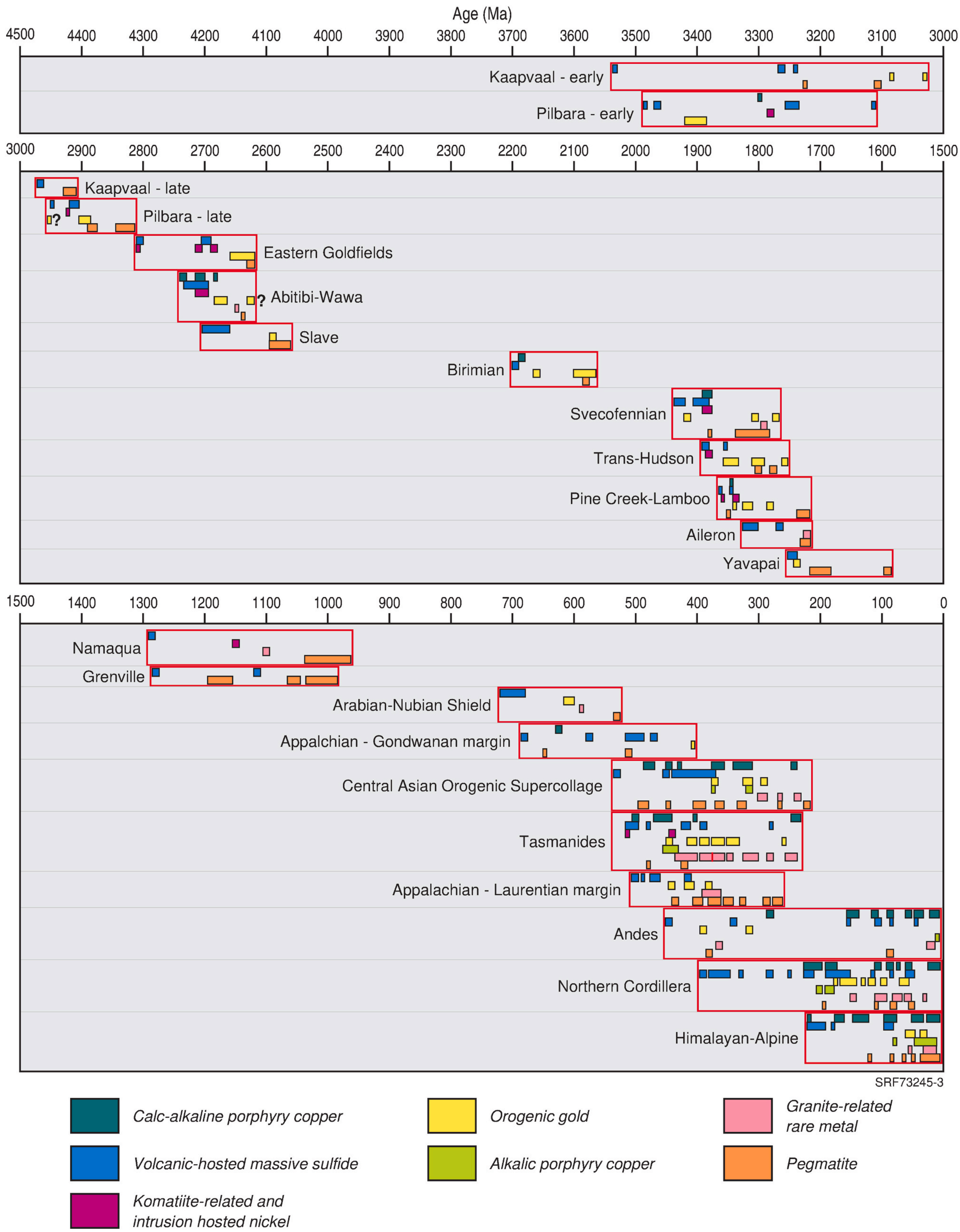

Fig. 3. Secular progression of convergent-margin deposits for selected mineral provinces (constructed using data in Table E1).

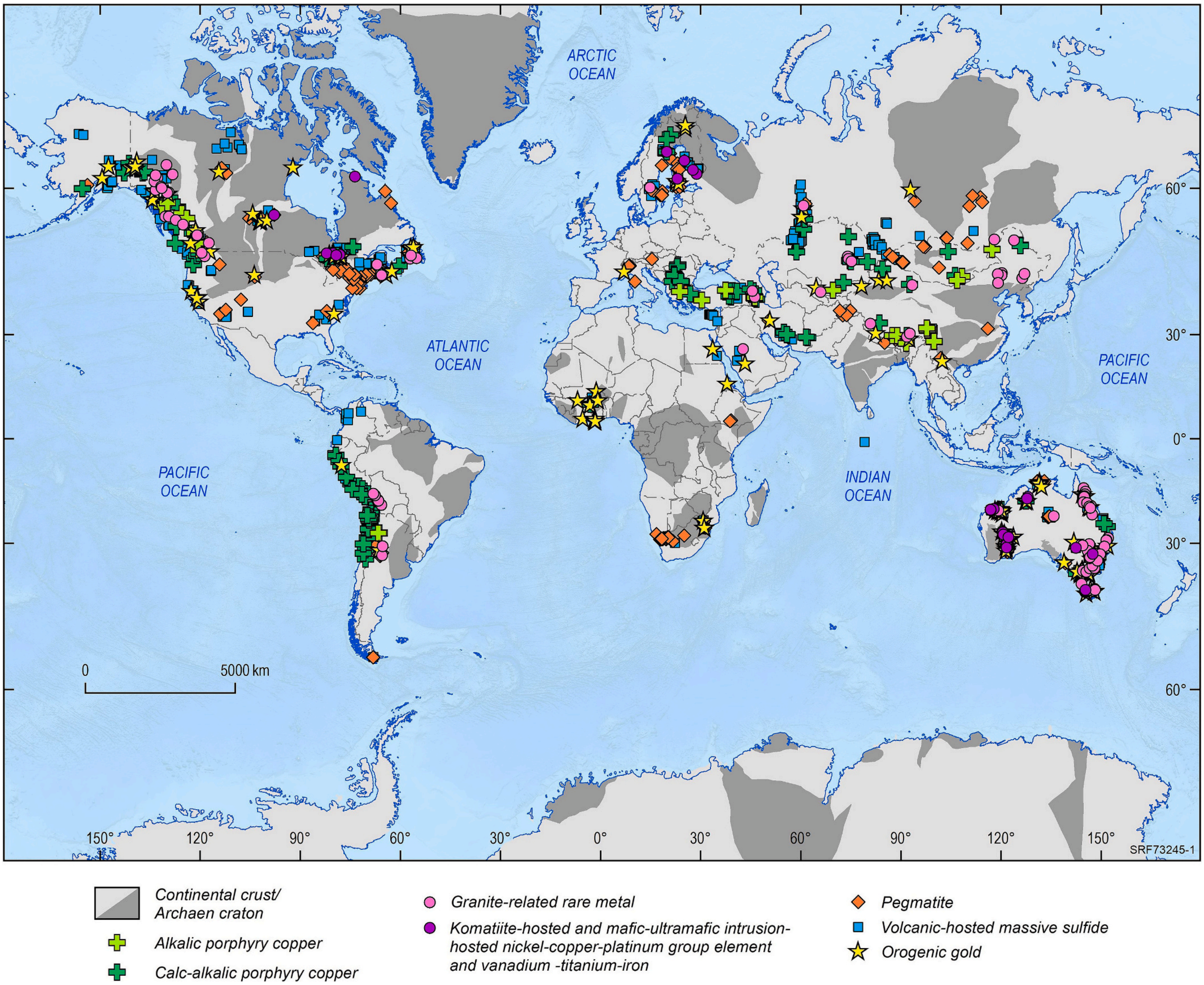

Fig. 4. Global map showing the spatial distribution of deposits considered in the contribution.

4.2. Duration of metallogenesis

The duration of metallogenesis for individual provinces shows a systematic evolution, starting with long life spans (>370 Myr) in Eo- to Early Mesoarchean provinces (Figs. 3 and 5). This differs from Meso- to Neoarchean provinces, which have the overall shortest metallogenic histories (60–140 Myr). An exception is the Eastern Goldfields province, where a minor, older VHMS/KANS event extends the metallogenic history to ca. 185 Myr. Paleoproterozoic metallogenic life spans (110–165 Myr) overlap with or are slightly longer than those of Meso- to Neoarchean systems. The longest metallogenic histories are from the late Neoproterozoic and Phanerozoic (220–440 Myr). Exceptions include the Arabian-Nubian Shield (ca. 200 Myr), which was terminated by continent-continent collision, and the Himalayan-Alpine system which is currently in progress.

The only constraints for the Mesoproterozoic are from the Grenville Orogen and Namaqua-Natal orogens, both of which have sparse data. However, the available data suggest metallogenesis lasted ca. 290–320 Myr, significantly longer than Paleoproterozoic provinces, and not dissimilar to the shorter durations observed in the Phanerozoic.

4.3. The convergent margin metallogenic cycle

The progression of deposit classes noted between ca. 2750–2500 Ma, ca. 1900–1700 Ma and ca. 400–200 Ma translates from the global scale (Fig. 2) to the province scale (Figs. 3 and 5), and defines the CMMC as discussed in the introduction and by Huston et al. (2016). Compilation of deposit age data of well-documented metallogenic provinces from around the world shows a distinct temporal progression from VHMS through orogenic gold to pegmatite deposits within individual provinces (Fig. 3). Importantly, the cycle can involve a range of other deposit classes at the metallogenic province scale. For instance, in some CMMCs, calc-alkalic porphyry copper and orthomagmatic nickel-copper deposits can accompany VHMS deposits at the beginning of metallogenic cycles. Calc-alkaline porphyry copper deposits are present in only 4 and orthomagmatic nickel-copper deposits in only 6 of 13 Mesoproterozoic and earlier convergent margins. In contrast, 6 of 8 Neoproterozoic and younger convergent margins contain calc-alkaline porphyry copper deposits, but only one of these convergent margins contain orthomagmatic nickel-sulfide deposits. Although both of these deposit types occur early in CMMCs, they form before, at the same time as or after VHMS deposits. Conversely, post-tectonic alkalic porphyry copper and granite-related Sn ± Mo ± W generally occur at the end of metallogenic cycles (Fig. 3).

This progression lasts 60–190 Myr, occurs from the Mesoarchean

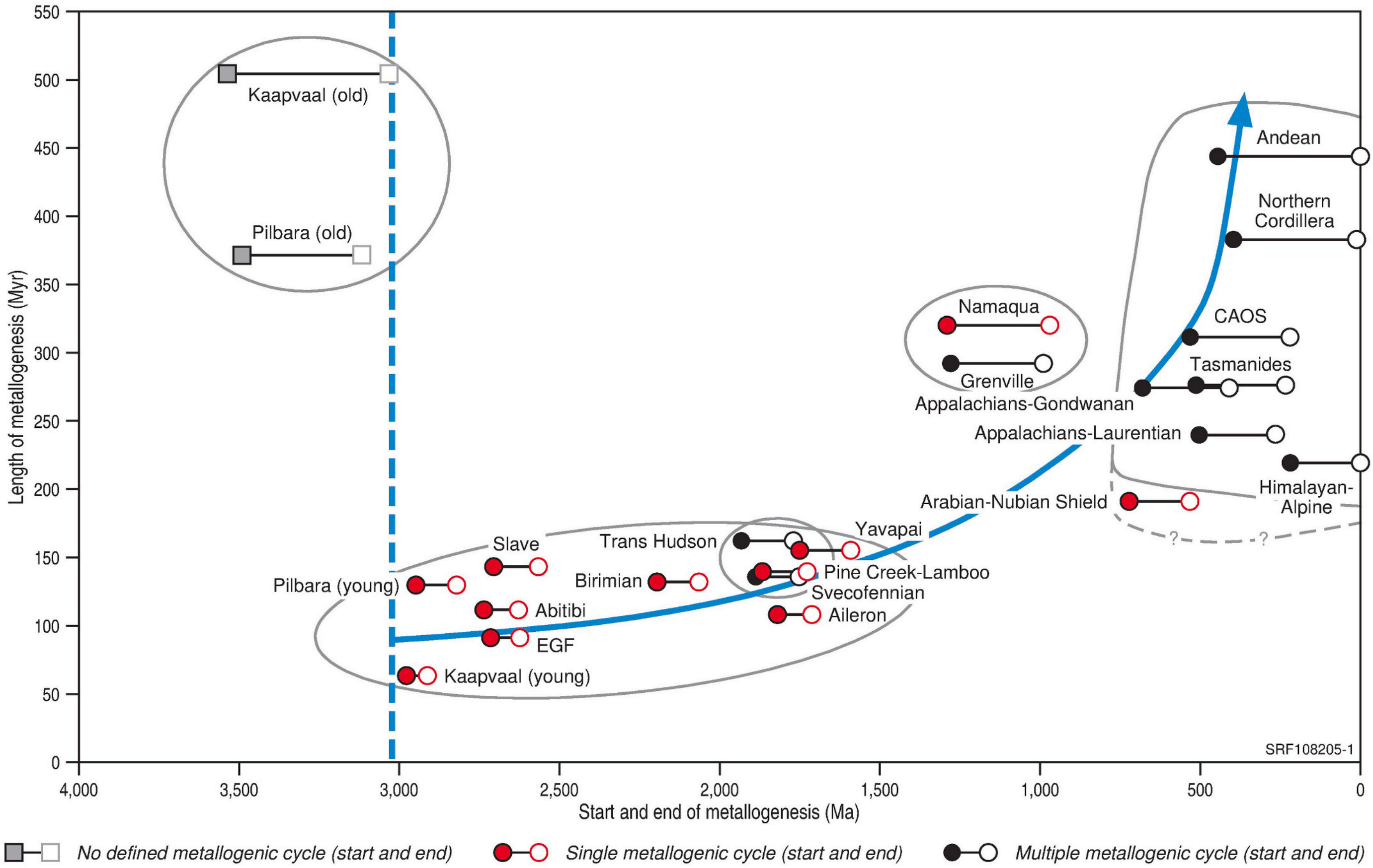

Fig. 5. Scattergram showing the relationship between the time of initiation and the duration of metallogenesis for selected provinces.

through the Phanerozoic, and can be related to Earth's tectonic evolution along convergent margins (e.g. Collins and Richards, 2008; Huston et al., 2016). The CMMC begins with subduction and associated arc magmatism (calc-alkalic porphyry copper deposits) and back-arc extension and/or basin formation (VHMS deposits). Subduction is then followed by orogenesis (orogenic gold), which reflects perturbation of subduction related to changes in the dip of subduction, accretion or continent collision. Orogenesis is commonly followed by post-orogenic extension and magmatism (pegmatites, granite-related Sn-W-Mo deposits and alkalic porphyry copper deposits). Along long-lived convergent margins, these tectonic and metallogenic cycles repeat (c.f. Tasman Element in Fig. 3), producing multiple mineralising cycles that result in metallogenic histories that can last many hundreds of millions of years (see below).

4.4. Fingerprinting convergent margin metallogenic cycles

Not all deposit types that form part of the modern CMMC occur evenly throughout Earth history (e.g. granite related Sn-Mo-W and alkalic porphyry copper). In order to be able to apply consistent criteria throughout the geological record, we use the sequence VHMS → orogenic gold → pegmatite as the main criterion for the existence of a CMMC. These three deposit types are ideally suited, because (i) they occur throughout Earth's history; (ii) they have a high preservation potential; (iii) they can be reasonably well dated; (iv) reasonably good data bases exist covering these deposit types, and (v) they correspond to the different stages of the convergent margin evolution, spanning the entire cycle. In some instances, for example in the Grenville Orogen, orogenic gold deposits are known but not well enough dated to meet the requirements for inclusion in our compilation. In these cases relative timing relationships have been assigned based on a range of available criteria such as deformation history and stratigraphy in order to apply the above criteria.

4.5. Convergent margin metallogenic cycles through time

Using the VHMS → orogenic gold → pegmatite progression as a criterion, the Eo- to Mid-Mesoarchean Provinces (older parts of Kapvaal and Pilbara) do not have the well-defined CMMCs seen in younger provinces (Fig. 3). In the older, eastern Pilbara, metallogenic evolution is dominated by pulsed occurance of VHMS deposits, with minor orogenic gold and calc-alkalic porphyry copper deposits, and pegmatites are absent. The older evolution of the Kaapvaal is similar, although pegmatites are present.

The metallogenic pattern changes by ca. 3000 Ma (Fig. 3): late Meso- to Neoarchean provinces have a metallogenic history of one well defined CMMC, and this cycle defines the metallogenic history and is relatively short (60–140 Myr), with the Eastern Goldfields Superterrane being an exception where older VHMS events exist. Single cycles also characterize some Paleoproterozoic (Birimian, Yavapai, Aileron and Pine Creek-Lamboo) provinces, with the length of CMMCs slightly increasing to 110–155 Myr. The end of the Paleoproterozoic also marks the end of dominant single CMMC metallogenic provinces in the geological record.

The Paleoproterozoic THO and Svecofennian Orogen are the first provinces with multiple CMMCs (Fig. 3), which may reflect their tectonic history (see below). In these provinces, individual CMMCs are not always fully developed, although recognizeble. For example, the THO has two orogenic gold → pegmatites cycles, but VHMS deposits are only known at the beginning of the first cycle, and there is a third, younger orogenic gold event. In both provinces, the duration of metallogenesis (135–160 Myr)) is similar to slightly longer than that of the single cycle provinces of similar age.

Currently available data from the Mesoproterozoic Namaqua Province and Grenville Orogen suggest long metallogenic histories with a single and multiple CMMCs, respectively, but the overall poor mineral endowment and the very limited data available make it very difficult to be definitive. From the late Neoproterozoic onwards, the metallogenic provinces show consistently multiple complete and partial CMMCs, and the total metallogenic histories are longer (220–440 Myr) than for Mesoarchean to Paleoproterozoic provinces.

4.6. Metallogenic evolution of convergent margins - synthesis

As described above and shown in Fig. 3, metallogenic patterns at the province scale have changed through time. These changes are systematic and distinguish five groups based on the range of deposit types, duration of metallogenesis and the presence and number of CMMCs (Fig. 5):

1) Group 1 – Eo- to Mid-Mesoarchean provinces. Metallogenesis of the oldest provinces (older Pilbara and Kaapvaal) is characterized by a large range in deposit types, pulsed mineralizing events and long duration (370–500 Myr; Fig 5); CMMCs are not recognized.
2) Group 2a – late Mesoarchean to Paleoproterozoic, single-cycle provinces. Provinces of this group include the post-3000 Ma Pilbara and Kaapvaal, Abitibi-Wawa, Slave, Eastern Goldfield, Birimian, Aileron, Pine Creek–Lamboo and Yavapai provinces. They mostly have a limited range of deposit types with a single CMMC of 60–155 Myr duration (Fig. 5).
3) Group 2b - Paleoproterozoic short-duration, multicycle provinces. This group, which includes the THO and Svecofennian Orogen, have multiple CMMCs, but the cycles are not always completely developed. At 135–160 Myr, the duration of metallogenesis is slightly longer than that of most single cycle provinces (Fig. 5).
4) Group 3: Meso to Neoproterozoic moderate-duration multi- and single cycle provinces. These provinces, which include Grenville and Namaqua provinces, have cycles 100–150 Myr longer than Group 2 (up to 320 Myr).
5) Group 4 – Latest Neoproterozoic to Phanerozoic long-duration multicycle provinces. Provinces in this group include the Andean, Appalachian – Gondwana margin, Appalachian – Laurentian margin, Central Asian Orogenic Supercollage (CAOS), Himalayan-Alpine, Northern Cordillera and Tasman. They have the greatest diversity in deposit types, multiple metallogenic cycles and long durations of metallogenesis (220–440 Myr or more where the evolution is completed; Fig. 5). In this group, provinces with single-cycle metallogenic histories disappear, and metallogenesis is quasi-continuous with few and short breaks.

This grouping integrates all metallogenic provinces presented here, except the Arabian-Nubian Province. The Grenville, Namaqua and Appalachian – Gondwana provinces are included with the caveat that the data in these provinces are relatively sparse. The Arabian-Nubian Province also has sparse data, although the existing data suggest a relatively long-lived single cycle province. The evolution of this province may have been terminated by continent-continent collision (Johnson et al., 2011), preventing additional CMMCs. The Arabian-Nubian Province is the northern extension of the East African Orogen (Kröner and Stern, 2004); and the metallogenesis of the southern part of this orogen is even less constrained than that of the northern part.

5. Results and discussion – secular tectonics and convergent margin metallogenesis

Although the importance of supercontinent formation for the metallogenic record is evident in global and province-scale data, first order differences in the CMMC can be related to the growth of different supercontinents through time. The formation of supercratons involved only short-duration Group 2a provinces, whereas Nuna assembly involved longer duration Group 2a and 2b provinces. Rodinia assembly is poorly represented in the global metallogenic record (largely restricted to the Grenville Orogen and Namaqua Province, i.e. Group 3 provinces), whereas Gondwana and Pangea assembly are well-represented and exclusively characterized by Group 4 provinces. These differences, together with the fact that the metallogenic groups are largely time exclusive, is best explained by fundamental changes to convergent margin tectonic through time as Earth has cooled. As a consequence, the metallogenic evolution may provide important new constraints for secular tectonic processes. Fig. 6 illustrates the possible links between metallogenic and tectonic styles through geological time.

5.1. Implications for modern-style convergence

Data from Phanerozoic metallogenic provinces indicate long-lived, quasi-continuous metallogenesis with multiple convergent metallogenic cycles. A hallmark of these provinces is the sustaining of long-lived subduction involving multiple tectonic cycles that start with subduction, arc formation and back-arc extension, followed by contraction due to perturbation of convergence, and then post-collisional extension when post-tectonic granites are emplaced (Fig. 5: Collins, 2002; Lallemand et al., 2005). The linkage of long-lived metallogenesis with subduction and Phanerozoic tectonometallogenic cycles are the result of deep-slab break-off, or modern, subduction in which the internal strength of the subducting slab allows maintenance of slab coherency (Brown, 2007, 2014; Sizova et al., 2014; Brown and Johnson, 2018). Although these systems are highly dynamic, at a large scale their activity focusses effectively on the same convergent margin setting which may grow and migrate laterally over time.

This evolution results in the observed formation of convergent margin-related mineral deposits repeatedly (Fig. 5) and in the same province, commonly with systematic time-space distributions a function of the (usually outboard) growth of the margin. A good example for such a system is the Tasman Element, which developed along the eastern margin of Gondwana from the late Neoproterozoic to the Triassic (Glen, 2005, 2013; Champion, 2016). This system was driven by repetitive cycles of alternating trench retreat and advance (‘tectonic switching’; Collins, 2002), where magmatism, deformation and stratigraphy broadly young towards the east (Rosenbaum, 2018), a trend also reflected in the time-space distribution of deposits.

Globally, the first evidence in the metallogenic record for long-lived convergent margin systems stems from the Appalachian – Gondwana margin province, starting at ca. 681 Ma (Table E1, Fig. 5). The timing of Group 4 coincides with the establishment of vigorous subduction during Gondwana assembly. This lends support to the hypothesis that modern convergent margins and deep subduction has been operating on Earth since at least 600 Ma.

5.2. Implications for the evolution of convergent margins through time

If commonality of results implies commonality of process, our data suggest that convergent margins, and, by inference, some form of subduction, have existed since at least 3000 Ma, when Group 2a provinces first show a well-defined CMMC. The fact that all provinces from 3000 Ma to 2400 Ma show this cyclicity might suggest that some form of subduction was the rule (rather than the exception) by the mid-Mesoarchean. That doesn’t necessarily imply operation of plate tectonics in the modern sense (e.g., Cawood et al., 2018, 2022) which is very difficult to demonstrate, but suggests that some type of subduction was present from this time onwards (Fig. 6).

Group 2a provinces differ from Group 4 Phanerozoic counterparts in that they comprise strictly one cycle, with short metallogenic histories. This behavior could reflect shallow breakoff or drip-off subduction (Fig. 6) which leads to shorter-lived subduction settings as the slab-pull is removed when the slab breaks off or drips off, respectively (van Hunen and van der Berg, 2008; Moyen and van Hunen, 2012; van Hunen and

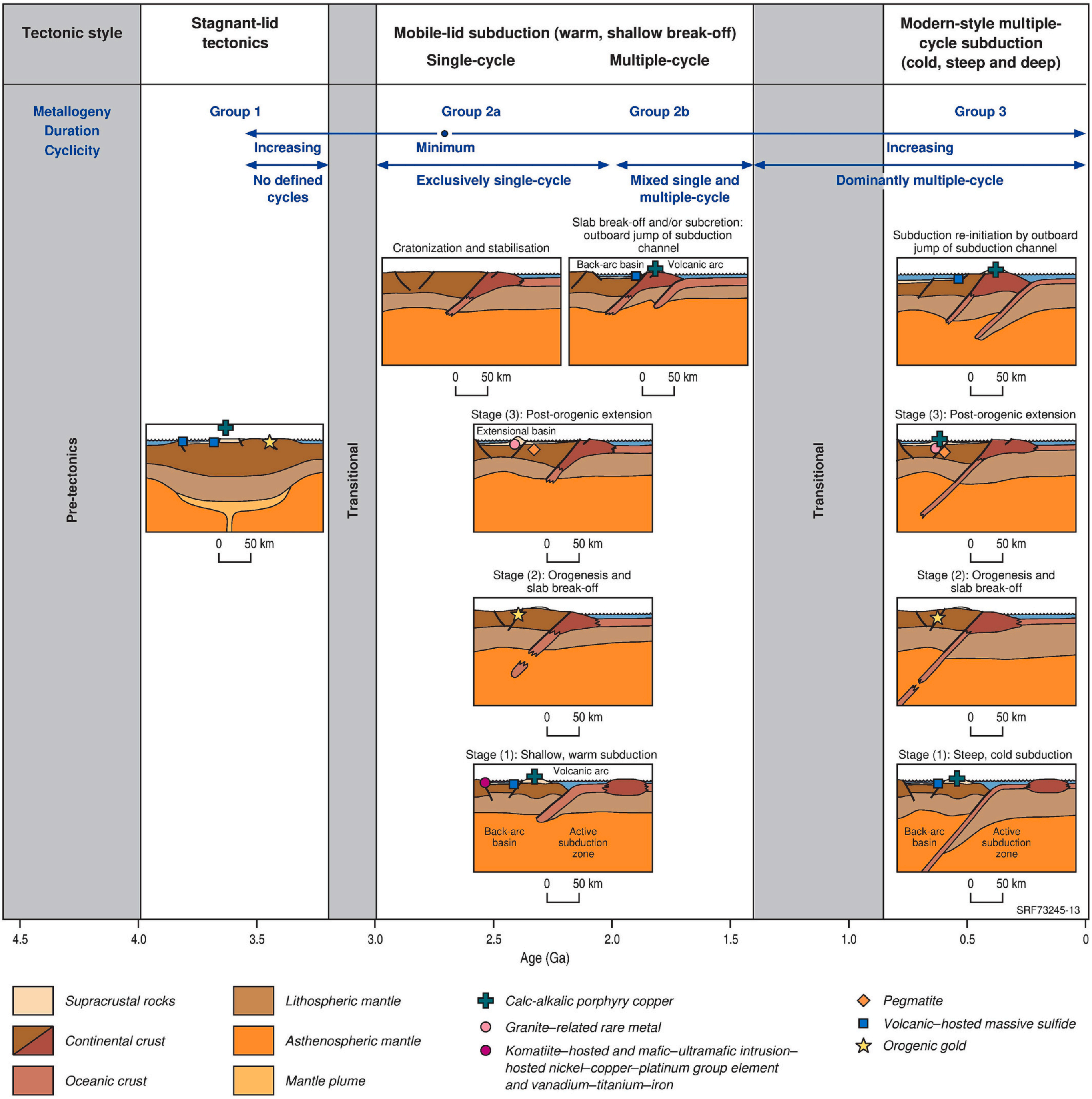

Fig. 6. Diagrams showing proposed relationships between metallogenic and tectonic styles through Earth's history: (a) stagnant lid (ca. 4000–3000 Ma), (b) shallow slab-breakoff and/or subcretion (ca. 3000–800 Ma), and (c) deep-slab-beakoff (modern) subduction (ca. 800–0 Ma). Each scenario illustrates temporal variations in metallogeny as the hypothesized tectonic system evolves.

Moyen, 2012; Fisher and Gerya, 2016). Alternatively, it could reflect subcretion or the thrusting of buoyant (and therefore unsubductable) oceanic lithosphere under the margins, or leading edges, of continents drifting in response to mantle traction in a form of squishy lid tectonic mode (Fig. 6: Harris and Bédard, 2015). This latter mechanism has been called upon to explain some geological characteristics of Archean cratons (c.f. Bédard, 2018), and zones of convergence resembling aspects of primitive subduction zones could possibly develop in a sqishy lid mode. Such a scenario could account for orogenic gold deposits and pegmatites, but it cannot readily explain the formation of VHMS deposits predating the orogenic gold events in all the provinces. In both modern and ancient settings, VHMS deposits require lithospheric thinning and related decompression melting, as reflected by their current position in back-arc basins or other extensional environments such as rifts (Hannington et al., 2005). For the Meso- to Neoarchean deposits considered here this is reflected in, and underpinned by, their general association with juvenile crust (e.g., Huston et al., 2014). We therefore view Group 2a provinces as forming in a mobile lid subduction setting mainly driven by negative bouyancy of the lithosphere (Fig. 6), which better accounts for some form of extension and lithospheric thinning prior to orogenesis. We note however that some form of transitional mode cannot completely be ruled out based on the data presented herein.

The Group 2b provinces mark the first time that a convergent margin was sustained with multiple CMMCs that possibly indicate re-initiation of new, outboard subduction zones following for example accretion of exotic blocks. From a metallogenic point of view, there is no evidence that this occured during the Archean, and this may indicate some changes to the subduction dynamics, in particular regarding the strength of the upper plate since that time. In both Group 2b provinces, the upper plate of the convergent margin is represented by Archean cratons. Those cratons have tectonothermally matured since cratonization in the Neoarchean, and most models for the secular development of mantle potential temperature suggest cooling in the order of 25–50 °C between the late Archean and the formation of Group 2b mineral provinces (e.g. Palin et al., 2020). It is feasible that these factors have contributed to the increased strength of the cratonic margins (Hyndman et al., 2009).

Cooler mantle temperatures also have a direct effect on mantle melting and the degree of depletion (Herzberg et al., 2010), and therefore on the thickness and composition of oceanic crust and mantle lithosphere. However, the metallogenic record bears no evidence that this has significantly modified the behavior of the lower, oceanic plate. Instead, we interpret the regular presence of VHMS deposits within the Group 2b CMMCs to indicate a similar behavior with a tendency for slab retreat and upper plate (back-arc?) extension, which is also consistent with the existence of the younger Group 2a provinces at the same time.

In our dataset, the Mesoproterozoic era is only represented by the Grenville Orogen and the Namaqua Province, which formed during Rodinia assembly (Li et al., 2008). The limited data indicates that metallogenic duration of both provinces is significantly longer than that of the older Group 2 provinces, whereas the metallogenic record does not show the dynamics, and mineral endowment, of the younger Group 4 provinces of similar length (Fig. 5). The Mesoproterozoic is a time period of particular features in the geological record, including abundant massif type anorthosites (Ashwal and Bybee, 2017), high thermobaric ratios in metamorphic rocks (Brown and Johnson, 2019), and a paucity of passive margins (Bradley, 2008). Recently hypothesis have been put forward suggesting “orogenic quiescence” (Tang et al., 2021) or “single-lid tectonics” (Stern, 2020) during this time. The observation of CMMCs suggests active convergent margins during this time, which is consistent with the overall geological record (Condie, 2021; Cawood et al., 2022; Roberts et al., 2022; Roberts et al., 2023). However, the length of the CMMC in particular of the Namaqua province, and the overall poor metallogenic endowment of Mesoproterozoic provinces could lend support to models invoking a subdued tectonic activity with a reduction in global plate velocity (O’Neill et al., 2022). This could be related to poor lubrication of subduction zones (Sobolev and Brown, 2019), or to cooling related changes in the mantle convection and rheology, prior to the onset of deep subduction as a sustainable driver of plate tectonics.

The Neoproterozoic Arabian-Nubian province seems to show a long-duration single cycle, although the lack of data precludes detailed discussion.

5.2.1. *Secular trends in subduction processes – implications for the metallogenic record*

A compilation of active subduction zones suggests that they preferentially retreat (Schellart et al., 2008), and this is consistent with 3D numerical models incorporating modern Earth-like conditions (Stegman et al., 2010). Deviation from the preference requires the arrival of buoyant features at the trench (e.g. oceanic plateaux, microcontinents or mid-ocean ridges) or very wide subduction zones (e.g., Schellart, 2008; Schellart and Rawlinson, 2010). We argue that the preference to retreat has been in place since the onset of subduction within the Mesoarchean, and is expressed as the omnipresence of VHMS deposit formation closely predating the formation of orogenic gold deposits as part of the CMMC in all mineral provinces.

This preference has implications for metallogeny, in particular as it provides context into the secular record of calc-alkalic porphyry copper deposits. These deposits form mostly in continental arcs where the crust is thick (35–80 km; Kesler, 1997; Sinclair, 2007). Recently, this has been attributed to a necessity of garnet driven oxidation during the priming for deposit formation at deeper crustal levels (Lee and Tang, 2020). Thick continental arc crust is typically the cumulative effect of magmatic and tectonic (contraction) thickening. Lee and Tang (2020) speculate that the latter point is an important factor for deposit formation, as such a setting may support the stalling of magma at favorable depth, whereas in extensional settings, such as in most island arcs, the magmas more readily ascend through the crust, reaching the surface. If this is true and a predominantly extensional character of convergent margins (i.e., retreating accretionary orogens such as the modern West Pacific margin: Cawood, 2009) back in the Paleoproterozoic and Archean bears out, this would mean that the paucity of porphyry copper deposits (which commonly form along advancing accretionary orogens such as the East Pacific (Andean) margin: Cawood, 2009) at that time is not solely related to poor preservation, but may also be partly primary (Frimmel, 2018). An endmember-scenario would be a hiatus of formation in certain periods if one considers the possibility of rapid trench retreat without or with very limited arc formation (Perchuk et al., 2019).

5.2.2. *Deposit formation in the Eo- to Paleoarchean*

Group 1 deposits do not show CMMCs, and therefore we interpret their metallogenic record to be unrelated to subduction-driven convergent margins. The data suggest that subduction was not a coherent process prior to ca. 3000 Ma. This timeframe is in good agreement with fundamental changes in the geological record (Fig. 1), which have been used to suggest that subduction (and possibly plate tectonics) started in the Mesoarchean (e.g. Smithies et al., 2006; Condie and Kröner, 2008; Cawood et al., 2006; Van Kranendonk et al., 2007; Palin et al., 2020 and references therein), although it has been proposed that the full transition to global plate tectonics was completed only by the end of the Archean (e.g., Cawood et al., 2018). These changes include the (widespread) appearance of passive margins (Bradley, 2008), the appearance of arc volcanic rocks (e.g. boninites and shoshonites; Smithies et al., 2004; Wyman and Kerrich, 2012) and paired metamorphic belts (Brown, 2006, 2014), the evolution of thicker continental crust of intermediate composition (Dhuime et al., 2015), the virtual disappearance of komatiites after the Archean (Arndt et al., 2008), among others (Condie, 2021).

A main implication is that Group 1 deposits may have formed in a different tectonic setting (Fig. 6) than later in Earth history. Predating subduction and the mobile lid regime, Earth’s tectonic mode was some form of stagnant lid (Lenardic, 2018; Stern et al., 2018; Cawood et al., 2022). A distinctive feature of the former is that the whole lithosphere is involved in convection, whereas in the latter only the lower, weaker part may be involved by dripping and/or delamination (Stevenson, 2003). Stagnant lid regimes are common in planetary bodies, where a range of types may occur (Lenardic, 2018; Stern et al., 2018).

The formation of VHMS deposits requires lithospheric thinning and extension, which is likely related to zones of convective upwelling and/or plume impingement (e.g. Huston et al., 2007), both processes that may be associated with stagnant lid regimes. Group 1 orogenic gold deposits differ from younger deposits. In the Pilbara, they are hosted by shear zones that ring and reflect the shape of the associated batholiths. That sets them apart from younger orogenic gold deposits that are in general associated with linear structural corridors (Vearncombe et al., 1989). The structural topology in the Pilbara, in contrast, suggests an association with the emplacement of the batholith, which is in turn is interpreted as a result of partial convective overturn processes (e.g. Van Kranendonk et al., 2007), a hallmark of vertical tectonics.

Although the setting for Group 1 porphyry copper deposits is not clear (Huston et al., 2007), these deposits also differ from their younger counterparts in that they are molybdenum-rich (Cu:Mo = 0.08:0.05), have lower gold grades (e.g., Frimmel, 2018) and have a strong association with pyrrhotite as opposed to pyrite (Cummins and Cairns, 2017). These observations, although not definitive, suggest that the formation of Paleoarchean porphyry copper deposits may have involved significantly different processes compared to their Phanerozoic counterparts.

6. Conclusions and future directions

Despite much progress in understanding tectonic processes since the concept of plate tectonics was broadly accepted in the late 1960s, many questions still remain as to how these processes have changed through Earth's history. Here we have presented a new dataset, the temporal distribution of convergent margin mineral deposits, which provides new insights into how convergent processes have changed through time. We have documented the temporal and spatial distribution of over 1100 of these deposits in 21 different provinces from all parts of Earth that span an age range from ca. 3500 Ma to the present.

Analysis of this dataset indicates that in most of the provinces considered there is a relatively consistent progression of deposits types, from early VHMS and calc-alkalic porphyry copper deposits, through intermediate orogenic gold deposits, to later pegmatite and granite-related rare metal deposits. We term this progression the convergent margin metallogenic cycle (CMMC). In some provinces, other deposit types, such as komatiite-associated Ni and alkalic porphyry copper deposits, also form part of this progression.

Using the CMMC as a basis, the metallogenic provinces can be classified into five, time-restricted groups. The earliest group (Group 1) comprises older (>3000 Ma) metallogenic provinces, such as the early Pilbara and Kaapvaal, which have long-duration metallogenic histories (370–500 Myr) but lack identifiable CMMCs. The second group (Goup 2a) includes Mesoarchean to Paleoproterozoic provinces that are characterized by a single CMMC of relatively short duration (60–155 Myr). The third group (Group 2b), which includes the Paleoproterozoic Svecofennian and Trans-Hudson orogens, have multiple CMMCs, but with a relatively short overall duration (135–160 Myr). Group 3 includes Mesoproterozoic to Neoproterozoic, single- or multi-cycle provinces with longer metallogenic histories (290–320 Myr), and Group 4 includes Neoproterozoic to Phanerozoic provinces with multiple short cycles that, when combined, led to long metallogenic histories (220–440 Myr).

Changes in convergent margin metallogeny can be understood in the context of models that account for secular changes in tectonic processes (e.g. Palin and Santosh, 2021: Fig. 6). The formation of Group 1 deposits occurred during a stagnant lid tectonic mode, where CMMCs did not develop. The first CMMCs are observed at around 3000 Ma, corresponding to the transition into a mobile lid tectonic mode, with an early form of subduction involving consumption of warm oceanic crust. Early subduction is interpreted to have been shallow (Palin and Santosh, 2021), leading to somewhat unstable convergent systems and subduction being easily shut down. This environment produced short-lived single-cycle metallogenic histories (Group 2a) that dominated the Mesoarchean through the Paleoproterozoic. As penetration of the subducted slab into the mantle deepened (Palin and Santosh, 2021), subduction became more stable and metallogenic provinces with multiple CMMCs developed (Group 2b). Based on the limited data presented herein, this also produced longer-lived single-cycle provinces in the Mesoproterozoic (Group 3). The development of cold, steep and deep subduction (modern-day plate tectonics) during the Neoproterozoic enhanced the stability of convergent margins such that usually only major events, such as continent-continent collision, could terminate subduction. In response to a perturbation, rather, subduction jumped and/or re-initiated. This led to the dominance of multi-cycle provinces that prevail today.

Begg et al. (2010) noted that many magmatic Ni—Cu deposits are associated with cratonic margins, and our dataset suggests that komatiite-associated and some intrusion-related Ni-Cu-PGE deposits are systematically associated with the early stages of the CMMC. Although orthomagmatic Ni-Cu-PGE deposits are generally interpreted to be associated with mantle plumes or large igneous provinces (Pirajno, 2000; Begg et al., 2010), commonly in intraplate settings, the temporal relationship to the early stages of CMMCs raises the possibility that some of these deposits form part of convergent margin metallogenesis, particularly during the Neoarchean and Paleoproterozoic, and this relationship requires further investigation. In making this suggestion, we are not suggesting that all orthomagmatic Ni-Cu-PGE deposits formed in this setting. Clearly deposits/districts such as Norilsk-Talnakh, Jinchuan and Sudbury did not (Barnes and Lightfoot, 2005).

In addition to questions arising directly from relationships noted in the data, there are a number of other questions regarding the relationship between tectonics and metallogenesis. For instance, although the Paleoproterozoic is dominated by type 2a mineral provinces, the consumption of internal seas associated with Nuna assembly resulted in multi-cycle type 2b mineral provinces. This may suggest that there are differences in tectonic processes involved in the consumption of internal seas (i.e. introversion) and consumption of external seas (extroversion), particularly for Nuna assembly. This may also extend to metallogenesis as the Trans-Hudson and Svecofennian orogens are the two most endowed Paleoproterozoic mineral provinces, whereas provinces that formed on the extremities of Nuna are less well endowed.

Another area of research that could directly affect exploration is the role that secular changes in tectonic processes can affect endowment of mineral provinces. It is well known that some provinces, such as the Eastern Goldfields (orogenic gold and KANS) and Abitibi-Wawa (VHMS and orogenic gold), are much more endowed compared to other provinces of similar age; however the unanswered question is why.

The last area for further work is the linkage of changes in metallogenesis to changes in other earth systems, not only tectonic systems, but environmental changes at the surface. These changes manifest themselves not only in mineral provinces associated with convergent margins, but more strongly in mineral provinces associated with divergent margins. Many deposit types that form along divergent or passive margins are time-restricted (e.g. Superior-type iron formation, basin-hosted Zn and Cu deposits, unconformity-related deposits, some gold deposits: Lambert and Groves, 1981; Myer, 1981; Frimmel, 2018). A similar analysis of these deposit types may provide additional insights into Earth system processes, including tectonic and environmental processes that drive the evolution of divergent margins and their metallogenesis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This contribution has benefited from discussions with many colleagues, most particularly Raimo Lahtinen who provided insight into the metallogenesis of the Svecofennian Province. It has benefited from reviews by Guillaume Sanchez, Andy Clark, Hartwig Frimmel and an anonymous reviewer. It is published with permission of the Chief Executive Officer of Geoscience Australia, and is a contribution of the Critical Minerals Mapping Initiative, a research consortium between Geoscience Australia, the Geological Survey of Canada and the United States Geological Survey. BE acknowledges financial support from an NSERC Discovery grant and from the Murray Pyke endowment to the University of Saskatchewan.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.

org/10.1016/j.earscirev.2023.104551.

References

Abbott, D., Drury, R., Smith, W.H.F., 1994. Flat to steep transition in subduction style. Geology 22, 937–940.
Abe, Y., 1997. Thermal and chemical evolution of the terrestrial magma ocean. Physics of the Earth and Planetary Interiors 100, 27–39.
Arndt, N., Lesher, C., Barnes, S., 2008. Komatiite. Cambridge University Press, Cambridge. https://doi.org/10.1017/CBO9780511535550.
Ashwal, L.D., Bybee, G.M., 2017. Crustal evolution and the temporality of anorthosites. Earth Sci. Rev. 173, 307–330.
Barnes, S.-J., Lightfoot, P.C., 2005. Formation of magmatic nickel sulfide ore deposits and processes affecting their copper and platinum group element contents. Economic Geology 100th Anniversary Volume, pp. 179–214.
Bédard, J.H., 2018. Stagnant lids and mantle overturns: implications for Archaean tectonics, magmagenesis, crustal growth, mantle evolution, and the start of plate tectonics. Geosci. Front. 9, 19–49.
Bédard, J.H., Harris, L.B., Thurston, P., 2013. The hunting of the snArc. Precambrian Res. 229, 20e48.
Begg, G.C., Hronsky, J.A., Arndt, N.T., Griffin, W.L., O'Reilly, S.Y., Hayward, N., 2010. Lithospheric, cratonic, and geodynamic setting of Ni-Cu-PGE sulfide deposits. Econ. Geol. 105, 1057–1070.
Bradley, D.C., 2008. Passive margins through time. Earth Sci. Rev. 91, 1–26.
Brown, M., 2006. A duality of thermal regimes is the distinctive characteristic of plate tectonics since the Neoarchean. Geology 34, 961–964.
Brown, M., 2007. Metamorphic conditions in orogenic belts: a record of secular change. Int. Geol. Rev. 49, 193–234.
Brown, M., 2014. The contribution of metamorphic petrology to understanding lithosphere evolution and geodynamics. Geosci. Front. 5, 553–569.
Brown, M., Johnson, T., 2018. Secular change in metamorphism and the onset of global plate tectonics. Am. Mineral. 103, 181–196.
Brown, M., Johnson, T., 2019. Time's arrow, time's cycle: Granulite metamorphism and geodynamics. Mineral. Mag. 83, 323–338.
Caruso, S., Fiorentina, M.L., Champion, D.C., Lu, Y., Ueno, Y., Smithies, R.H., 2022. Sulfur isotope systematics of granitoids from the Yilgarn Craton shed new light into the fluid reservoirs of Neoarchean orogenic gold deposits. Geochim. Cosmochim. Acta. https://doi.org/10.1016/j.gca.2022.03.023 in press.
Cawood, P.A., Kröner, A., Pisarevsky, S., 2006. Precambrian plate tectonics: criteria and evidence. GSA Today 16, 4–11.
Cawood, P.A., 2009. Accretionary orogens through Earth history. Geol. Soc. London Spec. Publ. 318, 1–36.
Cawood, P.A., Hawkesworth, C.J., 2013. Temporal relations between mineral deposits and global tectonic cycles. Geol. Soc. London Spec. Pub. 393, 9–21. https://doi.org/10.1144/SP393.1.
Cawood, P.A., Hawkesworth, C.J., Pisarevsky, S.A., Dhuime, B., Capitanio, F.A., Nebel, O., 2018. Geological archive of the onset of plate tectonics. Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. 376, 20170405.
Cawood, P.A., Chowdhury, P., Mulder, J.A., Hawkesworth, C.J., Capitanio, F.A., Gunawardana, P.M., Nebel, O., 2022. Secular evolution of continents and the earth system. Rev. Geophys. 60 e2022RG000789.
Černý, P.T., Ercit, T.S., 2005. The classification of granitic pegmatites revisited. Can Mineral. 43, 2005–2026.
Champion, D.C., 2016. Geodynamic synthesis of the Phanerozoic of eastern Australia (2nd ed.). Geosci. Austr. Rec. 2016/07.
Collins, W.J., 2002. Hot orogens, tectonic switching and creation of continental crust. Geology 30, 535–538.
Collins, W.J., Richards, S.W., 2008. Geodynamic significance of S-type granites in circum-Pacific orogens. Geology 36, 559–562.
Condie, K.C., 2021. Two major transitions in Earth history: evidence for two lithospheric strength thresholds. J. Geol. 129, 455–473.
Condie, K.C., Kröner, A., 2008. When did plate tectonics begin? Evidence from the geologic record. Geol. Soc. Am. Spec. Pap. 440, 281–2294.
Conrad, C.P., Lithgow-Bertelloni, C., 2002. How mantle slabs drive plate tectonics. Science 298 (5591), 207–209.
Crawford, A.J., Berry, R.F., 1992. Tectonic implications of Late Proterozoic-Early Palaeozoic igneous rock associations in western Tasmania. Tectonophysics 214, 37–56.
Cummins, B., Cairns, B., 2017. Spinifex Ridge molybdenum-copper deposit. Austr. Inst. Mining Metall. Mon. 32, 343–344.
Davies, G.F., 1992. On the emergence of plate tectonics. Geology 20, 963–966.
Dewey, J.F., Burke, K., 1974. Hot spots and continental break-up: implications for collisional orogeny. Geology 2, 57–60.
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.
Dhuime, B., Wuestefeld, A., Hawkesworth, C.J., 2015. Emergence of modern continental crust about 3 billion years ago. Nature Geosci. 8, 552–556.
Dostal, J., Mueller, W., 1992. Archean shoshonites from the Abitibi greenstone belt, Chibougamau (Québec, Canada): geochemistry and tectonic setting. J. Volcanol. Geotherm. Res. 53, 145–165.
Edwards, K.J., McCollom, T.M., Konishi, H., Buseck, P.R., 2003. Seafloor bioalteration of sulfide minerals: results from in situ incubation studies. Geochim. Cosmochim. Acta 67, 2843–2856. https://doi.org/10.1016/S0016-7037(03)00089-9.
Franklin, J.M., Gibson, H.L., Jonasson, I.R., Galley, A.G., 2005. Volcanogenic massive sulfide deposits. Econ. Geol. 100th Anniv. Vol. 523–560.
Fisher, R., Gerya, T., 2016. Regimes of subduction and lithospheric dynamics in the Precambrian: 3D thermomechanical modelling. Gond. Res. 37, 53–70.
Forsyth, D., Uyeda, S., 1975. On the relative importance of the driving forces of plate motion. Geophys. J. R. Astron. Soc. 43, 163–200.
Frimmel, H., 2018. Episodic concentration of gold to ore grade through Earth's history. Earth-Sci. Rev. 180, 148–158.
Gerya, T., 2014. Precambrian geodynamics: concepts and models. Gondwana Res. 25, 442–463.
Gerya, T., Stöckhert, B., Perchuk, A.L., 2002. Exhumation of high-pressure metamorphic rocks in a subduction channel: a numerical simulation. Tectonics 21, 6–1-6-19.
Glen, R.A., 2005. The Tasmanides of eastern Australia. Geol. Soc. London Spec. Pub. 246, 23–96.
Glen, R.A., 2013. Refining accretionary orogeny models for the Tasmanides of eastern Australia. Austr. J. Earth Sci. 60, 315–370.
Goldfarb, R.J., Groves, D.I., Gardoll, S., 2001. Orogenic gold and geologic time; a global synthesis. Ore Geol. Rev. 18, 1–75.
Granot, R., 2016. Palaeozoic oceanic crust preserved beneath the eastern Mediterranean. Nature Geosci. 9, 701–706.
Griffin, W.L., Belousova, E.A., O'Neill, C.O.S.Y., Malkovets, V., Pearson, N.J., Spetsius, S., Wilde, S.A., 2014. The world turns over: Hadean Archean crust mantle evolution. Lithos 189, 2–15.
Groves, D.I., 1993. The crustal continuum model for late-Archaean lode-gold deposits of the Yilgarn Block,Western Australia. Mineral. Deposita 28, 366–374.
Groves, D.I., Bierlein, F., 2007. Geodynamic settings of mineral deposit systems. J. Geol. Soc. Lond. 164, 19–30. https://doi.org/10.1144/0016-76492006-065.
Groves, D.I., Goldfarb, R.J., Robert, R., Hart, C., 2003. Gold deposits in metamorphic belts: overview of current understanding, outstanding problems, future research, and exploration significance. Econ. Geol. 98, 1–29.
Groves, D.I., Santosh, M., Muller, D., Shang, L., Deng, J., Yang, L.-Q., Wang, Q.-F., 2022. Mineral systems: their advantages in terms of developing holistic genetic models and for target generation in global mineral exploration. Geosys. Geoenviron. 1, 100001 https://doi.org/10.1016/j.geogeo.2021.09.001.
Hannington, M.D., de Ronde, C.E.J., Petersen, S., 2005. Sea-floor tectonics and submarine hydrothermal systems. Econ. Geol.100th Anniv 111–142.
Harris, L.B., Bédard, J.H., 2015. Interactions between continent-like 'drift', rifting, and mantle flow on Venus? Gravity interpretations and Earth analogues. Geol. Soc. London Spec. Pub. 401 https://doi.org/10.1144/SP401.9.
Herzberg, C., Condie, K., Korenaga, J., 2010. Thermal history of the Earth and its petrological expression. Earth Planet. Sci. Lett. 292, 79–88.
Hosono, N., Karato, S., Makino, J., Saitoh, T.R., 2019. Terrestrial magma ocean origin of the Moon. Nature Geosci. 12, 418–423.
Huston, D.L., Morant, P., Pirajon, F., Cummins, B., Baker, D., Mernaght, T.P., 2007. Paleoarchean mineral meposits of the Pilbara Craton: genesis, tectonic environment and comparisons with younger deposits. Dev. Precambri. Geol. 15, 411–450.
Huston, D.L., Pehrsson, S., Eglington, B.M., Zaw, K., 2010. The geology and metallogeny of volcanic-hosted massive sulfide deposits through geologic time and with tectonic setting. Econ. Geol. 105, 571–591.
Huston, D.L., Champion, D.C., Cassidy, K.F., 2014. Tectonic controls on the endowment of Neoarchean cratons in volcanic-hosted massive sulfide deposits: evidence from lead and neodymium isotopes. Econ. Geol. 109, 11–26.
Huston, D.L., Mernagh, T.P., Hagemann, S.G., Doublier, M.P., Fiorentini, M., Champion, D.C., Jaques, A.L., Czarnota, K., Cayley, R., Skirrow, R., Bastrakov, E., 2016. Tectono-metallogenic systems — the place of mineral systems within tectonic evolution, with an emphasis on Australian examples. Ore Geol. Rev. 76, 168–210.
Huston, D.L., Eglington, B., Pehrsson, S., Piercey, S., 2022. Global database of zinc-lead-bearing mineral deposits. Geosci. Austr. Rec. 2022/11.
Hutchinson, R.W., 1973. Volcanogenic sulfide deposits and their metallogenic significance. Econ. Geol. 68, 1223–1246.
Hyndman, R.D., Currie, C.A., Mazzotti, S., Frederiksen, A., 2009. Temperature control of continental lithosphere elastic thickness, Te vs vs. Earth Planet. Sci. Lett. 277, 539–548.
Johnson, P.R., Andresen, A., Collins, A.S., Fowler, A.R., Fritz, H., Ghebreab, W., Kusky, T., Stern, R.J., 2011. Late Cryogenian-Ediacaran history of the Arabian-Nubian Shield: a review of depositional, plutonic, structural, and tectonic events in the closing stages of the northern East African Orogen. J. Afr. Earth Sci. 61, 167–232.
Johnson, T.E., Brown, M., Kaus, B.J.P., Van Tongeren, J.A., 2014. Delamination and recycling of Archaean crust caused by gravitational instabilities. Nat. Geosci. 7, 47–52.
Kesler, S.E., 1997. Metallogenic evolution of convergent margins: selected ore deposit models. Ore Geol. Rev. 12, 153–171.
Kesler, S.E., Wilkinson, B.H., 2006. Exhumation dominates the temporal distribution of ore deposits. Econ. Geol. 105, 919–922.
Korenaga, J., 2006. Archean geodynamics and the thermal evolution of Earth. Am. Geophys. Union Mon. 164, pp. 7e32.
Kröner, A., Stern, R.J., 2004. Pan-Arcian Orogeny. Encyclopedia of Geology 1, 1–12.
Lallemand, S., Heuret, A., Boutelier, D., 2005. On the relationship between slab dip, back-arc stress, upper plate absolute motion, and crustal nature in subduction zones. Geochem. Geophys. 6, Q09006. https://doi.org/10.1029/2005GC000917.
Lambert, I.B., Groves, D.I., 1981. Early Earth evolution and metallogeny. Handbook of strata-bound and stratiform ore deposits 8, 339–447.
Laznicka, P., 1972. Development of nonferrous metal deposits in geological time. Can. J. Earth Sci. 10, 18–23.
Lee, C.-T., Tang, M., 2020. How to make porphyry copper deposits. Earth Planet. Sci. Lett. 529, 115868.

Lenardic, A., 2018. The diversity of tectonic modes and thoughts about transitions between them. Phil. Trans. R. Soc. A 376, 20170416. https://doi.org/10.1098/rsta.2017.0416.
Li, Z., Bogdanova, S., Collins, A.S., Davidson, A., De Waele, B., Ernst, R., Fitzsimons, I., Fuck, R., Gladkochub, D., Jacobs, J., 2008. Assembly, configuration, and break-up history of Rodinia: a synthesis. Precambrian Res. 160, 179–210.
Maruyama, S., Liou, J.G., 1998. Initiation of ultrahigh-pressure metamorphism and its significance on the Proterozoic-Phanerozoic boundary. Island Arc 7, 6–35.
Moyen, J.-F., van Hunen, J., 2012. Short-term episodicity of Archaean plate tectonics. Geology 40, 451–454.
Myer, C., 1981. Ore-forming processes in geologic history. Econ. Geol.75th Anniv 6–41.
O'Neill, C., Lenardic, A., Weller, M., Moresi, L., Quenette, S., Zhang, S., 2016. A window for plate tectonics in terrestrial planet evolution? Phys. Earth Planet. Inter. 255, 80–92.
O'Neill, C., Brown, M., Schaefer, B., Gazi, J.A., 2022. Earth's anomalous middle-age magmatism driven by plate slowdown. Nat. Sci. Rep. 12, 10460.
Palin, R.M., Santosh, M., 2021. Plate tectonics: what, where, why and when? Gondwana Res. 100, 3–24.
Palin, R.M., Santosh, M., Cao, W., Li, S.-S., Hernández-Uribe, D., Parsons, A., 2020. Secular change and the onset of plate tectonics on Earth. Earth-Sci. Rev. 207, 103172.
Pease, V., Percival, J., Smithies, H., Stevens, G., Van Krandendonk, M., 2008. When did plate tectonics begin? Evidence from the orogenic record. Geol. Soc. Am. Spec. Pap. 440, 199–228.
Penniston-Dorland, S., Kohn, M.J., Manning, C.E., 2015. The global range of subduction zone thermal structures from exhumed blueschists and eclogites: Rocks are hotter than models. Earth Planet. Sci. Lett. 428, 243–254.
Perchuk, A.L., Zakharov, V.S., Gerya, T.V., Brown, M., 2019. Hotter mantle but colder subduction in the Precambrian: what are the implications? Precambrian Res. 330, 20–34.
Percival, J.A., Sanborn-Barrie, M., Stott, G., Helmstaedt, H.H., Skulski, T., White, D.J., 2006. Tectonic evolution of the Western Superior Province from NATMAP and LITHOPROBE studies. Can. J. Earth Sci. 43, 1085–1117.
Piette-Lauziére, N., Guilmette, C., Bouvier, A., Perrouty, S., Pilote, P., Gaillard, N., Lypaczewski, P., Linnen, R.L., Olivio, G.R., 2019. The timing of prograde metamorphism in the Pontiac Subprovince, Superior craton; implications for Archean geodynamics and gold mineralization. Precambrian Res. 320, 111–136.
Pirajno, F., 2000. Ore Deposits and Mantle Plumes. In: Kluwer Academic Publishers, Dordrecht, p. 556.
Richards, J.P., 2001. Tectono-magmatic precursors for porphyry Cu-(Mo-Au) deposit formation. Econ. Geol. 96, 1515–1533.
Roberts, N.M.W., Condie, K.C., Palin, R.M., Spencer, C.J., 2023. Hot, wide, continental back-arcs explain Earth's enigmatic mid-Proterozoic magmatic and metamorphic record. Tektonika 1. https://doi.org/10.55575/tektonika2023.1.1.32.
Roberts, N.M.W., Salminen, J., Johansson, A., Mitchell, R.N., Palin, R.M., Condie, K.C., Spencer, C.J., 2022. On the enigmatic mid-Proterozoic: Single-lid versus plate tectonics. Earth Panet. Sci. Lett. 594, 117749.
Rosenbaum, G., 2018. The Tasmanides: Phanerozoic tectonic evolution of eastern Australia. Annu. Rev. Earth Planet. Sci. 46, 291–325.
Rozel, A.B., Golabek, G.J., Jain, C., Tackley, P.J., Gerya, T., 2017. Continental crust formation on early Earth controlled by intrusive magmatism. Nature 545, 332–335.
Sawkins, F.J., 1972. Sulfide ore deposits in relationship to plate tectonics. J. Geol. 80, 377–397.
Sawkins, F.J., 1990. Metal Deposits in Relation to Plate Tectonics. In: second edition. Springer-Verlag, Berlin Heidelberg, p. 461.
Schellart, W.P., 2008. Subduction zone trench migration: Slab driven or overriding-plate-driven? Phys. Earth Planet. Inter. 170, 73–88.
Schellart, W.P., Rawlinson, N., 2010. Convergent plate margin dynamics: new perspectives from structural geology, geophysics and geodynamic modelling. Tectonophysics 438, 4–19.
Schellart, W.P., Stegman, D.R., Freeman, J., 2008. Global trench migration velocities and slab migration induced upper mantle volume fluxes: constraints to find an Earth reference frame based on minimizing viscous dissipation. Earth Sci. Rev. 88, 118–144.
Sillitoe, R.H., 1972. A plate tectonic model for the origin of porphyry copper deposits. Econ. Geol. 67, 184–197.
Sinclair, W., 2007. Porphyry deposits. Geol. Assoc. Can. Min. Dep. Div. Spec. Pub. 5, 223–243.
Singer, D.A., Berger, V.I., Moring, B.C., 2008. Porphyry copper deposits of the world: database and grade and tonnage models, 2008. U.S. Geol. Surv. Open File Rep. 2008-1155.
Sizova, E., Gerya, T., Brown, M., Perchuk, L.L., 2010. Subduction styles in the Precambrian: insight from numerical experiments. Lithos 116, 209–229.
Sizova, E., Gerya, T., Brown, M., 2014. Contrasting styles of Phanerozoic and Precambrian continental collision. Gondwana Res. 25, 522–545.
Smithies, R.H., Champion, D.C., 2000. The Archaean high-Mg diorite suite: links to tonalite–trondhjemite–granodiorite magmatism and implications for early Archaean crustal growth. J. Petrol. 41, 1653–1671.
Smithies, R.H., Champion, D.C., Sun, S.-S., 2004. The case for Archaean boninites. Contrib. Mineral. Petrol. 147, 705–721.
Smithies, R.H., Van Kranendonk, M.J., Champion, D.C., 2006. The Mesoarchaean emergence of modern style subduction. Gondwana Res. 11, 50–68.
Sobolev, S.V., Brown, M., 2019. Surface erosion events controlled the evolution of plate tectonics on Earth. Science 570, 52–57.
Stegman, D.R., Schellart, W.P., Freeman, J., 2010. Competing influences of plate width and far-field boundary conditions on trench migration and morphology of subducted slabs in the upper mantle. Tectonophysics 483, 46–57.
Stern, R.J., 2007. When and how did plate tectonics begin? Theoretical and empirical considerations. Chi. Sci. Bull. 52, 578–591.
Stern, R.J., 2020. The mesoproterozoic single-lid tectonic episode: prelude to modern plate tectonics. GSA Today 30, 4–10.
Stern, R.J., Gerya, T., Tackley, P.J., 2018. Stagnant lid tectonics: Perspectives from silicate planets, dwarf planets, large moons, and large asteroids. Geosci. Front. 9, 103–119.
Stern, R.J., Moghadam, H.S., Pirouz, M., Mooney, W., 2021. The Geodynamic Evolution of Iran. Annual Review of Earth and Planetary Sciences 49, 9–36.
Stevenson, D.J., 2003. Styles of mantle convection and their influence on planetary evolution. Compt. Rendus Geosci. 335, 99–111.
Tang, M., Chu, X., Hao, J., Shen, B., 2021. Orogenic quiescence in Earth's middle age. Science 371, 728–731.
Tkachev, A.V., 2011. Evolution of metallogeny of granitic pegmatites associated with orogens throughout geological time. Geol. Soc. London Spec. Pub. 350, 7–23. https://doi.org/10.1144/SP350.2.
Turcotte, D.L., Schubert, G., 2002. Geodynamics – Applications of Continuum Physics to Geological Problems, second edition. Wiley, New York.
van Hunen, J., Allen, M.B., 2011. Continental collision and slab break-off: a comparison of 3-D numerical models with observations. Earth Planet. Sci. Lett. 302, 27–37.
van Hunen, J., Moyen, J.-F., 2012. Archean subduction: fact or fiction? AnnuRev. Earth Planet. Sci. 40, 195e219. https://doi.org/10.1146/annurev-earth-042711-105255.
van Hunen, J., van der Berg, A.P., 2008. Plate tectonics on the early Earth: limitations imposed by strength and buoyancy of subducted lithosphere. Lithos 103, 217–235.
Van Kranendonk, M.J., Smithies, R.H., Hickman, A.H., Champion, D.C., 2007. Secular tectonic evolution of Archean continental crust: interplay between horizontal and vertical processes in the formation of the Pilbara craton, Australia. Terra Nova 19, 1–38. https://doi.org/10.1111/j.1365-3121.2006.00723.x.
Van Schmus, W.R., 1995. Natural radioactivity of the crust and mantle. In: Ahrens, T.J. (Ed.), A Handbook of Physical Constants. American Geophysical Union, Washington, pp. 283–291.
van Thienen, P., Vlaar, N.J., van den Berg, A.P., 2004. Plate tectonics on the terrestrial planets. Phys. Earth Planet. Inter. 142, 61–74.
Vearncombe, J.R., Barley, M.E., Eisenlohr, B.N., Groves, D.I., Houstoun, S.M., Skwarnecki, M.S., Grigson, M.W., Partington, G.A., 1989. Structural controlos on mesothermal gold mineralization: examples from the Archean errances of southern Africa and Western Australia. Econ. Geol. Mon. 6, 124–134.
Weiss, Y., McNeil, J., Pearson, D.G., Nowell, G.M., Ottley, C.J., 2015. Highly saline fluids from a subducting slab as the source for fluid-rich diamonds. Nature 524, 339–342.
Wilson, J.T., 1966. Did the Atlantic close and then re-open? Nature 211, 676–681.
Wyman, D.A., Kerrich, R., 2012. Geochemical and isotopic characteristics of Youanmi terrane volcanism: the role of mantle plumes and subduction tectonics in the western Yilgarn Craton. Austr. J. Earth Sci. 59, 671–694.
Wyman, D.A., Bleeker, W., Kerrich, R., 1999. A 2.7 Ga komatiite, low Ti tholeiite, arc tholeiite transition, and inferred proto-arc geodynamic setting of the Kidd Creek deposit; evidence from precise trace element data. Econ. Geol. Mon. 10, 511–528.