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#### **ORIGINAL PAPER**



## Metallogenic models as the key to successful exploration — a review and trends

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#### Abstract

Metallogeny is the science of ore and mineral deposit formation in geological space and time. Metallogeny is interdisciplinary by nature, comprising elements of natural science disciplines such as planetology to solid state physics and chemistry, and volcanology. It is the experimental forefront of research and bold thinking, based on an ever-growing foundation of solid knowledge. Therefore, metallogeny is not a closed system of knowledge but a fast-growing assemblage of structured and unstructured information in perpetual flux. This paper intends to review its current state and trends. The latter may introduce speculation and fuzziness. Metallogeny has existed for over 100 years as a branch of Earth Science. From the discovery of plate tectonics (ca. 1950) to the end of the last century, metallogeny passed through a worldwide phase of formally published 'metallogenetic' maps. In the last decades, a rapidly growing number of scientists, digitization and splendid new tools fundamentally boosted research. More innovations may be expected by the growing use of an evolving systematic 'Geodata Science' for metallogenic research by an increasingly global human talent pool. Future requirements for metallic and mineral raw materials, especially the critical natural elements and compounds that are needed for the nascent carbon-free economy, already drive activities on stock markets and in the resource industry. State geological surveys, academia and private companies embrace the challenges. The new age requires intensified metallogenic backing. In this paper, principles of metallogeny are recalled concerning concepts and terms. A metallogenic classification of ore and mineral deposits is proposed, and the intimate relations of metallogenesis with geodynamics are sketched (ancient lid tectonics and modern plate tectonics). Metallogenic models assemble a great diversity of data that allow an ever better understanding of ore formation, foremost by illuminating the geological source-to-trap migration of ore metals, the petrogenetic and geodynamic-tectonic setting, the spatial architecture of ore deposits and the nature and precise timing of involved processes. Applied metallogeny allows companies to choose strategy and tactics for exploration investment and for planning the work. Based on comprehensive metallogenic knowledge, mineral system analysis (MSA) selects those elements of complex metallogenic models, which are detectable and can guide exploration in order to support applications such as mineral prospectivity mapping, mineral potential evaluation and targeting of detailed investigations. MSA founded on metallogenic models can be applied across whole continents, or at the scale of regional greenfield search, or in brownfields at district to camp scale. By delivering the fundamental keys for MSA, supported by unceasing innovative research, the stream of new metallogenic insights is essential for improving endowment estimates and for successful exploration.

Keywords Metallogeny  $\cdot$  Gold  $\cdot$  Lid tectonics  $\cdot$  Plate tectonics  $\cdot$  Metallogenic models  $\cdot$  Metallogeny in exploration  $\cdot$  Mineral system analysis

Dedicated to Prof. Dr. Ing. Friedrich-Wilhelm Wellmer.

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#### Introduction

The Earth's growing population and the steady move of humanity to higher living standards cause an ever-increasing consumption of natural resources, in spite of great efforts to 'make more with less'. Although in principle, metals and minerals are plentiful on the Earth, their provision to societies implies never-ceasing efforts to replace extracted reserves with ore in place. Copper, for example, is one of the metals, the consumption of which is predicted to increase far over past projections because of the world's decarbonation and electrification. In spite of prophets of looming scarcity, future 'ultimate' resources of copper are huge; there are good arguments for giant accessible resources at a depth down to 3.3 km below ground level (Arndt et al 2017). Equivalent arguments apply to other metals and minerals. Can metallogeny be the toolbox for locating these hidden deposits?

Moreover, annually, new metals, minerals, compounds or elements are declared as critical (e.g. CMMI 2021; European Commission 2020) as their essential role in the present and future economy is recognized. For some, such as lithium, cobalt, gallium and vanadium, consumption is predicted to explode.

As demand rises and existing mines deplete reserves, more deposits must be found, developed and exploited. This depends on preconditions such as lively stock markets that collect the required funds from investors. Growing restrictions to exploration and mining are environmental, social, and governance (ESG) issues that may become the main reason for metal and mineral shortages, more so than direct reserve depletion (Jowitt et al 2020). This shifts exploration into 'mining-friendly' or remote areas, and extraction toward giant underground operations, although there are strong economic and other arguments for opencut mining (Ericsson et al 2019). At the same time, research toward zero-entry autonomous mining has been launched by the large mining concerns. Unconventional metal sources that allow extraction without breaking, shifting and milling rocks are considered. Brines below active or dormant volcanos, for example, may deliver Cu, Li, Zn, Pb, Au and Ag (Blundy et al 2021).

Exploration methods that are founded on searching the Earth's surface for outcropping indications of mineralization recede in relevance, although subtle indications of buried ore deposits such as hydrothermal alteration halos or geochemical anomalies remain to be targets, and new shallow deposits are being found. Examples for deep search are gold-rich porphyry copper deposits that are sought by drilling for blind deposits beneath advanced argillic lithocaps and to depths of 1000 m and more (Sillitoe 2020a). The giant magmatichydrothermal, subvolcanic, low-sulphur, iron oxide-copper-gold (IOCG) deposit Olympic Dam (Australia), covered by > 250 m of overburden, was discovered by drilling high-amplitude Bouguer gravity and aeromagnetic anomalies. The motivation for the search had been satellite-image lineaments and copper-depleted basaltic rocks (Skirrow et al 2019). As shown by these examples, the search horizon is gradually pushed to greater depths. Consequently, we argue that ever better metallogenic models are required to find the next generation of ore deposits hidden below the surface.

Interestingly, metallogeny is more intensively and regularly used in brownfield exploration, extending resources near existing mines (Vearncombe and Phillips 2020), rather than in greenfield search, distant from established mines. In the second case, the nature of the target is necessarily reduced to some discoverable essentials of the respective class, whereas in the first, metallogenic details are fully known.

The term *metallogeny or metallogenesis* (from Greek *genesis* = origin) designates the science or the study *of the origin and distribution of mineral deposits in space and time* (de Launay 1905, and later books). Today, we should add: 'especially with regard to petrogenetic, tectonic and geodynamic process systems'. Following Lindgren (1909), who seems first to have used the term 'metallogenetic epoch', we strive to understand the geological timing of metallogenesis; the latter term rather designates the operation of metallogenic process systems. Metallogeny includes both metalliferous and non-metallic mineral deposits; for the latter, 'minerogeny' can be used. Note that the adjective form of the word 'metallogeny' is metallogenetic (*see* Lindgren 1909), although the abbreviated 'metallogenic' is commonly used.

De Launay (1905) already suggested that metallogenic understanding greatly assists in the search for ore. In the second half of the twentieth century, a new move towards realization of this hope came in the form of metallogenic mapping. For the first time in human history, the general public gained access to elementary information about global raw material deposits.

*Metallogenic maps* were produced in order to allow a synopsis of metallogenic, geological and basic economic data of ore deposits. A generalized geological background was used to display information on the main metals and elements contained, location, size, form and nature of deposits (ANNEX Fig. 1a, b). Many countries published national metallogenic maps, often advised and supported by UNESCO. Since the turn into the twenty-first century, digital maps and supporting mineral deposit data banks are replacing the printed media. The transition is marked by the 1:5,000,000 International Digital Metallogenic Map of Africa, sheets 5 and 6 (South of the Equator) compiled by Veselinovic-Williams et al. (1999) in GIS (geospatial/geographic information system) technology. The flood of digitization continues to rise unabatedly.

At about the same time, Wyborn et al. (1994) proposed a systematic approach to metal exploration in Australia, calling for *mineral system analysis (MSA)*, similar to the principles of the *petroleum system* (Magoon and Dow 1994). The latter had been conceived by Dow (1972) and, because of its demonstrated success in exploration, was quickly taken up by the global hydrocarbon industry. The gist was that by starting studies from the source rock, its origin, maturation and oil yield, the potential flow paths of oil fluids,

to charging traps, boosted modelling the system. Magoon and Sánchez (1995) wrote: 'As our ability to characterize and map a petroleum system improves, exploration risk decreases, and the probability of success increases'. Meanwhile, various data types and techniques are integrated towards a holistic petroleum system analysis (PSA). Big Data from basin analysis, wells, logs, cores, organic matter maturity, seismics and geochemistry offers the potential to make PSA an ever better predictor of the presence of hydrocarbons (Schlumberger 2022). In early 2021, accelerating its digital transformation, oil giant ARAMCO announced the launch of a new supercomputer (Dammam 7) that is among the ten most powerful in the world. It will assist in processing and analysing enormous oil and gas data sets. The aim is to use sophisticated imaging and deep-learning algorithms to run very detailed 3D Earth models.

Modern exploration for minerals and metals is based on mineral system analysis (Wyborn et al 1994). *Mineral system analysis (MSA)* as practiced among others in Australia, Canada and Scandinavia, and in the novel Critical Minerals Mapping Initiative (CMMI 2021; Hofstra et al 2021), is the compilation of geological processes, conditions and factors that contribute to the formation of a mineral deposit, and the selection of discoverable proxies. Basically, the aim is to build an exploration model of hydrothermal or magmatic deposits, from the source through migration to ore precipitation. Because of the derivation from petroleum system analysis (PSA), the essentials of both models, MSA and PSA, are similar. MSAs for other raw materials and genetic classes are multiplying.

So far, MSA is essentially a digital-age frame for quantitative metallogenic models that are introduced into the workflow as the 'knowledge base' (Skirrow et al 2019). In some cases, the metallogenic knowledge ('conceptual mineral system criteria') may be a minor part of the work ('hybrid or data-only MSA'). Data-driven methods based on geochemical, geophysical or remote sensing features of known mineral deposits can be used as training sets (Lawley et al 2021). Lawley et al.'s paper also serves as an example of the current trend that 'precompetitive' geoscience datasets are made available by state geological survey organizations, allowing the public to apply the unlimited power of ingenuity, and methods such as probability mathematics in the search for areas of higher prospectivity. The aim is to effectively reduce the search space of targeting for more detailed mineral exploration. In Canada, for example, less than 8% of map pixels contain more than 80% of indicated Ni mineralization (Lawley et al 2021).

In current ore geology research, metallogenic terms are frequently used, although most papers only treat single, specialized aspects of the whole source-to-deposit system. The usefulness of new contributions in exploration is often claimed by science authors but rarely backed up. This absence is comparable in company reports addressed to regulatory or listing authorities (e.g. SEDAR 2021) and in public websites of mining companies.

This review article intends to provide an overview and guide on metallogenic principles, models and terms, and metallogeny's use in exploration. Considering that the terms 'mineral system' and 'metallogenic system' are confusable, it will answer the question: *What is the difference, or relation, between metallogeny and mineral systems?* 

In this paper, gold is preferentially employed for reference cases, because methods vary greatly between different metals and other raw materials; also, gold is of highest interest considering that more than 50% of funds spent globally per annum for exploration target gold (S&P Global 2021). And, because 'orogenic' gold deposits deliver > 50 wt % of global mine production, orogenic gold metallogeny is more completely covered than other deposit classes. Finally, let us laud the numerous 'junior' exploration companies with limited resources targeting gold, often in greenfield settings. They are the innovative and most eager users of open-source precompetitive material.

#### Metallogeny principles and practice

Metallogeny (minerogeny) is the synthesis of scientific endeavours to understand ore and mineral deposit formation in space and time. Many thousands of scientists using a great variety of methods and tools contribute to the evergrowing body of metallogenic science. Metallogenic system research includes all scales, from planetary geodynamics to submicroscopic XCT (X-ray computed micro-tomography 3D) (e.g. Sayab et al 2020). Generally, exploration uses only some part of the acquired knowledge, narrowing the whole down to information and concepts ('mineral systems') that can be detected by broadly available methods such as geology, geochemistry, geophysics and remote sensing.

Metallogeny is not a consolidated body of knowledge but a fast-growing assemblage of structured and unstructured information in perpetual flux. Important targets of metallogenic studies are (i) the source of a valued element or compound, (ii) understanding of its mobilization and transport in space and time and (iii) the nature of the trap that caused the enrichment resulting in a mineral deposit. Each of these subsystems comprises processes and modifying factors that have to be elucidated.

Quantification of metallogenic analysis is increasing in importance. Statistical methods to identify metallogenic provinces and epochs were presented by Wilkinson and Kesler (2009), built from a large database on porphyry copper deposits. These authors proposed to determine regions with a special endowment (metallogenic provinces) and times of enhanced deposit formation (metallogenic epochs), after correcting the age-frequency and deposit-density distributions for loss by uplift and erosion as well as subsidence and burial. Although the authors discerned the Late Eocene and the Middle Miocene as epochs of enhanced porphyry copper mineralization in South America, they found that spatial distribution remains unpredictable. The key to *deciphering the predisposition of orogen segments for exceptional mineral endowment* (Sillitoe 2008) remains improved metallogenic understanding.

#### **Metallogenic terms**

Useful metallogenic concepts and terms include (modified from Petrascheck 1965; Neuendorf et al. 2005):

- *Metallogenic Domain* designates wide crustal sectors with a comparable geological evolution that may include a number of metallogenic provinces of different nature and ages; examples are the Himalayas, the South American Cordillera or the Tasman orogenic system of Eastern Australia.
- Metallogenic, or Ore Province describes regional units that host swarms of ore deposits such as the Paleozoic Victorian gold province of SE Australia, or the Early Neoproterozoic Kibaran rare metal (Sn, Ta, W) and gold province in the centre of Africa (Pohl et al 2013); metallogenic provinces extend over larger areas than districts.
- *Metallogenic District, or Zone* describes parts of an ore province; Sillitoe (2008) used the term 'metallogenic belt' such as the 'Cordilleran gold belts of North and South America' with the same meaning; deposits within such a zone are closely related, certain deposit types and styles predominate and metallogenic activity was typically restricted to a short geological time (5–20 My) (Sillitoe 2008); based on geology and geochemistry, Zheng et al. (2021) provide an exploration model of the eastern Tethys Himalayan metallogenic belt in Tibet.
- Metal Province contains the distribution of all deposits of one metal (or a related group of metals such as porphyry Cu–Au–Mo) irrespective of their age; this may illuminate regions of possible metallogenic heredity (recurrent ore formation in geological time).
- Metallotects are geological features that are related to formation or localization of mineral deposits; they include mantle structures (e.g. a slab window) or major crustal features such as the Boulder Lefroy-Golden Mile fault system at Kalgoorlie in Western Australia (McDivitt et al 2020), or ancient continental margins that may have acted as conduits for mineralizing liquids or fluids ('sutures') (e.g. Korsch and Doublier 2016), but also metamorphic, volcanic and plutonic centres (e.g. alkali–carbonatite complexes), regional geochemical barriers (the European Copper Shale) and discordances (uranium in the

Athabasca province). The term 'ore control', however, is preferably used to describe the causes for enrichment within individual deposits, similar to 'ore shoot';

- The term *Metallogenic Epoch (or Episode or Event)* was first published by Lindgren (1909), at a time when age determination was restricted to geological observations. Absolute age determination by radioactive decay (Reiners et al. 2017) had not yet been discovered. Today, we might speak of the 'Middle Miocene (17–14 Ma) Gandese porphyry Cu-Mo event' in Tibet. 'Event' indicates a short flare-up forming related deposits within a district or a province.
- *Metallogenic Maps* cover a region or a map sheet, showing the distribution of ore and mineral deposits related to geographic location and geological features such as age, host rocks, style and tectonic, stratigraphic or petrographic trends.
- Metallogenic Models are conceptual and mainly theoretical representations of a metallogenic system in geoscientific language; parts can be investigated by mathematical, physical or chemical simulation, attempting to describe quantitative aspects.

The term metallogenic inheritance implies that mantle lithosphere or crust contains a geochemically distinct trace metal reservoir, which is the source for repeated mobilization and mineralization. An opposing hypothesis dismisses this notion and claims that ordinary crust or mantle can be the source for most ore deposits. The formation of fertile tin granites, for example, can be traced to average crustal concentrations of tin, the critical factor being highly efficient magmatic differentiation (Lehmann 1990). There is no doubt, however, that both crust and mantle are geochemically heterogeneous. Anomalous metal contents in the source are possible, and the heredity need not even be based on the anomaly of a specific ore element such as tin, but can be due to other parameters, e.g. redox state or elevated F, Cl, B and Li contents of source rocks that are conducive to mobilization and concentration of tin (Michaud and Pichavant 2020; Sillitoe 2008). Both source types, enriched or average, are feasible for ore deposit formation.

### Metallogenic classification of ore and mineral deposits

Currently, ore deposits are differentiated as *types* that are haphazardly, not systematically, named and do not follow a logical system. Deposit types of gold, for example, in order of decreasing endowment and overall economic importance, comprise the following:

Paleoplacer, orogenic, porphyry, epithermal, Carlin, geologically young placer, reduced intrusion related, volcanogenic massive sulphide (VMS), skarn, carbonate replacement and iron oxide-copper-gold (IOCG) (Sillitoe 2020a). Only considering supergiants, Kerrich et al. (2000) distinguished six classes of gold deposits. Although in many respects alike to typical orogenic gold, the giant Jiaodong Province (China) deviates in some features such as the wide age spread between the host rocks (Precambrian) and the time of gold mineralization (Mesozoic). Therefore, some proposed it to be a new 'Jiaodong gold type' (Qiu et al 2020; Yang and Santosh 2020). Age gaps between gold emplacement and host rocks, however, are not infrequent, although with about 2 Gy Jiaodong exhibits the largest.

In his introduction to the SEG volume on 'The World's Major Gold Deposits and Provinces' (eds Sillitoe et al. 2020b), Sillitoe (2020a) provides a thumbnail sketch of each economically important gold deposit type listed above, including geologic and economic characteristics and widely accepted genetic models, as well as briefly discussing aspects of their spatial and temporal associations and distributions.

It may be argued with Cleland et al. (2021), however, that a genuine genetic classification as opposed to 'types' could assist in the '*articulation of successful scientific theories*' and, with this, improve (exploration) models. Walshe et al.'s (2005) critique on the common *empirical basis of deposit classification*, and their call for *adventurous conceptual thinking to aid efficient mineral exploration*, appears not to have evoked a wide echo.

The answer may be a *metallogenic classification*: Because ores and useful minerals are basically rocks, although often rare ones, a petrogenetic approach is rational, and was already chosen by de Launay (1905), the founder of metallogeny. The main petrogenetic domains (rock-forming systems) are magmatism, sedimentation, diagenesis, metamorphism and supergene alteration (ANNEX Fig. 2). Parallel to other classification systems in science, these five petrogenetic clans are the stems for a branching order of genetic superclasses, classes and subclasses (Pohl 2020). The descriptive term 'Genetically related features' in the newly proposed deposit classification scheme for Critical Minerals Mapping by Hofstra et al. (2021) might be used for fine-tuning the coarse net here suggested.

Because of the dynamic nature of the Earth, nearly all kinds of mineral deposits are related to geodynamic and tectonic processes. Examples of geodynamic–tectonic settings since about 2.5 Ga are suprasubduction island arcs, submarine shelf rift or continental collision, due to 'plate tectonics' (Schettino 2015; Frisch et al 2011; Kearey et al 2009). From the formation of the Earth in the Hadean, approximately 4.5 billion years ago, and decreasing during the Archean until 2.5 Ga, however, the Earth's dynamics were possibly dominated by 'Lid Tectonics' characterized by a periodically destabilized oceanic crust system with protocontinents gradually growing in size and number (Bédard 2018) (see

'Metallogeny and non-uniformitarian models of ancient earth geodynamics: lid, or subcretion tectonics').

Combining a petrogenetic classification with the geodynamic-tectonic setting should result in a useful metallogenic categorization as described for a general case by Cleland et al. (2021). In fact, this information is already now widely provided in metallogenic publications (e.g. Sillitoe 2008), without, however, taking the step to a formal classification. Patten et al. (2022) review ultramafic-hosted seafloor massive sulphide deposits (UM-SMS) and ultramafic-hosted volcanogenic massive sulphide (UM-VMS) deposits and carefully select sets of discriminant parameters for each tectonic environment and deposit type (the metallogenic class). The discriminant parameters are multi-scale (regional, district, deposit, mineralogical) and multi-disciplinary (tectonic, structural, petrologic, geochemical) to ensure a high degree of confidence. Three tectonic environments are recognized as relevant settings: mid-ocean ridge (MOR), ocean-continent transition (OCT) and supra-subduction-zone (SSZ) settings. Deposits are evaluated via matrix calculations, which allocate a degree of confidence to the tectonic environment and deposit classification (Patten et al 2022).

The porphyry Cu–Au class in the Andes, for example, might be called 'magmatic-hydrothermal diorite familyrelated porphyry Cu–Au deposits set in suprasubduction continental (Cordilleran) arcs'. This short designation should, of course, be supplemented by details.

#### Metallogeny, geodynamics and deep time

Mineral and metallic accumulations result from process systems of the dynamic Earth (Turcotte and Schubert 2014). Geodynamics is driven by secular planetary cooling. The Earth appears to be unique among planets so far known in space by an evolution towards plate tectonics and teeming life. Also unique is the abundance of water, in the atmosphere, in the geosphere and in the oceans. According to present-day understanding, primordial Earth formed during accretion and melting of cosmic matter. The planet's magma ocean stage facilitated differentiation of the mantle and the metallic core, which abstracted the siderophile elements (Fe, Co, Ni, Mo, PGE, C, P, Ge, Sn and Au), and produced the primitive mantle composition (Allègre 2008). The surface of early Earth, however, likely resembled other rocky planets and moons by the formation of a thin and initially stagnant crust (a 'lid') that enclosed a convecting hot mantle. Throughout geological history, the Earth's mantle was the driver and source of many ore forming systems. The Earth's abundance of water is taken for granted, although most metallogenic factories would not function without H2O. Hydrothermal ore formation is ubiquitous (Pirajno 1992).

In the last one or two decades, the transition from (1) the Earth's early stagnant shell pierced by volcanos, to

(2) an increasingly mobile oceanic komatiite-basalt crust with accretionary continental patches, followed by (3) first tentative spots of subduction ('proto-plate tectonics'), and finally (4) to modern plate tectonics (also confusingly by some called 'mobile lid stage') feeds a lively debate. For the Hadean (~4600-4000) and the Archean Eon (4000-2500 Ma), defenders of an early start of plate tectonics as the dominant geodynamic regime ('uniformitarians', e.g. Windley et al. 2021) were contradicted by a wave of various non-uniformitarian models. The latter include mainly vertical tectonics, such as heat pipes, gravity-driven sagduction, diapirism, delamination, drip tectonics and stagnant and mobile lid tectonics. Kamber (2015), for example, suggested that long-lived, slowly maturing, thick cratonic nuclei originated in the Archean. Oceanic basins did exist, but Archean oceanic lithosphere containing evidence for spreading is rarely preserved. Via repeated remelting, heatproducing K, U and Th were strongly distillated into the upper layer, causing non-uniformitarian geological phenomena. At about 3.8 Ga, geochemical signatures of zircons in the Barberton Greenstone Belt start showing similarities to those of zircons derived from modern subduction zones (Drabon et al. 2022). Garde et al. (2020) cite about 30 different papers, which suggest an onset of plate tectonics at times ranging from the early Hadean to the Neoproterozoic (700 Ma).

Hawkesworth et al. (2020) systematically reviewed the weight of proxies that have been used as evidence for the earliest onset of plate tectonics at the global scale, including paired metamorphic belts, magma geochemistry, the first dyke swarms, large sedimentary basins, high-pressure metamorphism and evidence for crustal thickening. They settle on a combination of the first supercontinents/supercratons, dyke swarms, oldest granulites, slowing crustal growth and the first peak of crustal reworking as indicated by Hf isotope ratios in zircon, of significant peaks in the age distribution of zircons and of juvenile crust tending from mafic to more intermediate compositions. The overall conclusion is that the end of the Archean is the most likely time, when plate tectonics became the dominant tectonic regime on Earth (Hawkesworth et al. 2020).

Meanwhile, the debate is rekindled by two reports from regions that affirm Archean plate tectonics, although not globally but restricted to individual cratons: (1) reviewing extensive work covering the 700-km-long North Atlantic Craton (NAC) of West Greenland, Garde et al. (2020) present evidence for Meso-to-Neoarchean operation of plate tectonic processes. This includes rock geochemistry, structural style, zircon and whole-rock Hf isotope geochemistry, the presence of mafic to intermediate volcanic belts (supporting formation by modern-style plate tectonic processes with slab melting of wet basaltic oceanic crust) in island arcs and active continental margins. Evidence for tectonic convergence, accretion, collision and high-pressure metamorphism between terranes was observed. Geochemical modelling of the Eoarchean Isua basalts, however, disproves subduction and plate tectonics as an agent of petrogenesis in this unit of the NAC but implies the activity of a mantle plume and/or a heat pipe (Rollinson 2021). Mineralizations in the NAC include banded iron formations (BIF), chromite, unspecified gold in the famous Eoarchean Isua supracrustal belt and more than a dozen sites of epithermal gold with associated hydrothermal alteration in andesitic-dacitic metavolcanic arcs; at one site, hydrothermal arsenopyrite was dated at 3.18-3.13 Ga (Mesoarchean). Mineralization resembling the deposits in Tethyan ophiolites of the eastern Mediterranean ('Cyprus type sulphides') was located in a Mesoarchean supra-subduction zone forearc (Garde et al. 2020). Typical for Archean orogens, the style of the NAC is predominantly accretionary. Accretionary orogens are mainly built from small fragments of mid-ocean ridges, ophiolites, oceanic plate blocks, seamounts, oceanic plateaus and island arcs (Windley 1995). Archean Earth's lithospheric plates were formed by oceanic tectonics of isolated short-length compressive structures. The modern global network of plate boundaries evolved later (Garde et al. 2020).

A second recent paper (2) describes the Neoarchean 1600-km-long suture between two blocks of the North China Craton (NCC), exposed in the Central Orogenic Belt (Zhong et al. 2021). In this collision, subduction and large-scale horizontal plate motions culminated in the emplacement of a series of subhorizontal fold nappes with regional-scale overturned limbs, onto a formerly distant continental margin, very similar to Phanerozoic collisional orogens such as the European Alps. Observations supporting this interpretation include evidence for Mariana-type subduction-initiation events, orogenic mélange with MORB-type ophiolitic blocks, paired metamorphic belts, ultra-high pressure mineral inclusions and forearc-ophiolitic remnants. Parts of the Central Orogenic Belt host important Mesozoic gold districts that may be derived from deep Archean sources (cf. 2.2; Yang and Santosh 2020).

The unidirectional evolution of the Earth in time is of superordinate rank compared to geodynamic cycles. In the ~4600 million years (Myr) of geological history, Earth systems experienced severe changes of the atmosphere, the biosphere, the oceans and the mantle. Metallogenic evolution, of course, reflects these changes (Goldfarb et al 2010). An important factor controlling the distribution of ore deposits in geological time is the preservation potential.

### Metallogeny and non-uniformitarian models of ancient earth geodynamics: lid, or subcretion tectonics

Hadean zircons from the Jack Hills (Western Australia) and other localities currently are the only window into the

earliest terrestrial felsic crust. They formed at shallow depths involving a primordial weathered ultramafic protocrust and local basaltic intrusions (Borisova et al 2021). Non-uniformitarian models have been proposed in order to explain the peculiar geological features of ancient cratons. Lid tectonics conceptualize a system of processes in the mantle, the oceanic realm and the formation and nucleation of protocontinental crust and lithosphere (Bédard 2018; Kamber 2015). Although details of lid tectonics remain disputed, this hypothesis is a valuable contribution to discussions concerning the transition of the Earth system from the magma ocean to modern plate tectonics.

Stagnant lid tectonics may have started in the darkness of the Hadean with a thin crust on the Earth's magma ocean and ended with the Archean when modern-type plate tectonics were fully evolved (Hawkesworth et al. 2020; Palin et al 2020; Mole et al 2019). Episodically during lid tectonics (Bédard 2018), heat accumulation resulted in cracking of the lid along fissures that became oceanic upwelling zones (OUZOs). Stored heat was released by mantle overturn events that produced giant outpourings of basalts and komatiites, which were derived from fertile mantle or mantle plumes (Wyman 2020). Above OUZOs, differentiation of felsic melts formed embryonic patches of Archean felsic crust (protocontinents). Likely, overturn phases were protracted (ca. 100 Myr), and alternated with long stagnant-lid intervals (ca. 300-500 Myr). Between OUZOs, most of the Earth should have been covered by a mosaic of intermittent basaltic and komatiitic shield volcanos (Hawkesworth et al. 2020; Bédard 2018). Wyman (2020, 2018) discusses the role of plumes and boninites, and suggests change between stagnant and mobile phases of lid tectonics. The surface of planet Venus may preserve a likeness to a stagnant lid state of ancient Earth (ANNEX Fig. 3).

Protocontinents were moved by shallow mantle flow alike to 'continental drift' (ANNEX Fig. 4). The leading edge of drifting protocontinents would have been convergent margins (orogens) characterized by terrane accretion, imbrication, subcretion and anatexis of unsubductable oceanic lithosphere (sensu stricto stagnant lid tectonics: Bédard 2018). Collision and amalgamation of protocontinents gradually formed cratons and supercratons (Liu et al 2021a, b, c). A detailed growth history of the long-lived Yilgarn Craton in W-Australia, based on Hf-isotopes in zircons (Mole et al 2019), affirms a minor role of subduction and adds details on the lid tectonic model.

Until the Neoarchean, subduction was not possible because the strength of the lithosphere was too low to be thickened by tectonic processes, and to be subducted (Hawkesworth et al. 2020). Yet, imbrication or subcretion of metabasaltic/komatiitic packages would introduce large volumes of wet rocks to depths where they could yield anatectic, syn-kinematic melt that crystallized to TTGs (barren tonalite, trondhjemite and granodiorite: ANNEX Fig. 4). Roman and Arndt (2020) maintain, however, that only subduction, not sagduction, can explain the generation of these granitoid magmas. The characteristic Mesoarchean domeand-keel architecture in the *Carajás* Province, Brazil, displays TTG domes that are encircled by keels of greenstone belts, which host gold deposits; Neoarchean to Proterozoic reworking produced banded iron formations and IOCG (iron oxide copper gold) deposits (Costa et al. 2019). Eclogitization and delamination created space for hot mantle to well up and interact with fluids and melts emanating from the basaltic mass, generating subordinate suites of syncollisional magmas with arc-like geochemical signatures.

Metallogenic systems in terms of lid tectonics are sketched as follows (ANNEX Fig. 4; Bédard 2018): Within the basalt-komatiite units, thick BIF (Algoma type, or volcanogenic exhalative basalt-related banded iron formations) and chert sequences are intercalated. Komatiites (Arndt et al 2008) host orthomagmatic rivers of Fe-Ni sulphide in submarine lava channels or as disseminated bodies in subvolcanic intrusions (Barnes et al 2017). Archean volcanogenic polymetallic massive base metal-sulphide (VMS) deposits may have formed from fluids mobilized by reheating of the hydrated submarine volcanic pile, caused by new magma pulses. Deep sections of imbricated foreland terranes were the source of gold-carrying metamorphic fluids and magmas, resulting in orogenic or volcanic-epithermal Au deposits. In the Neoarchean Abitibi greenstone belt of the supercraton Superia, large faults tapped particularly fertile upper mantle to lower crustal gold reservoirs; metamorphic fluids produced rich synvolcanic epithermal and synmetamorphic orogenic gold deposits. The Abitibi gold province had a premining endowment of nearly 10,000 t Au (Dubé and Mercier-Langevin 2020).

Archean to Paleoproterozoic orogenic gold deposits typically occur in long-lived transpressive shear zones affecting metamorphic belts. Europe's largest gold producer, the Suurikuusikko gold deposit (*Kittilä Mine*) in Finland, with a 2019 production of 186,000 oz and a total resource of about 9 Moz Au, for example, was discovered during road works in a major strike–slip shear zone of the Central Lapland Greenstone Belt. Mineralization at Suurikuusikko was controlled by changing stress vectors of tectonic activity (Sayab et al 2020). The frame was the Svecofennian orogeny, which is dated to between ca. 1.92 and 1.76 Ga.

The supergiant Neoarchean Kalgoorlie Gold Camp in the Yilgarn Craton of Western Australia was discovered by prospectors in 1893. Similar to Kittilä mine, it is also situated in a prominent structural corridor that is one of the controlling factors of ore location. Others include prograde metamorphism, magmatism and orogeny, which may have been part of the amalgamation of the supercraton Superia (Wang et al 2020a, b; Wyman 2020). The host rocks are greenstone-dominated, with preserved greenstone sequences mainly relating to episodes of plume-crust interaction (Smithies et al 2018). Plume impingement would be expected to drive greater melting by increasing temperatures and geothermal gradients, as well as reactivating pre-existing metasomatized SCLM pockets (Mole et al 2019). The majority of deposit styles throughout the Eastern Goldfields Superterrane are quartz-carbonate veins and stockworks; others include sulfidic replacement in banded iron formation, intrusion-hosted vein stockwork and disseminated mineralization and gold-bearing skarn (Tripp et al 2020).

Apart from numerous smaller deposits, the Golden Mile provided most of the total production in the Eastern Goldfields and holds the majority of remaining reserves and resources. Its total endowment is estimated at ~ 2300 t Au. Precise dating of gold mineralization revealed a protracted nature from ca. 2675 to 2640 Ma and reflects the interplay of early magmatic and late metamorphic hydrothermal fluid systems in the formation of hybrid intrusion-related and metamorphic orebodies (McDivitt et al 2022, 2020). Stocks and dykes of high-Mg monzodiorite-tonalite porphyry are part of a late-orogenic (2665-2645 Ma) mantle-derived suite of adakitic affinity; hornblende and apatite compositions indicate that these intrusions were characterized by high water contents (5-6 wt % H2O in melt), by high oxidation states  $(\delta NNO + 1.0 \text{ to} + 2.4 \log \text{ units})$  and by contents of igneous anhydrite (Mueller et al 2016). Originally discovered in the Pacific Ring of Fire, adakites are andesitic to dacitic magmatic rocks that characterize convergent plate margins, originating from a subducting slab or a fertilized mantle source at high pressure. The essential role of mantle fertilization for gold mineralization in accretionary orogens was first emphasized by Hronsky et al. (2012). Deduced from Hf-isotope data in zircon, the background geodynamic setting in the Yilgarn was accretionary plume-lid tectonics (Mole et al 2019). The heat source driving the system at Kalgoorlie may have been a mantle plume.

The thorough review by Palin et al. (2020) suggests that plate tectonics started at about 3 Ga. Most likely, lid tectonics ended in the late Archean (Liu et al 2021a, b, c; (Hawkesworth et al. 2020; Mole et al 2019). Nonuniformitarian geodynamic models including the lid tectonics hypothesis (LTH) are still controversial, however, and much work remains to be done (Bédard 2018). By LTH, many existing narratives in geology are brought into question, including current metallogenic models. Studies of Archean metallogeny (e.g. in Sillitoe et al. 2020b) are yet to include the new concepts. A wave of new discoveries might be the consequence.

#### Metallogeny and plate tectonics

The Earth's mantle convection facilitates planetary heat loss. At the surface, it is manifested by 'modern' plate tectonics (Schettino 2015). Plate tectonics is 'A theory of global tectonics powered by subduction, in which the lithosphere is divided into a mosaic of plates, which move on and sink into weaker ductile asthenosphere. Three types of localized plate boundaries form the interconnected global network: new oceanic plate material is created by seafloor spreading at mid-ocean ridges, old oceanic lithosphere sinks at subduction zones, and two plates slide past each other along transform faults. The negative buoyancy of old dense oceanic lithosphere, which sinks in subduction zones, mostly powers plate movements' (Stern and Gerya 2018).

As shown above, global subduction-driven plate tectonics likely began in the Late Archean (Hawkesworth et al. 2020). This would explain kimberlite ages, the Neoproterozoic climate crisis and the acceleration of biologic evolution (Stern 2020). Modern plate tectonics are the main agent in the dynamic Earth system (Turcotte and Schubert 2014; Frisch et al 2011; Kearey et al 2009). Plate margins control a large number of mineral deposits (Yang et al 2022). Process systems of plate tectonics include a great part of the global *metallogenic factories* (Sillitoe 2020a; Sillitoe et al. 2020b; Pohl 2020; Huston et al 2016; Mitchell and Garson 1986) (ANNEX Fig. 5).

Intracontinental rifts, hot spots, mantle plumes and sedimentary basins (within-plate settings and incipient divergent plate boundaries) Typically, intracontinental rifting causes thinning of the continental crust, upflow of hot mantle, elevated heat flow and updoming of rift shoulders. Volcanic activity within the rift is a frequent consequence, organized into large centres (hot spots) that may be related to an asthenospheric bulge, to mantle plumes or to overheating (incubation) of the mantle. Globally, alkaline igneous complexes with carbonatites host significant orthomagmatic to hydrothermal PO<sub>4</sub>, Nb and REE deposits (Simandl and Paradis 2018; Goodenough et al 2016). Extension with a strong detachment vector may induce fluid convection that is unrelated to magmatism and causes formation of, for example, base metal, barite and fluorite deposits (Zappettini et al 2017).

*Mantle plumes* transfer heat from the core, and matter towards the Earth's surface, and are prominent metallogenic agents (Pirajno 2000). Plumes cannot be directly observed but geophysical methods provide images; likely, plumes are the cause of many within-plate geological processes. Rising from the immediate boundary layer near the core, some plumes sample material with high metal tenors that may be derived from the core. As the solid-state hot column ascends from depth, decompression induces partial melting that results in oceanic hot spot volcanism. Plume-related oceanic plateaux may be a potential source of gold (Bierlein and Pisarevsky 2008). Large igneous provinces (LIPs) may form, some of which have metallogenic significance. An outstanding example is the Siberian LIP that originated at the end of the Permian period (~250 Ma) and is related to the giant Ni-Cu-PGE deposits of Noril'sk. When plumes and associated melts encounter thick lithospheric mantle below cratons, flow is deflected towards thinner lithosphere, favouring higher partial melting and transfer of melt into the crust. Intrusions and volcanic activity appear preferentially along craton margins, which control many of the world's great Ni-Cu-PGE sulphide deposits (Griffin et al 2013). In the Deseado gold province of Patagonia, sub-continental lithospheric mantle (SCLM) fertilization by a mantle plume is demonstrated by Au particles in mantle xenoliths (Tassara et al 2017).

The evolution of passive continental margins, continent-ocean transition and the disruption of older ore provinces (divergent plate boundaries) Globally, suboceanic and subsalt strata of passive margins are locations of prodigious present hydrocarbon production and ongoing exploration. Barite may occur in sedimentary exhalative (sedex) deposits that form at within-plate locations, such as epicontinental shelf regions grading into rifts and passive continental margins. Monomineralic sedex barite or barite associated with base metals can occur in these settings as, for example, the giant Red Dog district, Alaska (Reynolds 2019). At Red Dog, massive Zn–Pb–Ag ore includes traces of Tl (<1.0 ppm), Sb (2.6 ppm), As (10.3 ppm) and *Ge* (0.7 ppm), but no Au.

The Pyrenean metallogenic domain (talc, barite, magnesite, Fe, Pb, Zn) is set in a mid-Cretaceous hyperextensional passive margin leading to exhumation of subcontinental mantle that triggered ubiquitous fluid migration. Although supporting data are yet rare, the genetic context of the Trimouns giant talc deposit with formation of this newly recognized plate-tectonic *ocean-continent transitional (OCT)* setting, also termed continent-ocean transition (COT), is very likely (Quesnel et al 2019). COTs with exhumed mantle domains are common and form about half of the world's present rifted continental margins (Sapin et al. 2021). The latter authors provide an analysis of submarine global continent-ocean transitions and elements for their classification, mainly based on data from the oil industry.

Seafloor spreading and the production of new lithosphere at mid-ocean ridges (oceanic-divergent, or 'constructive' plate boundaries) This geodynamic setting is the home of MOR-type metalliferous black smoker fields and of volcanogenic massive sulphide (VMS) mounds (ANNEX Fig. 5) that occur on land in ophiolites. Ophiolites are mafic and ultramafic rock bodies common in orogenic belts, which were formed by oceanic spreading processes that may have been *subduction-unrelated* (passive continental margin (CM), mid-ocean ridge (MOR) and plume-type (P), or *subduction-related* such as suprasubduction zone (SSZ, e.g. intra-oceanic primitive subduction initiation forearcs, and backarc basins) and volcanic arc (VA) ophiolites (Dilek and Furnes 2014).

The volcanogenic massive sulphide (VMS) superclass comprises a wide variety of geodynamic and petrogenetic settings. They occur throughout the geological past from as early as the Archean, and they appear to cluster in periods of supercontinent assembly (Huston et al. 2010). Generally, deposits occur at convergent plate boundaries, although the prevailing bimodal nature of related volcanic rocks and geochemical indices implies that most VMS were generated during phases of major crustal extension, possibly related to delamination followed by extensional collapse or slab rollback (e.g. in back arcs), resulting in rifting, subsidence and deep marine conditions. A newly recognized class are the ultramafic-hosted (UM-)VMS deposits that are often named 'ophiolite-hosted'. This group of more than sixty known deposits may host untapped mineral resources of a high potential (Patten et al 2022).

The relative complex fluid circulation pattern and fluid mixing leads to diverse styles of mineralizations such as chimney, massive sulphide mound, stockwork, breccia and quartz veins, associated with alteration types such as serpentinite, carbonate, talc and silica. Ore mineralogy is diverse but dominated by pyrrhotite, chalcopyrite, cubanite, sphalerite, pentlandite and pyrite. Marcasite, galena, magnetite, gold and Cu-rich phases related to seafloor weathering (e.g. covellite, digenite, atacamite) are also common. Ultramafichosted SMS deposits are enriched in Cu, Zn, Co, Ni and Au relative to mafic-hosted ones, which is commonly assumed to be related to leaching of metals from the ultramafic basement rocks, although a magmatic degassing source has also been suggested (Patten et al 2022). The newly discovered Cheoeum vent field of an ultramafic-hosted seafloor massive sulphide deposit is sited in the middle part of the Central Indian Ridge. Sulphide ore atop a chimney is characterized by high concentrations of Au (up to 17.8 ppm) and Sn (up to 1720 ppm) (Choi et al 2021). Volcanogenic massive sulphide Cu-Zn-Au-Ag deposits form in mid-oceanic or suprasubduction settings (ophiolite-hosted Cyprus class) (Bali et al 2020).

*Polymetallic nodules and crusts* occur in abyssal plains (~4000–6000 m water depth) of all major oceans as thin sheets rich in metals of economic interest such as manganese (Mn), nickel (Ni), copper (Cu), cobalt (Co), molybdenum (Mo), titanium (Ti), lithium (Li), platinum-group elements (PGE) and rare earth elements (REE), several of which are critical metals (Hein et al 2020). Apart from ophiolite-hosted

deposits on land, extraction of submarine resources is not imminent. All these metals may feed, however, alike to a giant conveyor belt (Pitcairn et al 2014), the fertilization process of the mantle wedge or subcontinental lithospheric mantle (SCLM) above subduction zones.

Subduction of lithospheric plates at convergent ('destructive') plate boundaries, island and continental ('Cordilleran') arcs, arc-hosted and back arc basins Subduction recycles oceanic lithosphere back into the mantle (ANNEX Fig. 5). The trace of subduction on the seafloor is marked by deep oceanic trenches that move oceanward (trench retreat). The passive migration of the upper plate in response to trench retreat ('suction') is one of the causes for Wegener's (1924) continental drift, whereas subduction and foundering of the oceanic slab is the main driving force of plate tectonics (Turcotte and Schubert 2014). Accretionary orogens constructed from fore-arc ophiolites, volcanic arcs, plutonic belts, continental fragments, terranes, back-arc and intra-arc sedimentary basins develop on the overriding plate. Many of the Earth's richest ore domains are found above subduction zones. Paradigmatic are the margins of the Pacific Ocean, which are largely formed by long-lived destructive plate boundaries. These are dotted by numerous ancient and active volcanic arcs and display a myriad of ore deposits. Flareup of fertile magmas may be caused by extraordinary heat pulses from the mantle, caused by slab tear, subduction of oceanic volcanos or plumes.

Most Cu-rich porphyry deposits formed during active subduction in continental ('Cordilleran') and island volcanic arcs. They are of magmatic–hydrothermal origin related to intrusive porphyry fingers, stocks or dykes, typically of dioritic, monzodioritic to quartz dioritic composition (Sillitoe 2020a). Episodes of tension in the generally compressive arc facilitate upflow. Postsubduction, collisional to extensional back-arc settings seem to favour Au endowment (Paolillo et al 2022; Chiaradia 2021). Porphyry gold deposits are distinguished by much lower (<0.25 wt %) copper contents than those defining the porphyry copper–gold class (Sillitoe 2008).

*Kışladağ* in western Anatolia, Turkey, is a recently discovered greenfield, magmatic–hydrothermal, gold-only porphyry deposit located in one of several mid- to late Tertiary volcanic complexes related to subduction along the Hellenic trench that lies to the Southwest in the Aegean Sea. Miocene magmatism was postcollisional and was focused in extension-related volcano sedimentary basins that formed in response to slab rollback and a major north–south slab tear. Multiple monzonite porphyry stocks are differentiated, of which the earliest (1 and 2) contain the highest grades with average median tenors of 0.64 and 0.51 g/t Au, respectively (Baker et al. 2020). Mafic rejuvenation of a slowly crystallizing magma reservoir below Kışladağ immediately preceded porphyry deposit formation. Zircon trace elements and geochronology (Paolillo et al 2022) suggest a longer and deeper evolution for the early fertile magmas compared to the later infertile magmas. Whole-rock Nd and Sr radiogenic isotopes show that under accelerated regional extension, magma evolution at Kışladağ was increasingly dominated by asthenosphere-derived melt input, which caused a loss in fertility of the system over time (Paolillo et al 2022). In 2020, total resources plus reserves of the mine amounted to ~ 17 Moz Au (Eldorado Gold Corporation 2021).

The supergiant Lihir (or Ladolam) mine (ANNEX Fig. 6; Papua New Guinea) exploits an alkalic epithermal, magmatic-hydrothermal gold deposit, discovered by rock chip exploration in 1982 that located auriferous alunite (Cooke et al 2020). In 2019, total resources were estimated at 690 Mt @ 2.3 g/t Au, equivalent to 50 Moz in situ gold. Ore bodies occur on the floor of a large volcanic amphitheater of Luise volcano, a Pleistocene stratovolcano built of shoshonitic volatile-rich, silica-undersaturated, and highly oxidized igneous rocks (Cooke et al 2020) comprising alkaline lavas and tuffs of trachybasalt, basaltic trachyandesite and latite. The deposit is remarkable for the overprinting of epithermal gold mineralization over earlier porphyry-style veins and altered rocks with abundant anhydrite and carbonate but low-grade Au. The transition was probably caused by the collapse of a sector of Luise volcano into the sea (Sillitoe 1994). In an extensional setting from 0.6 Ma onwards, the mineralization changed to epithermal-style with sulphide and adularia alteration, during which the main resource was emplaced. High-T geothermal activity is ongoing, and the recovered energy is used in the mine. Epithermal activity produced at least six discrete mineralized zones that are all dominated by refractory gold in arsenian pyrite. Gold is associated with adularia-pyrite-carbonate-anhydrite ± illite alteration assemblages, cemented breccias and veins that overprinted the early porphyry-style features. Bonanza gold grades are associated with late-stage quartz and/or anhydrite veins.

Lihir lies in a broad, complex deformation zone caused by convergence and collision of the Pacific and the Australian plate. The geodynamic setting is described as postcollisional and back arc by Cooke et al. (2020). Based on a synthesis of data from ship-based multibeam and seismic studies, satellite gravimetry, geochemistry and geochronology, Brandl et al. (2020) place it into a former forearc followed by displacement to its current location in a rear- or backarc setting relative to active subduction along the New Britain Trench. The zone broke into microcontinents when colliding with the Ontong Java Plateau (OJP). Protracted, transtensional motion between distinct crustal blocks controlled the location and timing of magmatism and mineralization (ANNEX Fig. 6).

Extensional (volcano-) sedimentary basins comprise various settings. Gold-rich volcanic massive sulphide (VMS) deposits — defined by Mercier-Langevin et al. (2011) as those containing above ~ 3.5 g/t Au — occur mainly in rifted magmatic arcs and immature back-arc basins marked by submarine bimodal volcanism of tholeiitic to calc-alkaline affinity (Sillitoe 2020a). Felsic domes and calderas are preferential locations of gold ore bodies that resemble in nature and geometry the more common base metal VMS class.

The epithermal, intermediate sulfidation, completely concealed *Fruta del Norte Au–Ag* deposit in Ecuador is situated in a 16-km-long pull-apart basin that occurs along an extensive strike–slip fault zone affecting the continental volcanic arc. Discovered in 2006 during greenfield exploration, it is remarkable by an average grade of 9.61 g/t Au and a total endowment of ~9 Moz Au. Known for much visible gold and bonanza grades, the ore is hosted by Jurassic andesite flows (Leary et al. 2020).

Similar to many Pacific rim countries, Aotearoa New Zealand's gold metallogeny is intimately linked to pulses of hydrothermal activity resulting from magmatism, metamorphism and tectonism. Situated at an active convergent plate boundary (Australia/Pacific), an accretionary orogen experienced extensional and contractional phases that control epithermal gold in the North Island and orogenic deposits in the South Island (Rowland 2021).

**Orogeny, collision, sutures and terrane accretion** Plate tectonics creates three different styles of orogens: (i) Tethyanstyle continent–continent collisional belts are thickened and characterized by nappe tectonics; sutures mark the final stage in the evolution of a Wilson Cycle (Windley 1995), (ii) circum-Pacific-style (Cordilleran) accretionary orogens, mainly growing by igneous processes, and (iii) volcanic island arcs and back-arc basins (Frisch et al 2011). A complicated geodynamic setting was presented by Weihed et al. (2005) for the evolution of the Fennoscandian Shield in the Paleoproterozoic when rapid accretion of island arcs and several microcontinent–continent collisions in a complex array of orogens were involved in short-lived but intensive orogenies accompanied by voluminous magmatism and fertile metallogenesis.

Oceans that are consumed by subduction, trench retreat and continental drift leave a suture in the newly welded continent that is often marked by ophiolites. Continental collision may lead to subduction of continental crust and lithosphere, although this is limited by the buoyancy of crustal rocks. The process results in thickened crust below collisional belts and the formation of profuse anatectic S-type granitoid melts. Less frequent are post-subduction porphyry Cu-Au and related epithermal gold deposits, which are formed where former magmatic arcs are involved in the collision. As sutures are principally subduction related, they may have a potential of old fertilized subcontinental mantle (ANNEX Fig. 5). The global paradigm of continental collision is the Himalayas. Terrestrial and satellite gravity data modelling by Singh and Mahatsente (2020) shows in detail how the lithosphere of the eastern Tibetan plateau is underlain by a low-velocity zone at shallow depths, which is interpreted as asthenospheric material in the uppermost mantle. Its upflow was enabled by a combination of lithospheric delamination and the slab break-off of the Greater Indian slab. The heat flow from the asthenospheric intrusion (>1100° C) was the cause for the formation of the recently discovered great Himalayas–Tibet metallogenic domain that contains four metallogenic belts (Zheng et al 2021).

Based on thermal regimes recorded in metamorphic rocks, volcanic suites and related xenoliths, and main mineralization types, Zhang et al. (2022a, b) propose to distinguish collisional orogens into *two fundamental types, cold and hot*. The European Alps, for example, mostly remained in a relatively cold regime from oceanic subduction to post-collisional stages, and are poorly endowed with ore deposits (Pohl 2020). The Himalayan–Tibetan orogens, however, rapidly reached and were maintained in a relatively hot regime during the whole course of the collision. Hot orogens are characterized by magmatic deposits (i.e. granite-related W–Sn deposits and porphyry Cu–Au deposits); the cause of greater heat flow is suggested to be delamination of suborogenic mantle lithosphere and upwelling of the asthenosphere (Zhang et al 2022a, b; Zheng et al 2021).

The continental crust of the lower plate can be subducted to depths of > 100 km and exhumed after ultrahigh-pressure metamorphism. Also, collision causes giant systems of hydrothermal fluid flow involving metamorphic, basinal and meteoric fluids. Similar features are reported from intercontinental mountain belts involving very narrow oceans and from purely intracontinental orogens. Typically, collisional orogens exhibit (i) granitoid-related deposits of tin, tungsten, gold and rare metals, (ii) deposits of the 'collisional gemstones' ruby and jade (Stern 2018) and (iii) deposits formed by migrating metamorphic fluids. Gold is especially common in this setting (orogenic gold deposits: Groves et al 2020).

Mineralization in orogenic belts is favoured by phases of extension or transtension, because melts and fluids can more easily rise to shallow depths. Extension may be related to causes such as colliding indentors, changes of plate convergence vectors, to lithospheric delamination (foundering of eclogitic lower crust and mantle) and to orogenic collapse, among other post-collisional processes.

Orogenic gold deposits (OGD) are widely believed to have formed in accretionary and collisional orogens (Groves et al 2020) at paleodepths of ~5 to 15 km from low-salinity, gold- and arsenic-bearing, aqueous-carbonic fluids generated by devolatilization reactions accompanying the downward transition from regional greenschist- to amphibolite-facies metamorphism (Gaboury 2019; Phillips and Powell 2010). Although the orogenic and back-arc setting unites OGD types, the group may comprise several different petrogenetic-tectonic classes (Pohl 2020).

The giant (> 20 Moz at 1 g/t) Au–Cu deposit *Telfer* in Western Australia is thought to be collisional and magmatichydrothermal in origin (Wilson et al 2020). Telfer occurs within the Neoproterozoic Paterson orogen between the West and North Australian cratons; thick marine siliciclastic greenschist-metamorphic folded and thrusted metasediments include pyrite and organic-rich shales. The district also contains magnetite- and ilmenite-series granitoids dated between ca. 645 and 600 Ma (Porter 2017). Au-Cu mineralization at Telfer was discovered in 1970 when a prospecting geologist found lenses of quartz-limonite gossans and limonitic siltstone; mining commenced in 1975 (Porter 2017). Gold is hosted in multistage, bedding-parallel quartz-dolomite-pyrite-chalcopyrite reefs and related discordant veins and stockworks of similar composition that were emplaced into two NW-striking doubly plunging domes. Mineralization is late orogenic in timing, with hot ( $\leq$ 460 °C), saline (< 50 wt % NaCl equiv) and carbonic ore fluids channelled into pre-existing domes along a series of shallow, ENEverging thrust faults and associated fault-propagated fold corridors. Based on the nature of the reduced Au-Cu-W-Bi-Te-Sn-Co-As assemblage, the hydrothermal fluids in Telfer ore, and widespread ilmenite-series granites locally associated with W skarn mineralization, Telfer is considered to be a distal, intrusion-related gold deposit. The copper content may be explained by the predominance of saline magmatic fluids in gangue assemblages cogenetic with ore (Wilson et al 2020). The plate tectonic setting was intracontinental dextral transpressive shearing in the Paterson Orogen in response to the collision of Neoproterozoic India with the western margin of Neoproterozoic Australia (Wilson et al 2020).

*Muruntau* in Uzbekistan is the world's largest sedimenthosted epigenetic Au deposit, with a premining resource of about 5300 t Au at an average grade of 3.5 to 4 g/t. Its discovery was due to follow-up work of geochemical As anomalies found during exploration for uranium (Seltmann et al 2020). Its geological frame is the accretionary South Tien Shan range, the southernmost part of the Central Asian orogenic belt, or Altaid orogen. In the late Paleozoic, the closure of ocean basins between the Siberian craton and the Kazakhstan, Tarim and North China blocks led to the formation of the Central Asian orogenic belt and included formation of the 2500-km-long and Au-rich Tien Shan belt.

The giant Muruntau deposit formed soon after suturing and development of a regional fold-and-thrust belt affecting Neoproterozoic to late Carboniferous turbidites, shales, molasse, cherts and carbonates (Seltmann et al 2020). Main ore-bearing rocks are early Paleozoic, siliciclastic metasediments in greenschist to amphibolite facies. These units enclose an extremely carbonaceous and pyritic sericite-chlorite schist member. The district exhibits outcrops of igneous rocks with I-, S- and A-type characteristics. In the mine, felsic, syenitic and lamprophyre dykes are frequent. A 4000-m-deep drillhole showed that the mineralized column extends all the way to this depth. Ore styles comprise mainly near-vertical thinly veined stockwork bodies that surround central quartz  $\pm$  K-feldspar veins. Proximal altered host rocks contain low-grade disseminated mineralization, the grades correlating with vein and veinlet density. Aqueous-carbonic ore-forming fluids deposited most gold at temperatures of  $400^{\circ} \pm 50^{\circ}C$  and at probable depths of 6 to 10 km. Along with the quartz gangue, the ore mineralogy comprises native gold (fineness ranging from 770 to 980), and arsenopyrite, pyrrhotite, base metal sulphides, scheelite, Bi tellurides, tetrahedrite and related Ag- and Sb-bearing sulfosalt minerals; traces of albite, dolomite, tourmaline, biotite and chlorite are also reported. The mineralization overprints a hornfels aureole formed during emplacement of a postcollisional granite (at ca. 290 Ma) at a depth between 6 and 10 km below the mine. The entire hydrothermal column is located within a wide zone of Mg-biotite-K-feldspar ± actinolite alteration, with minor arsenopyrite, pyrite and pyrrhotite. The genetic setting is described as 'Uplift induced by mantle upwelling, triggering conductive heat flow and decompression with release of deep and subcrustal fluids and crustal melt generation' (Seltmann et al 2020). The enormous heat and energy pulse necessary for penetrating and brecciating a vertical rock column of > 4 km, and the giant mass of gold transported along imply extraordinary events in the mantle (see 'Metallogenic models').

Assemblage and breakup of megacontinents and supercontinents In the cycle of amalgamation of a large part or of all continental plates into megacontinents and supercontinents, a time of stasis is followed by breakup, the birth of new oceans and dispersion. This sequence has been related to specific characteristics of the metallogenic evolution, such as orogenic deposits (see 'Discussion'; e.g. gold) during convergence and suturing, and the incidence of anorogenic within-plate ore formation (e.g. diamondiferous kimberlites) and of continental, sediment-hosted deposits (e.g. the diagenetic European Kupferschiefer). During distension, rift-related Pb–Zn–Ag is characteristic (1). For Proterozoic Western Australia, Aitken et al. (2018) confirm a strong relationship between mineralization and supercontinent cycles.

Continents may be divided into a continental size hierarchy, from supercontinent (e.g. Pangea) to > megacontinent (Gondwana) to > continent (Africa) and to > microcontinent (e.g. Japan) (Wang et al 2020a, b). Megacontinents are precursors to every supercontinent since 2 Ga when the modern plate tectonic network was first established (Wan et al 2020). Megacontinent Nuna preceded (until 1750 Ma) supercontinent Columbia, Umkondia (1110 Ma) Rodinia, Gondwana (520 Ma) Pangea and Eurasia (0 Ma) the future Amasia. The geodynamic model for megacontinent assembly and subsequent supercontinent amalgamation refines models of the supercontinent cycle (Wang et al 2020a, b). Feedbacks between mantle convection and supercontinent formation are, for example, the formation of supercontinents above mantle downwellings (Wang et al 2020a, b).

The assembly of megacontinents is geodynamically distinct from the amalgamation of supercontinents, and the two generate contrasting proxy signals: The assembly of megacontinents is generally associated with negative EHf values of zircon, indicating their assembly was accompanied by significant crustal reworking that characterizes Tethyanstyle collisional orogens. By contrast, positive EHf values reflect the reworking of juvenile crust that is typical of collisions between continents flanked by circum-Pacific-style accretionary orogens (Wang et al 2020a, b). In this scheme, metallogenic keys may possibly be found in observations concerning the greatest rates of crustal reworking, subduction, within-plate and orogenic magmatism. With better resolution, mantle convection modelling and paleomagnetics may be able to precisely indicate prospective stages of supercontinent assembly, suturing, wander paths and evolution.

#### Metallogenic models

Metallogenic models are conceptual representations of oreforming systems in geoscientific terms; this may include confirmed theories (plate tectonics), accepted knowledge (such as differentiation and fractionation of magma bodies) and components of partly hypothetical character (fertilization of subcontinental mantle). Geodata such as seismic evidence for delaminated lithosphere and shallow asthenosphere can support models. Parts of models can consist of mathematical, physical or chemical experiments and information, or simulation, describing quantitative aspects.

The main parts of metallogenic models are (i) the source of the valued element and its companions such as pathfinder elements; (ii) understanding of the nature and timing of causes and processes of the mobilization such as heat pulses, metamorphic dehydration, the physical state (e.g. sub- or supercritical) and the sulfidic and oxidized composition of partial melts and fluids; (iii) the architecture, the stress field and timing of flow paths from the source to the ore deposit and possible stages in between; and (iv) the nature and time of the trap and the processes that cause the enrichment resulting in a mineral deposit. The petrogenetic, tectonic and geodynamic setting in geological space is essential (e.g. Rowland 2021). Each of these subsystems comprises processes and modifying factors that need to be elucidated.

A paradigm of metallogenic models is the US Geological Survey's series of descriptive mineral deposit booklets, the latest of which is Kelley et al.'s (2020) *Alkalic-Type Epithermal Gold Deposits*. The USGS models are comprehensive and valuable descriptions of deposit classes including characteristics, grade-tonnage, genetic, geoenvironmental, geophysical, probability of occurrence and quantitative process models. Here, we aim to limit the depth of treatment to the essentials.

#### Sources of gold

Similar to other elements and metals, the ultimate source of gold may be average crust or mantle, if the extractive process is effective and leaches large volumes. In other cases, pre-enriched sources are possible. Often, sources of gold and the rock suites hosting gold deposits are independent and separated by the passage of Au-fertile melts or fluids through upper mantle and continental crust. Therefore, source and host rocks of gold deposits (the trap) must be sharply distinguished.

By differentiation and fractionation, mafic and felsic magma bodies may evolve into sources of gold. In rare cases, the first may concentrate gold into orthomagmatic ore. Granites, in contrast, concentrate the metal by fluid segregation and magmatic-hydrothermal ore deposit formation. Orthomagmatic, for example, is gold and PGE mineralization in the Triple Group of the Middle Zone of the Eocene Skaergaard Mafic Layered Intrusion in eastern Greenland. The metals are hosted in a stratabound sulfidic layer ~2 m thick (the Platinova 'reef') within banded gabbroic cumulates. The reef is related to fractional crystallization and silicate-sulfide liquid immiscibility in the ferrobasaltic melt (Andersen et al. 2017). Melt inclusions in plagioclase support the model that the Au-PGM concentration is due to fractionation below, and coinciding aqueous fluid exsolution and sulphide saturation across the mineralized horizon (Pedersen et al 2020). The Platinova Reef is by far the richest and most extensive resource in the Skaergaard intrusion; two separate zones of inferred resources contain 106 Mt with 1.68 ppm Au, and 103.5 Mt with 1.91 ppm Pd (Andersen et al. 2017).

Lode gold deposits in metamorphic terranes — called the orogenic type (Groves et al 1998) — formed in accretionary or collisional orogens at paleodepths of ~ 5 to 15 km during late stages of regional orogeny. The prevailing genetic hypothesis is a crustal metamorphogenic dehydration source of gold (Phillips and Powell 2010). Main source rocks are assumed to be either (1) volcano-sedimentary hydrated greenstone sequences or seafloor rocks such as iron formations (BIFs), or (2) turbidite-dominated accretionary terranes

or metasedimentary slate belts (Gaboury 2019). Some giant Neoarchean gold provinces mentioned earlier may occur in greenstones of accretionary settings where the precise source is still debated (ANNEX Fig. 4).

The generalized metamorphogenic model describes extraction of gold from rocks as an effect of the exudation of crystal water from hydrated minerals, at ~ 550 °C and 2-10 kbar at the greenschist-amphibolite facies transition (Gaboury 2019; Phillips and Powell 2010). Metamorphic reactions at this transition are essentially controlled by temperature over a wide range of pressures (Gaboury 2019). Concurrently, sulphur together with Au is liberated as free aqueous sulphur (HS<sup>-</sup>, S<sup>2-</sup>) when diagenetic pyrite recrystallizes to pyrrhotite, and organic matter to graphite. Metabasalt exudes ~ 5 wt % H<sub>2</sub>O that flows along the pressure gradient to lower P/T domains. The intimate fluid-rock interaction at the source favours dissolution of trace metals. In the case of high H<sub>2</sub>S activity in the fluid, iron and base metals are nearly insoluble so that gold is relatively enriched. Even at low gold concentrations, the giant mass of fluids moves a considerable mass of gold.

This model is confirmed by studies in New Zealand, where ore-forming elements (Au, Ag, As, Sb, Hg, Mo, W) are depleted in higher-grade metamorphic rocks relative to unmetamorphosed protolith samples. The same elements are enriched in the island's orogenic gold deposits (Pitcairn et al 2014). Nineteen gold deposits distributed in the Mesozoic Otago schist belt (NZ) contain a total of approximately 580 t of gold (past production and resources). The presence of  $C_2H_6$  in fluid inclusions is interpreted to be an indication that gold was sourced from primary gold-bearing pyrite hosted in carbon-rich turbidites, which are the source for fluid generation and its hydrocarbon components (Gaboury et al. 2021). Yardley and Cleverley (2015), however, doubt that orogenic metamorphism can provide a large enough mass of fluids in a short time for the formation of large and giant gold deposits. High heat flow events may be the critical booster.

An example of the metasedimentary source group (2) is the supergiant, high-grade, Paleoproterozoic Obuasi district in Ghana, West Africa. Obuasi holds a mineral resource plus past production of 70 Moz gold. It is hosted by ~2135-Ma siliciclastic rocks of the Eburnean Kumasi Basin, which was obliquely shortened along an inverted boundary with the older Eo-Eburnean Ashanti belt to the East. Greenschist facies metamorphism was coeval with mineralization and related alteration at ~ 2095 Ma. Steeply dipping lodes extend over an 8-km strike length and to depths of > 2.5 km. The native gold-rich quartz veins are surrounded by refractory auriferous arsenopyrite and carbonate-muscovite alteration halos in carbonaceous phyllites (Oberthür et al 1997). The mineralizing fluids were derived primarily from deeper, As- and C-rich metasedimentary sources by basinal fluid expulsion and metamorphic devolatilization triggered by

inversion and shortening, followed by transpression (Oliver et al 2020a, b).

Increasingly, the source of orogenic and of magmatic-hydrothermal porphyry gold (or Cu-Au) deposits is suggested to have been metasomatized, hydrated and/or fertilized mantle (Yang et al. 2022; Groves et al 2020; Griffin et al 2013; Hronsky et al 2012; Richards 2009; Sillitoe 2008). The fertilization may be caused by asthenospheric partial melts (Lü et al 2021), by devolatilization, dehydration and partial melting of subducting oceanic crust and sediments, or by plume-derived melts (ANNEX Fig. 5). Hydrothermal chimneys at the ultramafic-hosted Cheoeum vent field, Central Indian Ridge, are characterized by high concentrations of Au (up to 17.8 ppm) and Sn (up to 1720 ppm) (Choi et al 2021). A ~4500-m-deep borehole in Iceland penetrated the root of an active seawater-recharged hydrothermal system below the Mid-Atlantic Ridge. Fe-K-rich brine contained 2000 µg/g Cu, 3.5 µg/g Ag, 1.4 µg/g U and  $0.14 \mu g/g$  Au (Bali et al 2020). Arsenian iron sulphides of mid-ocean ridges concentrate gold and silver (28-140 ppm Au, 800-2400 ppm Ag: Halbach et al 2003). Ore of suprasubduction Cyprus class deposits approaches tenors of up to 8 ppm Au. Subducting seamounts may cause conductive, fluid-rich regions in the over-riding plate (Chesley et al 2021). For the oceanic slab subduction case, plate tectonic velocity determines the possible duration of these processes; along the Pacific Ring of Fire, for example, the feeding system may have operated for nearly 200 Myr (a giant simile to the 'Gold Conveyor Belt' of Pitcairn et al 2014).

The mantle source hypothesis of gold is plausible, and hard data are accumulating. The co-occurrence of gold ore and mafic magmas, the petrochemistry of which indicates derivation by melting of metasomatized mantle wedge or SCLM (e.g. adakitic melts; Mueller et al. 2016), supports the model. Volcanic xenoliths of mantle fragments with gold or sulphide traces erupted near gold deposits such as giant Lihir (ANNEX Fig. 6) are the strongest confirmation (Brandl et al 2020; Tassara et al 2017; McInnes et al 2001). For the North China Craton, Wang et al. (2020b) question if melting of metasomatized SCLM alone was sufficient to produce Au-rich melts and fluids: they suggest that efficient metal extraction by hydrous magmas of elevated oxygen fugacity was the key, triggered by heat released from upwelling asthenosphere. Partial melting of metasomatized SCLM resulted in the formation of hydrous S-, C-, Cl-bearing and high Mg# basalts that attain enriched tenors of Au (up to 4 ppb, about three times the values of primitive mantle), and of other highly siderophile elements (Wang et al. 2020b).

*Fertile mantle magmas* commonly are oxidized. Early, primitive porphyry Cu–Au melts, for example, are characterized by magmatic anhydrite although the ore is sulfidic. The key for the reduction is interaction of SO<sub>2</sub> segregated into fluids with Fe<sup>+2</sup> (of silicates) producing magnetite (Fe<sup>+3</sup>) as

suggested earlier by Hattori and Keith (2001) and lately, by Sulaksono and al Furqan (2021) and Sulaksono et al. (2021) for the *Grasberg* gold deposit.

Systematic investigations of fluid inclusions and H–O–He–Ar–S-Pb isotopic data of the *Tudui–Shawang* orogenic deposit in the Jiaodong Peninsula, north China, reveal a mixture between crustal fluids and mantle components, related to subduction of the Paleo-Pacific Plate and the decratonization of the North China Craton during the Early Cretaceous (Liu et al 2021a, b, c). In the *Ailaoshan orogenic gold belt* of eastern Tibet, the application of microthermometry, fluid composition and stable isotope analyses to fluid inclusions sampled from regional metamorphic quartz veins and from gold quartz veins showed a clear distinction (Wang et al 2021a, b). The gold-related veins were different from the metamorphic veins. Lamprophyre dikes in several gold deposits suggest a mantle connection. The authors suggest an SCLM source for the mineralizing fluids.

#### Mobilizing the gold: supercritical hydrous melts and fluids

At high pressure and temperature, fluids and hydrous melts occur in the supercritical state (Kono and Sanloup 2018; Manning 2018; Ni et al 2017; Mysen 2014; Norton and Dutrow 2001). Supercritical fluids and hydrous melts (the fluid/melt phase of Thomas et al. 2019) have properties that differ from the subcritical state: The density of supercritical fluids and hydrous melts varies widely with changing pressure and temperature; they have higher pH, are able to dissolve many organic substances and exhibit extreme dissociation of water and diffusion coefficients. In the context of metallogeny, they display strong selective partitioning  $(10^4-10^9)$  into the supercritical melt/fluids leading to an extraordinarily strong enrichment of some common and rare elements, such as gold, and of compounds (Thomas et al 2019). This property and the variable density (from dense fluid or hydrous melt to gas), low viscosity and high reaction rates control metal uptake, transport and precipitation. Cumulative data from numerical experiments, equation-ofstate relationships and geologic and geochemical observations support the suggestion that magmatic-hydrothermal processes should be thought of as complex dynamical systems whose behaviour at state conditions near the supercritical region of the fluid is likely oscillatory and chaotic (Norton and Dutrow 2001).

Because of the relatively cool state of the oceanic slab at incipient subduction, direct melting is unlikely except at great depth (Ni et al 2017). Devolatilization of the slab beneath the volcanic arc (at subarc depths between ca. 80–130 km), is often described in terms of water or fluids that induce fluid-fluxed melting (Rustioni et al 2021). In fact, at high temperature and at upper-mantle pressures, all silicate– $H_2O$  systems exhibit full miscibility and partial melting occurs simultaneously. The product is coexisting  $H_2O$ -saturated silicate melt and silicate-saturated aqueous fluid (Mysen 2014). Although there remain uncertainties (Ni et al 2017), including the many potential temperature fields of the subduction zone, a major role of supercritical hydrous melts in mobilizing and transporting gold, other metals and dissolved matter upwards is most likely.

Supercritical fluid/melts may have any composition intermediate between silicate melt and  $H_2O$ , and possess very high  $H_2O$  activity, which endows them with great power of dissolution or metasomatism. Supercritical hydrous silicate liquids are less dense, but more compressible than their anhydrous equivalents, translating into a high likelihood of neutral buoyancy at depths where magnetotelluric data suggest melts may be present. If density differences enforce flow, high-pressure  $H_2O$ -bearing silicate liquids are reactive with the rock matrix, and probably form high-permeability channels (ANNEX Fig. 6) that enable rapid transport. Mobility is also enhanced by water-like viscosity (Thomas et al 2019). Electrical conductivity and diffusivity, however, decrease with pressure, as observed by magnetotelluric observations from a range of deep settings (Manning 2018).

Pulses of energy and heat are essential factors for the origin and mobilization of Au-fertile melts and fluids. Possible triggers include delamination of subcontinental lithospheric keels, or breakoffs and windows, or rollback and tear (as at Kışladağ) of the subducting oceanic slab, which allow intrusion of hot asthenosphere ('asthenospheric underplating': Singh and Mahatsente 2020). Supercritical hydrous melts are able to sample the most fusible components from a large volume of the mantle source, including hydrous, volatile-rich and gold-bearing components, which contribute fluids and gold for giant deposits such as Lihir (2.3.2/4) (ANNEX Fig. 6).

#### Architecture and timing of flow path activation

Supercritical hydrous, hot (approximately 1100 °C), auriferous basaltic magmas intrude below the Moho ('underplating'), fractionate and cool to the regional geotherm to between 750 and 800 °C. Ascending exsolved liquids and volatiles may cause fluid-fluxed melting of overlying mafic underplates and other crust, generating juvenile granitoids of continental arcs (Collins et al 2020). In the case of direct connection with translithospheric structural flow paths, the fertile melts may rise directly towards the surface, favoured by phases of tensional or transtensional stress states that provide permeability, and generate porphyric or volcanogenic epithermal or VMS gold mineralization. Exsolved supercritical fluids and mantle volatiles may ascend to form orogenic gold or IOCG deposits. Fertile melts or fluids pass through vertically extensive column-like conduit systems, with or without transient traps, until reaching physical or chemical conditions of ore precipitation. The lithospheric-scale structural pathways may originate at the same time with the activation of the fertile melts and fluids; more often, the structures record multiple earlier reactivation (Hronsky 2020). High transport capacity is attained by self-reinforcing, solitary wave propagation. While enhancing flow, high fluid pressure triggers seismicity on the faults and causes the commonly multiphase, but moderate deformation seen in many gold deposits (Gaboury 2019).

After collisional orogeny of the *Lower Yangtze Metallogenic Belt*, melts and metal-rich (Fe–Cu–Au) fluids produced by the upwelling asthenosphere following delamination are thought to have metasomatized the lithospheric conduits and part of the SCLM before forming ore deposits in the crust (Lü et al 2021). Hydration and carbonation reactions that are part of mantle metasomatism cause an increase in solid volume by up to several tens of vol %, which can induce stress, strain, rock fracture and enhanced permeability (Uno et al 2022; Klein and Le Roux 2020).

Details of tectonic activity along structural corridors hosting orogenic gold deposits are complex. The Kittilä Mine in the Central Lapland Greenstone Belt, Finland, (see 'Metallogeny and non-uniformitarian models of ancient earth geodynamics: lid, or subcretion tectonics'), for example, is located on a slight bend of the strike-slip Kiistala Shear Zone. High-resolution aerial UAV images, X-ray computed tomography scans of selected rock samples and regional geological and geophysical datasets (e.g. reflection seismic profiles) were used for an integrated structural analysis (Sayab et al 2020). Five discrete deformation phases could be discerned, between ca. 1.92 and 1.76 Ga. Refractory gold ore formed during E-W compression related to D1 thrusting. A rotation of stress vectors initiated a dextral strike-slip regime (D3) along the Kiistala shear zone. This caused exsolution of invisible gold from sulphides and deposited native gold in fractures and veins. The absolute age for the D3 hydrothermal event is 1.87-1.86 Ga. Late ductile to brittle transition related to the D5 deformation event produced most of the gold (80%)at the nearby Iso-Kuotko deposit where it occurs in native gold-bearing pyrrhotite-rich veins. Xenotime associated with visible gold yielded U-Pb ages of ca. 1.77-1.76 Ga (Sayab et al 2020).

Rapid burial of source rocks (~ 1 My), high topography and the main tectonic deformation is typically established by the mountain building phase of an orogen. The wave of thermal equilibration, however, that is responsible for the key reactions liberating fluids at the transition of greenschist to amphibolite boundary, arrives later. There is no standard time gap, but numerous mineralization ages suggest a delay in the range of 10–100 My after the orogenic peak (Gaboury 2019).

# Controls on sites and physico-chemical conditions of gold ore deposition: the formation of a gold deposit

At the deposit scale, structural control of orogenic gold deposition is eminent. Higher-grade mineralization (ore shoots) will always be small parts of a wider structural host system. Empirical correlations between structural heterogeneities such as brittle and ductile strain and ore shoots have long been recognized. In the same deposit, host rocks with different chemical and mechanical properties may display different mineralization styles, e.g. at Telfer (Wilson et al 2020: see 'Metallogeny and plate tectonics'/'Discussion'). Flow of fertile fluids is driven by overpressure and 'seeks' permeable pathways, which are often heterogeneously distributed within large structural host systems (Hronsky 2020).

Deposits form in vertically extensive conduit systems linked to a source at depth. The flow pattern displays the behaviour of injection-driven swarms (Hronsky 2020). This model consists of three elements including (a) the integrated swarm volume (ISV), which is the rock volume within the limits of the mineralization-hosting structural system and is the geological entity that encloses the deposit; (b) fluid pathways, which are 3D pathways through the ISV where dynamic fluid flow is repeatedly focused; and (c) ore shoots, which are localized volumes of gold ore deposition. Ore shoots are interpreted to represent volumes of anomalous dilation or second-order valve sites within flow pathways. The structural control is dominated by the rheological architecture of the host rock mass, the understanding of which is pivotal to any attempt of prediction (Hronsky 2020).

Gold-precipitating fluids in orogenic gold deposits typically have a low salinity aqueous-carbonic composition, apparently with uniform physico-chemical properties through geological time. Ore fluids are characterized by 5–20 mol % CO<sub>2</sub>, significant concentrations of CH<sub>4</sub> and/ or N<sub>2</sub>, 0.01–0.36 mol % H<sub>2</sub>S, a near-neutral pH of 5.5 and salinities of 3–7 wt % NaCl equiv with Na>K>>Ca and Mg. The solubility of Au in hydrothermal solutions is mainly controlled by the concentration of reduced S (or Cl), and is insensitive to temperature. At~300 ppm H<sub>2</sub>S, the solution holds a maximum concentration of~1 ppm gold (Simmons et al. 2020). Consequently, high-grade ore originates mainly by focused precipitation of gold from a large dilute mass of fertile fluid.

The chemical mechanisms that induce *Au deposition* are divided into two broad groups: (i) Au supersaturation by perturbations of solution equilibria can be caused by physical and chemical processes, such as phase separation (boiling), fluid mixing, and pyrite deposition via sulfidation of Fe-bearing minerals. Therefore, fluid inclusion compositions in orogenic gold deposits display a great variability, with almost pure H<sub>2</sub>O or CO<sub>2</sub> or CH<sub>4</sub> pointing to a frequent

incidence of phase separation (Hronsky 2020); (ii) the sorption of ionic Au on to the surfaces of growing sulphide crystals, mainly arsenian pyrite (ANNEX Fig. 7). Both groups of mechanisms have the capability to produce ore, although of distinct mineralogical and geochemical characteristics (Simmons et al. 2020).

*Phase separation* refers to the transition of a hot singlephase liquid into a two-phase mixture (liquid plus gas), usually due to decompression, which causes any nonaqueous volatiles in the fluid ( $CO_2$ ,  $H_2S$ ,  $H_2$ ,  $CH_4$ ), plus  $H_2O$  vapor, to fractionate into the gas phase (Simmons et al. 2020). Variants of phase separation include boiling, flashing, effervescence and fluid unmixing. The process is of wide importance for the formation of ore in epithermal and orogenic Au systems, and for the nucleation of Au colloids (ANNEX Fig. 8). Chemically, this process can be expressed by Eq. (1) where the Au hydrosulphide complexes control solubility (Simmons et al. 2020):

$$Au(HS)_{2(aq)}^{-} + 0.5H_{2(g)} = Au_{(s)} + H_2S_{(g)} + HS_{(aq)}^{-}$$
(1)

The essential consequence is the loss of  $H_2S$ , driving reaction (1) to the right, which causes Au to precipitate. Phase separation is a highly efficient mechanism of Au precipitation as observed in geothermal systems. Overall, a range of processes of Au precipitation is expected to operate over space and time within hydrothermal systems where metal transport is sustained or pulsed for relatively long periods of time (Simmons et al. 2020).

Gold ore typically ranges in grade from <1 to 10 g/t Au (Au/Ag ratios ~ 1–10), and contains 2 to 5 wt % sulphide minerals that are dominated by pyrite and arsenopyrite, or pyrrhotite occurring with hotter and deeper mineralization. Quartz, carbonates and sericite,  $\pm$  tourmaline, make up the dominant gangue minerals. Ores display elevated tenors of As,  $\pm$  Sb,  $\pm$  Hg,  $\pm$  W,  $\pm$  Te and  $\pm$  Bi, with little evidence of mineralogical or geochemical zonation in the vicinity of the ore. Gold correlates strongly with As in many deposits; auriferous arsenopyrite is particularly common in metasedimentary host rocks. In free-milling ore, Au forms discrete grains (fineness > 850), but in refractory ores, Au occurs as inclusions in sulphides.

Hydrothermal host rock alteration halos of gold deposits (Halley et al 2015) are important features of metallogenic models and are regularly used in exploration. The nature of the host rocks and properties of the hydrothermal fluids determine the resulting alteration parageneses (Pohl 2020). Hydrothermal alteration causes changes in colour, texture, mineralogical and chemical composition including stable isotopic ratios in the host rocks. The end product is a function of the fluid/rock ratio, the nature of both the solutions (pH, Eh, T, P, chemistry) and the host rocks (mineralogy, permeability, porosity). Ion exchange is ubiquitous, implicating an open system. Dissociated water plays an eminent role because of reactions with silicate minerals that include incorporation of  $OH^-$  groups and exchange of cations by  $H^+$  (hydrolysis). Changes such as phase separation of  $CO_2$  cause acidification and subsequent gold precipitation, and proximal illite–sericite alteration (Yao et al 2021; Gaboury 2019).

The giant Golden Mile deposit of the Kalgoorlie gold camp in Western Australia provides a good example (McDivitt et al 2020) (see 'Metallogeny and non-uniformitarian models of ancient earth geodynamics: lid, or subcretion tectonics'). In this mining district, the most important host rock in terms of gold production is the Golden Mile Dolerite, a greenschist metamorphic differentiated tholeiitic dolerite sill (Phillips et al 2017). Its magmatic-metamorphic paragenesis is overprinted by hydrothermal alteration, caused by auriferous fluids typical for orogenic gold, of a low-salinity  $H_2O-CO_2-H_2S$  character and at T ~ 300 °C. Gold ore occurs mainly in altered doleritic rock, in brittle-ductile micaceous shear zones, in quartz stockworks and breccias and as vein infill. In the dolerite, pyritization caused precipitation of the dissolved gold. Accordingly, the zones from ore to distal settings include (1) gold, pyrite, sporadic tellurides, arsenopyrite, pyrrhotite and minor base metal minerals; (2) a pale carbonate siderite-ankerite-hematite zone; (3) chlorite-calcite that occupies a wide propylitic halo around the deposit; and (4) unaltered actinolite-bearing dolerite. Mapping the alteration zones provides a direct vector to ore (Phillips et al 2017).

Metallogenic systems comprise many interacting subsystems and parts. Therefore, they might be fruitfully investigated with methods of Complexity Science. In current practice, however, metallogenic models are often simplified to essentials that can be handled in exploration.

#### Metallogeny in gold exploration practice

Initially in all explorations, the collection of literature, maps, data and reports will lay the base for drafting the strategy and a work program. Metallogenic knowledge will provide the frame.

Sillitoe's (2008) paper on major gold deposits and belts (metallogenic provinces, zones or districts) of the North and South American Cordilleras provides a unique metallogenic analysis of a giant gold domain, among numerous valuable observations. The author states that economically viable gold concentrations containing  $\geq$  10 Moz (300 metric tonnes) form 22 discrete individual gold belts that are typically several tens to hundreds of kilometres long, dominated by single deposit types (see 'Metallogenic classification of ore and mineral deposits') and metallogenically active for relatively brief periods (< 5–20 My). Five major isolated gold deposits are situated outside of the belts. Interestingly, gold, copper and tin belts are mutually exclusive, the causes of which are still discussed. For Cu and Sn, the enigma is resolved by the presence of thick metasedimentary crust underneath Cu-rich tin districts. Decompression mantle melting in back-arc or post-collisional settings generates mafic magmas, which are commonly invoked as triggers for partial melting of thick overlying metasedimentary crust. Oxidized mafic melts and fluids contribute copper into the chambers of fractionated, peraluminous, silicic, ilmenite-series magmas required to generate the Sn mineralization (Sillitoe and Lehmann 2022).

American gold belts and nearly all isolated deposits formed over the last 160 million years during active subduction, commonly in close spatial and temporal association with intermediate to felsic, medium- to high-K calc-alkaline igneous arc rocks. The observed upper-crustal concentration of gold in association with both oxidized and reduced magmas seriously challenges existing ideas of gold deposit formation (Sillitoe 2008). Cordilleran gold deposits formed in phases of contraction or extension, depending on different subduction configurations. A steep subduction angle and regional extension are caused by slab retreat, whereas slab flattening induces contractional tectonism, crustal thickening and magmatic quiescence. A far greater percentage (>90%)of the copper than of the gold (< 50%) is related to compressive settings. In accretionary orogens, terrane boundaries may control gold deposits. The overall distribution of the large Cordilleran gold deposits at the orogen scale (provinciality) remains enigmatic, because apparently similar events elsewhere resulted in only relatively small or no gold deposits. Also uncertain is the role of inheritance ('Metallogenic terms') (Sillitoe 2008).

Sillitoe et al. (2020b) is an excellent source of possible keys for building metallogenic gold systems and models of various deposit classes and styles. Apart from the partly hypothetical source (see 'Sources of gold'), gold metallogeny such as the structural control and tectono-magmatic setting is generally well understood. Mappable criteria for near-surface mineralization include structures and hydrothermal alteration (remote sensing), soil and rock geochemistry and geophysical signals. In underexplored greenfield regions, such as the Himalayas, this kind of approach is still promising and much applied.

Covered targets down to 3300 m below the surface (Arndt et al 2017) demand the development of novel approaches. Mineralogical and geochemical halos (the footprint) above an ore deposit produced by spent ore fluids must be found. Sillitoe et al. (2016) describe the exploration history of a porphyry Cu–Au body beneath the exposed *Valeriano* lithocap in Chile. Lithocaps are hydrothermally altered rocks that cover porphyry copper systems, reaching a thickness

from 1 to 2 km and up to tens of square kilometres in areal extent. The Valeriano alteration zone was discovered in 1986 by Jozsef Ambrus, who appreciated that exposed silicic ledges (ribs) and breccias are reminiscent of those in the high-sulfidation epithermal deposits farther south in the El Indio belt.

In the Lowell-Guilbert (1970) model, the outer(upper)most alteration zone of porphyry-Cu deposits is propylitization (cal-chl-ep-adl-ab) that may reach much larger dimensions compared to the argillic zone. Minerals formed by propylitization such as chlorite display traces of exposure to the hypogene fluid and vapour stream as a function of distance and consequently, trace elements guide explorers to the centre of deeply buried porphyry deposits (Wilkinson 2021).

At the Valeriano porphyry copper-gold prospect, a classic vertical zoning pattern from quartz-alunite/kaolinite through quartz-pyrophyllite, quartz-illite and quartz-sericite in the volcanic wall rocks led explorers stepwise down to potassic alteration where porphyry intrusions became volumetrically important. No geophysical investigations assisted the discovery. Conventional microscopy and short-wave infrared (SWIR) spectroscopy were useful, as the downward increase in the 2200-nm sericite absorption feature provided a valid vector to the hot core of the mineralizing system (Sillitoe et al 2016). Local high grades and long mineralized intercepts were encountered by drilling, such as 724 m at 0.60 wt % Cu and 0.27 g/t Au between 1030 and 1754 m. For deep underground mining, these grades were not considered to be sufficiently high. Yet, Valeriano will certainly be one of the future mines when lower-grade deep resources reach economic viability.

#### Metallogeny in present-day industry sources

According to the Fraser Institute's 2020 annual survey of mining and exploration companies, perceived mineral endowment of a country is the main reason for the choice where to invest; policy ranks second (Stedman et al 2021). The employment of metallogeny in targeting exploration for gold can be considered as part of a company's strategy. Commonly, stock market–listed exploration and mining companies publish basic data and news in their websites for investors; the character of this information ranges from tactical, such as information on new drill intersections and their gold tenors, to sizeable reports such as prefeasibility and feasibility studies, and the declaration of resources and reserves.

An example is the giant *Red Chris* porphyry Cu–Au mine in British Columbia, Canada. Currently, this brownfield project stands at measured and indicated mineral resources of 980 Mt @ 0.41 g/t gold and 0.38 wt % copper, containing 13 Moz Au and 3.7 Mt Cu. Inferred mineral resources comprise 190 Mt @ 0.31 g/t gold and 0.30 wt % copper containing 1.9 Moz Au and 0.57 Mt Cu (Newcrest Mining Limited 2021). In the announcement, geology is very briefly described (hosted by 'Late Triassic to Early Jurassic diorite to quartz monzonite stocks and dykes'), but metallogeny is not mentioned. The term 'mineral system' appears in connection with proximal mineralization drilling outside of the main mine area.

Yet, in many countries, thorough reports on mines or prospects due to regulations are not published. These reports may enclose metallogenic considerations although this is rarely required, depending on specific rules of the local authorities. In Canada, for example, mining regulations across the country include federal, provincial and territorial environmental and regulatory processes. Listing on stock exchanges requires Technical Reports (NI 43–101) to the Canadian Securities Administrators who file them in an open-access data bank (SEDAR 2021). One of the recently uploaded reports presents the feasibility study of an open pit gold mine in Canada (Anaconda Mining Inc 2022).

NI 43–101 (or in Australia Jorc 2012) reports comprise a complete set of information on the property (mine or prospect), such as location, access, climate, infrastructure, history, geology and mineralization, deposit type, exploration, drilling, sampling, analyses and data verification, mineral processing and metallurgical testing, the mineral resource and reserve estimates, the mining and recovery methods, infrastructure, markets, environmental permits and social impact, capital and operating costs, economic analysis, adjacent properties, conclusions, interpretations and references. The report must be certified by qualified persons.

SEDAR sources are extremely useful for learning the present-day practice of exploration and mining, not only in Canada, because many companies globally use the Toronto Stock Exchange (TSX) for listing. This includes the abovementioned Newcrest, one of the world's largest gold mining companies.

Globally, several thousand mining firms trade their shares on stock markets. We selected a sample of 50 reports submitted from 2019 to 2021 from gold explorers and miners that are accessible on SEDAR (2021). The firms range from juniors to mid-tiers and include several international giants, presenting new, early-stage discoveries, to projects in the feasibility study stage, and others profitably working century-old giant operations. Out of the fifty, 20 reports refer to 'metallogeny' or to the novel term 'mineral system' (see below). Often cited metallogenic sources are Goodfellow (2007) and various papers by Sillitoe (cited in this paper).

#### Current innovations and trends in gold exploration

There are numerous printed and online resources on the current practice of exploration in general and more specifically, concerning gold (Brown and Vearncombe 2014; and *see* selected references in Pohl 2020). In the following, we report on some of the newest approaches, sources and trends.

Major stages and activities in greenfield exploration comprise geological mapping, remote sensing and geophysics, geochemistry, mineral system modelling and target generation in GIS followed by increasingly more detailed investigation and evaluation of selected prospects. For this stage, as with brownfield targets, larger teams work on trenching, drilling, core logging and sampling, assaying and statistical and geostatistical processing of data. All earlier open pits and underground mines in the search area are visited and geologically surveyed. 3D modelling of geology and mineralization, and dense near mine drilling follow. The metallogenic nature of mineralization is investigated and compared with other deposits of the same or similar classes. First resource estimates and valuations lead on to the assembly of prefeasibility and feasibility reports by a multi-professional team, all in compliance with one of the international reporting codes such as JORC (2012) or NI 43-101.

The number and ingenuity of recent innovations in methods across a full exploration program is stunning. Digitization and progress in instrumentation induced profound changes. One platform that allows a larger overview of upto-date engineering, mining and geology software such as popular *Leapfrog* is Bentley (2021). *Leapfrog* is leading in 3D geological modelling and visualization.

In the last decades, the volume of data acquired in metallogeny, geoscience and exploration multiplied considerably, parallel to the growth of data generally, spear-headed by the field of image processing. Resulting challenges were met by the development of new mathematical and statistical methods for processing and interpretation of data. Algorithms, deep learning, artificial intelligence, machine learning and highly ambitious deep network models enabled by vast computing resources in the cloud preceded the emergence of the new 'Science of Deep Learning' (Baraniuk et al 2020). Much employed in geological mapping, remote sensing, geochemistry and geophysics, a systematic 'Geodata Science' has become a novel tool for metallogenic research (Yin et al. 2021a).

**Geological mapping** Geological concepts and maps are the indispensable foundation for any exploration project (Law 2017), and understanding the geology is crucial (Pohl 2020). Geology is both the starting point and the unifying frame for merging and analysing data resulting from a wide variety of methods. Older geological maps always need to be checked and updated, preferably by integrating remote sensing, geophysical and geochemical data. Also, allow your geologists generous time for reconnaissance and field work. Geoscience Australia (2021) regularly releases updated interpretations of potentially prospective geology. This work integrates

geological and geophysical data from the *Exploring for the Future Program* and includes observations from new drill core. The data is to be used for mineral prospectivity mapping.

A useful source for studying state-of-the-art depiction of geological mine maps and sections is Sillitoe et al. (2020b). Garwin (2022) shows how geological mapping of key features of porphyry Cu–Au–Mo deposits, such as quartz veins amounting to > 10% of rock volume, or visible molybdenite in outcrops and drill core can guide exploration drilling towards the ore body. One example of innovative and digitized mine mapping is the large open pit of the former *Atalaya* Cu–Pb–As–Zn VMS mine, Rio Tinto, Spain, where the mapping was carried out based on hyperspectral and Lidar data, using machine learning techniques. Drones acquired precise maps of the steep slopes, and of lithologies, as well as hydrothermal and supergene alteration (Thiele et al 2021).

**Remote sensing** Available satellite imagery grows rapidly in abundance and quality. Multiple public and private sensors launched in recent years provide temporal, spatial and spectral information on state and changes of the Earth's surface. In exploration, hyperspectral mapping with high resolution and advanced mineral discrimination features is possible from aircraft (HyMap 2021), but only satellites provide nearly total coverage of the Earth that is available to the general public. Still much used are the LANDSAT series (1–8) data. The US-Japanese ASTER system on board of the TERRA (\*1999) satellite carries 5 bands in the short-wave infrared (SWIR) range, enabling detection of different clays, carbonates, sulphates and other minerals. Better SWIR resolution (3.5 m) provides popular WorldView-3 (\*2014) data.

Rajendran and Nasir (2019) demonstrate the application of the ASTER sensor (Advanced Space borne Thermal Emission and Reflection Radiometer) for mapping mineral resources in the hot, exotic, inaccessible, rugged and arid desert mountains of the eastern Arabian Peninsula where conventional mapping is extremely difficult. An example of intricate airborne hyperspectral alteration discrimination in the shallow epithermal environment of the Yerington porphyry copper district, Nevada (USA), report Portela et al. (2021). Drawing attention to limits and pitfalls of field-portable visible, near-infrared and shortwave-infrared spectroscopy (VNIR-SWIR) analyses in exploration and assessment of the Zhengguang Au-Zn deposit, Northeast China, Wang et al. (2021a, b) provide valuable and detailed information on the science and practice of the method. By identifying infrared-active indicator minerals such as white mica and chlorite, VNIR-SWIR can assist to delineate alteration zones and to generate targets for drilling or underground development. Zhengguang is an intermediate sulfidation epithermal deposit, formed at ca. 450 Ma in an Early Ordovician continental arc in the northeastern part of the Central Asian orogenic belt. It contains measured and indicated resources of 13.2 million metric tonnes (Mt) grading 2.59 g/t Au, and 7 Mt at 1 wt % Zn and 12.0 g/t Ag. Illite spectral maturity (ISM) and XRD control across the deposit were employed to locate the high paleotemperature upflow zones of the hydro-thermal system responsible for formation of the Zhengguang Au–Zn ore (Wang et al 2021a, b).

Remote sensing complements rather than replaces stateof-the-art ground-based data collection such as geological mapping and geochemical sampling. Many critical indicators of interest may possibly never be accurately located by satellites. For searches where satellites do have predictive power, high-quality local training data will nearly always improve results.

**Geochemistry** Comprehensive geochemical surveys in greenfield exploration involve sampling many media types, including soil, glacial sediments (till), plants, water, soil gas, stream sediment, heavy mineral concentrates, rock chips and indicator minerals. Trace element contents of indicator minerals are increasingly used in metallogenic research and in exploration. CSIRO (2021), for example, investigates the potential of chromite, magnetite, pyroxene, olivine and arsenides to serve as indicator minerals for Ni-sulphide ore.

Many analytical methods may be used, such as inductively coupled plasma-atomic emission spectroscopy (ICP-AES), inductively coupled plasma-mass spectrometry (ICP-MS), X-ray fluorescence (XRF), X-ray diffraction (XRD), instrumental neutron activation analysis (INAA), electron probe microanalyzer (EPMA), gamma-activation analysis (e.g. Chrysos 2021), atomic absorption spectroscopy (AAS), ionic leach, bulk leach extractable gold (BLEG) and electrochemical means such as specific ion electrodes. Portable XRF (pXRF) and pXRD analysers help to rapidly build large, multi-element datasets and generate targets in nearreal time. For the investigation of gold-depositing geofluids, a great number of methods are available (Hurai et al 2016).

The timing of gold mineralization relative to volcanism, plutonism, sedimentation, metamorphism and tectonics in geological terranes plays a key role in the formulation of genetic models for gold deposits (McDivitt et al 2022). Using U-Pb and Sm-Nd geochronological studies of zircon, apatite and titanite in the Kalgoorlie gold camp, these authors show that fluid flow was protracted from ca. 2675 to 2640 Ma and reflects the interplay of early magmatic and late metamorphic hydrothermal fluid systems in the formation of hybrid intrusion-related and metamorphogenic orebodies. For precise age dating, the Sensitive High Resolution Ion Microprobe (SHRIMP) delivers zircon U-Pb data, and Laser Ablation Multi-Collector Inductively Coupled Plasma Mass Spectrometry (LA-MC-ICPMS) provides zircon Hf isotopic data, as well as time- and cost-efficient precise dating of carbonate, cassiterite and garnets (Reinhardt et al 2022; Reiners et al 2017).

The mapping function of LA-quadrupole (Q)-ICP-MS systems provides a wealth of spatial information on the petrogenesis of igneous, metamorphic and sedimentary rocks and on ore mineral formation (Chew et al 2020). The Chemical Abrasion Isotope Dilution-Thermal Ionization Mass Spectrometry (Ca-*ID-TIMS*) is one of the most accurate and precise methods of isotopic dating techniques (Zhong et al 2017).

Exemplary targets for geochemical mapping are porphyry Cu–Mo–Au deposits that display shells and caps of hydrothermal alteration and geochemical dispersion above fertile intrusive fingers and columns of fluids and vapour (Halley et al 2015). The central ore zone is surrounded by an extensive outer halo of more mobile elements such as As, Ag, Sb, Hg, Tl, Te and Mn. Recognizing the vector pointing to the centre helps to target drilling for ore. Extending detailed geochemical bedrock regolith on-the-ground sampling and mapping to wider areas by multispectral/multi-sensor satellite imagery (ASTER and WorldView-2) remote sensing data, Cheng et al. (2021) demonstrate the potential to considerably save time and costs in exploration.

Hydrothermal alteration zone mapping tools include handheld or UAV-mounted short-wave infrared (SWIR) spectroscopy (Yao et al 2021) or portable X-ray fluorescence spectrometry (pXRF) supplemented by micro-X-ray fluorescence–energy-dispersive spectrometry ( $\mu$ -XRF); data can be processed by principal component analysis (PCA) (Heidarian et al 2021). In the Shihu gold deposit, North China, petrographic microscopy and short-wave infrared spectroscopy (SWIR) illuminated the presence of three types of alteration: (i) a proximal illitic alteration, (ii) a transitional chlorite alteration and (iii) a distal propylitic alteration (Yuzeng et al 2021). The illitic alteration wavelength of the 2200-nm absorption varies. Only domains with higher 1400D, 1900D and 2200D coincide spatially with the economic ore bodies, enabling successful search for new ore bodies. Grid sampling at the Ernest Henry iron oxide copper-gold deposit in the Cloncurry District of Queensland, Australia, analysed by a combination of quantitative mineralogy with multielement data of P, Mn, As, P and U obtained by p-XRF and positive U anomalies from radiometric measurements showed the potential to point exploration toward higher Cu-Au grades (Schlegel et al 2022).

Lately, geochemical mapping generally, and of gold distribution specifically, expanded from high-density sampling (HGM) (1 sample/km<sup>2</sup>) to super-low density (SLGM) (1 sample/180 km<sup>2</sup>) and ultra-low-density sampling (ULGM) (1 sample/1600 km<sup>2</sup>). Lesser density requires a higher quality of sampling. For ULGM, fine-grained overbank sediments deposited by rare extreme floods are required. This way, one ultra-density mapping sample can control thousands of km<sup>2</sup> of catchment area. Liu et al. (2021a, b, c) resampled the Altai gold domain and report that HGM serves best the detection of single gold deposits, SLGM delineates metallogenic gold districts and ULGM can indicate metallogenic provinces to domains. In stream sediments, compared to gold, common pathfinder elements such as As, Sb and Hg often display a statistically independent behaviour and their use is questionable. Therefore, many anomalies of Au are not expressed in As, Sb or Hg highs (Liu et al 2021a, b, c).

Yin et al. (2021a) investigated a set of 2100 stream sediment samples within a 1:50,000 scale regional geological and mineral survey of the Daqiao area in the Qinling belt, which is one of the largest prospective gold districts in China. Metals analysed included Cu, Pb, Zn, Cd, W, Mo, Au, Ag, Sn, Ba, Mn, As, Sb, Bi and Hg. Sited in a swarm of gold deposits, the Daqiao gold mine ore (>105 t Au, 3–4 g/t) is hosted in Triassic turbitites. Subjacent Paleozoic metasediments are intruded by diorite porphyry (zircon U-Pb age 188 Ma). Elsewhere in the district, Silurian graphite schists host gold ore. Often, faults control ore bodies. The authors' objective was the discovery of geochemical patterns that might improve exploration in the area. Explaining their approach, they recount briefly the evolution of datadriven methods for geochemical pattern extraction from initially simple (such as the time-tested formula mean  $\pm 2$ times standard deviation) to the current evolved methods of systematic 'Geodata Science' (including statistical data analysis, data mining, interpretation and prediction) in order to reveal geochemical patterns such as spatial properties, element associations and anomalies indicating favourable targets (Yin et al. 2021a).

Geochemical domains and metallogenic anomalies were mapped in an area of 200,000 km<sup>2</sup> within the Sanjiang orogen, which is part of the eastern segment of the Tethys orogenic belt of SW China (Liu and Wang 2021). Using stream sediment samples, element associations were determined by principal component analysis (PCA) and related to the geological and tectonic structure. The belt contains many large mining districts currently in production, and the work indicated a large additional metallogenic potential.

Till sampling in the formerly inland ice–covered Amaruq gold deposit region in Nunavut, northern Canada, revealed mineralized debris dispersal trains that lead to the mineralization (Bronac de Vazelhes et al 2021). Principal component analysis identified a gold mineralization signature associating As, Ag, Au, Cu, Pb, Sb, W, S, Fe and Zn and its mafic-BIF (Banded Iron Formation) host rock.

Scheelite and native gold particles are useful indicator minerals, often observed with orogenic and granite-related gold mineralization. Using a laser ablation split-stream (LASS) inductively coupled plasma mass spectrometer (ICPMS) and the <sup>147</sup>Sm-<sup>144</sup>Nd decay system within a single thin section, Palmer et al. (2021) show that it is possible to (1) establish the initial Nd isotopic composition of the mineralizing fluid and (2) to date scheelite crystallization. This

approach makes it possible to (i) rapidly generate a reconnaissance age for mineral deposits, in which there are no other suitable minerals (ii) potentially date multiple stages of scheelite growth and (iii) determine the age and isotopic composition of detrital scheelite to help establish the source provenance.

Native gold is a significant indicator mineral for Au-bearing deposits. Mineral inclusions in placer gold (Chapman et al 2022) and Pd, Ag, Sb, Pb, Cu, Hg and Te contents in gold grains determined by Laser-ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) and electron probe microanalyzer (EPMA) have a high potential to discriminate gold from different deposit types (Liu and Beaudoin 2021) and from metallogenic classes.

Stable isotopic data such as oxygen, hydrogen and sulphur are often useful for defining the source of metals and fluids but there are cases where doubts remain. The Paleoproterozoic Fäboliden orogenic gold deposit in Sweden is atypical in being sited in amphibolite facies metagreywacke host rocks.  $\delta^{18}$ O from quartz,  $\delta$ D from biotite and  $\delta^{34}$ S in arsenopyrite and pyrrhotite allow no distinction between a granitic or a metamorphic source (Bark et al 2021).

Criteria for the discrimination of fertile and barren magmatic rocks is a recurring theme of metallogeny (e.g. Chiaradia 2021). Based on zircon trace element signatures of felsic magmas, Wade et al. (2022) found that zircon composition can be related to fertility of volcanic and intrusive suites within IOCG-hosting mineral provinces in Australia. Often, porphyry intrusions consist of multiple magma fingers, few of which are mineralized. At the giant Pulang porphyry Cu-Au deposit in western Yunnan (SW China), only one of three porphyry bodies is Cu-Au mineralized. Based on geological knowledge of the deposit, and zircon U-Pb-Hf-O isotope systematics, Yang and Zhang (2021) found that the middle age generation, a quartz monzonite porphyry, contains the major ore volume. Petrologically, the fertile magma was more oxidized, and had higher water and ore-element tenors. The geodynamic background was Late Triassic subduction of the Paleo-Tethys ocean, with gradually increasing subduction-related slab dehydration, and the addition of mantle-wedge material to the ore-forming magmas.

Lamprophyres and other mafic dykes are frequently observed near gold deposits. Exhaustive petrogenetic and Sr–Nd–Pb isotopic investigation of mafic dykes associated with gold deposits can clearly expose the derivation from enriched mantle and their highly oxidized and hydrated nature (Li and Yan 2021). Evaluating the oxidation conditions of igneous rocks during area selection and targeting can be a cost-effective way to identify favourable rocks. Confirmation of fertile igneous centres, however, requires petrological and mineral chemistry studies to ascertain that magnetite and other mineralogical indicators record the oxidized magmas that are conducive to generating porphyry Cu–Au deposits (Sun et al. 2015).

Geophysics There are no principally new geophysical methods in the current exploration, but digitization, improvement of sensors and devices and advanced data processing leads to unprecedented innovations. One example is the use of gravity, magnetics, and VTEM<sup>TM</sup> (Versatile Time Domain Electromagnetic) surveys for the detection of alkalic porphyry Cu-Au-PGM stocks beneath 100-400 m of cover rocks in British Columbia, Canada (Mitchinson 2022). Another is deep exploration in the North China Craton (NCC) (Yang et al. 2021b), which hosts a domain of Early Cretaceous gold deposits that formed during a change of the subduction orientation of the paleo-Pacific Plate. This resulted in transition of the tectonic stress regime from regional compression to transpression or transtension, prior to peak extension caused by thinning of the lithosphere. The giant Jiaodong metallogenic province in the easternmost NCC is a world-scale gold producer hosting more than 150 'Jiaodong type' gold deposits with total resources of over 5000 t Au ('Metallogenic classification of ore and mineral deposits') (Qiu et al 2020; Sillitoe 2020a; Yang and Santosh 2020). Ongoing deep exploration in the area is supported by geophysics (Yang et al. 2021b). In this region, deep gravity and magnetic investigation of crustal structures reveal control by a shallow MOHO and lithosphere-asthenosphere boundary corresponding to thinned crust and eroded subcontinental lithospheric mantle. Known gold deposits are mainly related to regional faults along structural and lithological contacts between Mesozoic granites and Precambrian metamorphic rocks, and by intersections of ore-controlling faults. An exploration drillhole intersected gold-related alteration at the depth of 2428 to 3234 m. The total intersection of gold mineralization amounted to ~180 m. Gold-bearing rocks are pyritic sericitized gneissic and granitic cataclasites, which confirm the high exploration potential for concealed and deep gold mineralization in the Jiaodong Province. Large and super-large gold deposits, however, have not yet been found (Yang et al. 2021b).

Because of the economic importance of the mining sector in Australia, the government is heavily investing in programs and projects that improve exploration and increase the discovery rate. A sizeable part of the funds is dedicated to geophysical subsurface investigations. Australia holds some of the best and most extensive geophysical data coverage in the world (Kennett et al 2018). Under the Exploring for the Future program, new deployments for the Australian Passive Seismic Array (AusArray) and Australian Lithospheric Architecture Magnetotelluric Program (AusLAMP) have commenced. Passive seismic instruments deployed in the Northern Territory at 11 sites represent the first of ~ 180 sites that will comprise a national,  $200 \times 200$  km seismic array across Australia. Acquisition of long-period magnetotelluric data at 32 AusLAMP sites in southwest Queensland is due for completion by the end of 2021 (Geoscience Australia 2021).

Deep seismic reflection profiling illuminates crustal structures, sedimentary and tectonic history and relations to flow of mineralizing fluids. The widespread coverage of the seismic profiles now allows the construction of a new map of major crustal boundaries across Australia, which will better define the architecture of the crustal blocks in three dimensions (Gibson et al. 2016; Korsch and Doublier 2016). Major crustal-scale breaks can be conduits for fluids or melts from the mantle or lower crust to near-surface ore. Based on locations of the crustal breaks identified in the seismic profiles, geological (e.g. outcrop mapping, drill hole, geochronology, isotopes) and geophysical (gravity, aeromagnetic, magnetotelluric) data are used to map crustal boundaries in plain view, between the seismic profiles. The Deep Earth Imaging Program (CSIRO 2021) is developing holistic joint analysis of seismic, magnetotelluric and potential field methods for the next generation of exploration. Privately financed current exploration programs in Australia particularly favour the geophysical techniques EM (electromagnetics) and SAM (subaudio magnetotellurics).

In early 2021, regional, precompetitive Airborne Electromagnetic (AEM) surveys were finalized by Geoscience Australia (GA) (2021) covering large areas of Western Australia (typically flown at 120 m above ground level with a 20-km line spacing). Complementing existing geophysical, geochemical and geological datasets, the final products (including GA inversion data) will assist under-cover resource and groundwater investigations. In areas with less cover (e.g. Tasmania), radiometric aerial surveys were acquired at a 200-m line spacing, assisted by funding through the Federal Government's Exploring for the Future program. Using a combination of rotary and fixed-wing platforms, the survey was aimed at facilitating base metal, gold and critical mineral exploration. Since late 2020, acquisition of long-period magnetotelluric data under the Australian Lithospheric Architecture Magnetotelluric Project (AusLAMP) has continued in northern New South Wales, in order to assist the development of mineral exploration concepts in the state.

With the increasing role of magnetotellurics (MT) in metallogeny and deep exploration, the method is of great interest. Yin et al. (2021b) obtained a lithospheric electrical resistivity model of the Nanling Range through 3D inversion of magnetotelluric data from 118 sites forming an array covering this giant tungsten porphyry metallogenic province. Processing, inversion, interpretation and implications for metallogenesis are *in extenso* explained. As in Nanling, targets for deep MT surveys can be concealed by large granitic intrusions, which are represented by high-resistivity masses in the crust. Conductive anomalies in the lower crust and upper mantle may be evidence for partial melting and fluid metasomatism. Narrow high-conductivity zones along transcrustal faults and shear zones such as those related to the Olympic Dam iron-oxide copper gold deposit may image flow paths of mantle-sourced ore-forming melts and fluids. Interpretations must, of course, consider that geophysical methods only show the present-day state of the lithosphere, whereas geodynamic and metallogenic events may have taken place in the geological past. Yet, Yin et al. (2021b) suggest that their work provides an improved understanding of Jurassic geodynamics and metallogeny. Geological interpretations imply the presence of a Neoproterozoic suture that coincides with outcropping ophiolites and an island arc, but was reactivated during the Phanerozoic and is marked by significant conductors in crust and mantle. They describe the spatial distribution of asthenosphere and lithosphere thinned by delamination. Cu-Mo and Pb-Zn deposits occur near the suture whereas thinned lithosphere controls the W-Sn deposits.

An example of the power of MT is the description of the complete architecture and plumbing system of Pleistocene to Holocene basaltic intraplate volcanos in NE China that are sourced from asthenospheric mantle fed by a C-melt–rich plume (Li et al 2021). Marked by low-resistivity anomalies, vertical flow zones related to translithospheric faults and several storage levels are recognized. The configuration is very similar to that of silicic stratovolcanos in suprasubduction settings (Li et al 2021). It appears likely that many features of similar igneous systems (such as IOCG) resemble this pattern.

Heinson et al. (2021) employed long-period magnetotelluric (MT) and geomagnetic depth sounding (GDS) data across western Victoria and south-eastern South Australia that image the electrical resistivity of the crust and mantle, which in turn depends on past thermal and fluid processes. The project area  $(500 \times 800 \text{ km})$  covers the Victorian gold province hosting the Bendigo and Ballarat fields, once fabulously rich gold producers in SW Australia. Victorian gold is 'shale, or turbidite hosted', or in current common nomenclature, of the 'orogenic type'. The geodynamic setting was a Paleozoic subduction-related active margin of Gondwana (Taylor et al 2017). Interpretation by Heinson et al. (2021) implies that gold deposits are underlain by a source zone at a crustal depth of > 20 km, and by pathway zones of low resistivity that lead up to gold deposits with > 1 t total Au production. At about 440 Ma, orogenic amphibolite metamorphism at depth mobilized fluids and HS<sup>-</sup> ligands for Au, and CO<sub>2</sub>. Organic carbon of the marine sediments was graphitized, explaining the low resistivity. Is it likely that Heinson et al.'s (2021) resistivity slices may assist exploration? In the case of the Victorian Gold Province, the results definitely refine the metallogenic model and generally, better models lead to improved exploration. If the Victorian Gold Province, one of the world's richest, would be buried beneath > 250 m of cover similar to the giant Olympic Dam IOCG, Heinson et al. (2021) might have reported a giant propitious anomaly.

We conclude that deep imaging of crust and mantle by MT, and many other innovative methods reported above, are an extremely promising exploration tool, especially for cases of buried hydrous or otherwise conductive sources, such as metasomatized subcontinental mantle.

#### The role of metallogeny in mineral system analysis

For decades already, Geoscience Australia supported the resource industry in discovery, by offering precompetitive science, data and maps. After Wyborn et al.'s (1994) paper, selected important papers on MSA include McCuaig et al. (2010), Barnes et al. (2016), Wyman et al. (2016) and Davies et al. (2020). A novel project using MSA, the Critical Minerals Mapping Initiative (CMMI 2021; Hofstra et al 2021), has been launched by the national geological agencies of Australia, Canada and the USA to advance understanding and foster development of critical mineral resources in their respective countries. For many years, professional application of MSA remained with Geoscience Australia, in the search for new mineral provinces and major resources concealed beneath cover. An instructive paper by Skirrow et al. (2019) describes the methods used, based on the example of iron oxide Cu-Au (IOCG) mineral prospectivity mapping in Australia.

Earlier, in the introduction to this paper, we referred to the discovery of the giant magmatic-hydrothermal iron oxide-copper-gold (IOCG) deposit Olympic Dam in South Australia. In the following, we summarize the procedure of Skirrow et al. (2019) in employing the metallogenic knowledge gathered from the archetype IOCG deposit Olympic Dam between 1975 (the discovery) until 2019 (Dmitrijeva et al 2019; Ehrig et al 2017; Verdugo-Ihl et al 2017). Globally, numerous ore deposits were soon identified as members of the IOCG clan. Skirrow et al (2019) included worldwide research on IOCG metallogeny in building a metallogenic model and with it, a knowledgedriven mineral system. In their paper, Skirrow et al. (2019) investigate three metallogenic themes:

- What is an Iron Oxide Copper Gold deposit, what are key diagnostic features of IOCG globally and what is the difference to eight similar deposit classes such as the orthomagmatic Kiruna iron oxide apatite (IOA) class that is not IOCG?
- How to model the IOCG mineral and metallogenic system (theoretical considerations)?

• How to map large regions for indications of hitherto unknown IOCG (input data sets, workflow and results for five regions within Australia)?

The Cu–U–Au–Ag–REE *Olympic Dam* deposit is located within the Gawler Range silicic large igneous province (SLIP) in a postorogenic oxidized potassic granite (dated at ~ 1590 Ma), set in a Paleo- to Mesoproterozoic graben and is covered by > 250 m of younger, unmineralized rocks. Host rocks are coarse hematite-rich granite breccias of likely explosive volcanic and phreatomagmatic origin. The breccia complex contains thick sections of bedded clastic rocks, which appear to be remnants of an eroded, previously overlying crater lake or a basinal cover.

The hematite breccia ore contains 2.5 wt % fluorite, copper sulphide (chalcocite, bornite, chalcopyrite) and by-product grades of rare earth elements, uranium, gold and silver. Hematite is marked by elevated traces of granitophile elements such as U–W–Sn–Mo (Verdugo-Ihl et al 2017). Ore and litho-zoning in the hematite breccia is defined by > 10 k multi-element geochemical data (Dmitrijeva et al 2019). Diagnostic alteration minerals include fluorite, hematite, chlorite and sericite (phengite). The total resources amount to ~10,000 Mt at 0.77 wt % Cu, 250 ppm U<sub>3</sub>O<sub>8</sub>, 0.32 g/t Au and 1 g/t Ag. The proven reserves are 150 Mt with 2 wt % Cu, 620 ppm  $U_3O_8$ , 0.63 g/t Au and 5 g/t Ag (Ehrig et al 2017). The mineralization appears to be the product of the mixing of ascending hot magmatic brines and volatiles (carrying reduced sulphur species and hydrofluoric acid) with shallow highly oxidized hematite-forming groundwater. The source of iron, copper and gold can hardly have been the host granite. Mingling of mafic and silicic melt, deep crust, fluorine-intensified leaching and metasomatized subcontinental lithospheric mantle enriched by prior subduction or by a plume may have contributed to the metal endowment. Skirrow et al. (2019) discuss the unresolved fluid source question of the IOCG clan - magmatic-hydrothermal only or non-magmatic mixed with basinal or metamorphic brines; the authors include both cases in their global analysis.

Olympic Dam's Cu–Au mineralization age is syngenetic with igneous host rocks at 1.59 Ga. It is late-collisional, proximate to the suture and likely associated with lith-ospheric mantle delamination and melting of subduction-related metasomatized lithospheric mantle (Skirrow et al 2019). Probably, the orogen is of the hot type (Zhang et al 2022a, b). Hot, hydrous and supercritical melts may have originated in the fertile SCLM (cf. 3.2), when the hot asthenosphere closed in. Uranium, however, appears to have been upgraded at 0.7–0.5 Ga during perturbation of regional fluid flow triggered by global climatic (deglaciation) and tectonic (breakup of Rodinia) events (Ehrig et al 2021).

Systems need to have borders. For the purpose of mapping general IOCG prospectivity, not only for the Olympic Dam deposit, Skirrow et al. (2019) developed an IOCG mineral system model based on inclusion of the criteria listed below (here condensed), which are common to the whole IOCG clan but exclude other deposit classes:

- Highly elevated Cu and Au;
- Cu-bearing sulphides and Au associated with > 10 vol % of low-Ti magnetite and/or hematite;
- Hydrothermal quartz is minor;
- Hydrothermal alteration is zoned: (a) a wide regional halo of Na-Ca (albite, amphibole, clinopyroxene); (b) proximal at mid-depth Fe<sup>2+</sup>and K enriched (magnetite-biotite); (c) uppermost levels Fe<sup>3+</sup> (hematite) and sericite, or chlorite ± carbonates;
- IOCG deposits are generally epigenetic and syntectonic;
- Ore styles include breccias, metasomatic veins or vein stockworks;
- IOCG deposits are distal from bimodal intrusions (A- or I-Type), and proximal to bimodal volcanics;
- Host rocks are diverse, ranging from granite and felsic volcanics to mafic igneous and metasedimentary rocks;
- Mineralizing fluids comprise (a) high-T (> 300 °C) brines and (b) low-T aqueous fluids, commonly with some CO<sub>2</sub> and evidence for phase separation.

Because of the diversity of facts and opinions concerning global IOCG metallogenesis, the resulting model comprises genetic alternatives, mainly concerning the fluid and metal sources (ANNEX Fig. 9). Yet in the Gawler Craton, magneto-telluric data show conductive zones extending directly beneath the Olympic Dam and other IOCG deposits downwards through the crust into the upper mantle (Skirrow et al 2019); at the time of writing, the authors hesitated to give this observation much weight, but today, there can be little doubt that the upflow of melts and fluids from a deep and hot source is one of the critical processes of IOCG formation.

The unified model of IOCG mineral systems is described by (i) theoretical criteria (*'metallogenic knowledge'*: the lower-most level in ANNEX Fig. 10) and (ii) mappable criteria (next level up in Fig. 10; listed and fully explained in Skirrow et al. (2019). *Sources* of metals, fluids and ligands, for example, are deduced from solid geology (the presence of evaporites, or felsic intrusives, mafics–ultramafics, ironrich magnetic meta-sediments, regional sodic alteration) or from magneto-telluric data indicating hydrated lithospheric mantle. Crustal *energy drivers* can be identified by hot Aand I-type intrusions (employing zircon saturation data) or in the case of mafic intrusions near the MOHO by seismic tomography-derived Vp > 7.1 km/s. *Fluid flow pathways* may be marked by high-conductivity columns, detected by magneto-tellurics, rising from the mantle to IOCG deposits on top. *Ore depositional gradients* such as a change in oxidation degree can be recognized in solid geology, by 3D inversion modelling of magnetic and gravity data, by hyperspectral remote sensing and by radiometrics (high U/Th).

Skirrow et al. (2019) provide detailed data, not least in how weightings are applied. Extensive discussion of the 14 single criteria (such as fluid and metal sources) based on available global data on IOCG is instructive. Workflow comprises identification of critical geological processes, their mappable features ('proxies'), selecting the digital spatial data best representing the mappable features, and assigning importance, applicability and confidence weightings between 0 and 1 to the mappable input data sets. The next step in the workflow (ANNEX Fig. 10) is the preparation of maps in 2D GIS (geospatial information system) for each of the four system components. The four single maps are then combined into one final prospectivity or mineral potential endowment map.

The results on Olympic Dam-type prospectivity in the Gawler Craton clearly show the giant Olympic Dam and the sizeable Prominent Hill IOCG deposit, but miss the similar-sized Carapateena. All three are producing mines. Low-density geophysical data are probably the reason for the failure (Skirrow et al 2019). An evolving Australian megaproject is *Oak Dam*, an Olympic Dam-style IOCG deposit located only 65 km to the SSE of Olympic Dam mine. Recent drill intersections include 312 m at 2.14 wt % Cu, 0.55 g/t Au, 390 ppm U<sub>3</sub>O<sub>3</sub> and 3.14 g/t Ag; the mineralization covers 2.3 km × 800 m and is located under 800 m of younger cover sequences (Meares 2021).

In one experimental run, Skirrow et al. (2019) achieved a very significant area reduction (> 80%) with the selected use of geophysical data such gravity, magnetics, seismic velocity from passive seismic data, magnetotelluric and seismic reflection data. The prospectivity mapping results are further improved; however, when the full suite of input data sets are utilized as listed in the bullet table above, including metallogenic knowledge. As presented, the resolution is appropriate to aid exploration area selection and government prospectivity or endowment studies at craton- to regional scale. It is not designed for deposit-scale targeting. The results of the method will be improved wherever new and higher-resolution input data are incorporated (Skirrow et al 2019). Finally, the authors recommend transfer of the results to industry such as mineral exploration companies as a decision-support tool for identifying previously unrecognized regions with high mineral potential or regions concealed by younger cover.

Today, the mineral systems approach to exploration, prospectivity mapping and mineral potential evaluation appears to be mainly pursued by academics, junior explorers and a number of geological survey organizations, including Australia (Ford et al 2019), Canada, USA, China, Finland (Molnár et al. 2020) and Sweden. Australia is exemplary though not alone in providing free access to precompetitive material such as geological, geophysical and geochemical data. Meanwhile, some international mining industry consultants offer mineral system application as part of their services in exploration and mineral endowment analysis. An advantage of the mineral system approach is the greater number of more types of search criteria compared with previous guides to ore such as the proximity to the transition from amphibolite to greenschist metamorphism, hydrothermal alteration zones (remote sensing), soil and rock chip geochemistry, and geophysics. Employing MSA, greenfield exploration can locate favourable parts within large regions, as shown by Skirrow et al (2019), even under cover.

Innovation in MSA is continuing: Xu et al. (2021), for example, built a deep regression neural network to map the mineral prospectivity in the *Daqiao Gold Mine* region, Gansu Province, China. The neural network was trained using multi-source data including expert knowledge (metallogeny), and geological, geophysical, and geochemical data. Deep learning was applied because algorithms can more effectively deal with complex problems, and enhance the identification of anomalies and hidden patterns. The prospectivity map obtained proved to be useful for searching gold mineralization in the study area (Xu et al 2021). Demonstrably, MSA profits by applying artificial intelligence, deep learning and machine learning in order to accelerate the pace, and improve the quality of data analysis.

By deepening and expanding scientific understanding, metallogeny delivers output that MSA may turn into new search criteria. For this reason, metallogeny is a never-ceasing source of new discovery models and tools.

#### Discussion

Today, we still define metallogeny as the science of the origin and distribution of mineral deposits in geological space and time (de Launay 1905), but we would add 'especially with regard to petrogenetic, tectonic and geodynamic process systems'. For a full understanding, relative and precise absolute dating of single events in metallogenic systems is essential.

Metallogeny is not a closed system but is a fast-growing, often disruptive and ever innovative body of interdisciplinary scientific knowledge. We estimate that annually, more than 1000 papers are added to this field. Since the turn into the twenty-first century, digitization has transformed all geoscience work, and not least, metallogeny. Now, metallogenic knowledge and geodata are digitally processed, analysed and displayed by geospatial software.

Metallogeny is the sum of scientific work at all scales that concerns the three essentials of the formation of mineral and metal deposits in space and time: i) the metal source, ii) the mobilization from the source and iii) transport and deposition to form a concentration, which is economically extractable. Further important components are the related geodynamic and petrogenetic process systems, including information on heat sources and their timing.

In this review, we suggest a modern use of metallogenic terms ('Metallogenic terms') and we sketch the frame of a formal classification of ore and mineral deposits in the metallogenic system ('Metallogenic classification of ore and mineral deposits'), although both need fleshing out. The current 'deposit type' terms are haphazardly, not systematically named, and do not follow a logical system. Yet, of course, they may be informally employed if desired. In our opinion, a truly metallogenic classification should include petrogenesis (ANNEX Fig. 2) and the geodynamic–tectonic setting (ANNEX Fig. 5). The descriptive term 'Genetically related features' in the newly proposed deposit classification scheme for Critical Minerals Mapping by Hofstra et al (2021) can be used for fine-tuning the coarse net here suggested.

The novel geodynamic history of the early Earth with a stage of oceanic 'lid tectonics' is a yet unsettled, speculative and unproven hypothesis in understanding the Earth and its metallogeny ('Metallogeny, geodynamics and deep time'). During lid tectonics, the Earth may have resembled planet Venus (ANNEX Fig. 3). In lid tectonic times, the leading edge of drifting protocontinents would have been convergent margins (orogens) characterized by terrane accretion, imbrication, subcretion and anatexis of unsubductable oceanic lithosphere (sensu stricto lid tectonics: Bédard 2018). Ore deposits formed in basalt-komatiite units, such as thick BIF ('Algoma type', or volcanogenic exhalative basalt-related banded iron formations) and chert sequences. Remarkable are komatiite hosted rivers of orthomagmatic nickel sulphide in lava channels or disseminated in subvolcanic intrusions (Barnes et al 2017). Archean volcanogenic polymetallic massive base metal-sulphide (VMS) deposits may have formed from fluids mobilized by reheating of a hydrated submarine volcanic pile, like their more recent equivalents caused by plumes and other magma pulses. The deep sections of imbricated foreland terranes were the source of gold-carrying metamorphic fluids and magmas, resulting in orogenic Au deposits (ANNEX Fig. 4), such as (possibly) the supergiant Neoarchean Kalgoorlie Gold Camp in Western Australia ('Metallogeny and non-uniformitarian models of ancient earth geodynamics: lid, or subcretion tectonics').

In spite of the presently hypothetical level of understanding, the non-uniformitarian models of the early Earth's geodynamics, including lid tectonics, we speculate that continuing research in this field may yield great advances in metallogenic comprehension.

Plate tectonics ('Metallogeny and plate tectonics') is the main agent in the modern dynamic Earth system (Turcotte

and Schubert 2014; Frisch et al 2011; Kearey et al 2009). Process systems of plate tectonics include a great part of the global *metallogenic factories* (Sillitoe 2020a; Sillitoe et al. 2020b; Pohl 2020). Main metallogenic settings and examples of related deposits include ('Metallogeny and plate tectonics'):

- Within-plate settings and incipient divergent plate boundaries; examples are Ni–Cu–PGE deposits at Noril'sk; the Deseado gold province of Patagonia;
- Divergent plate boundaries; giant Red Dog district, Alaska, Ba–Zn–Pb–Ag; continental rifts are not favourable gold factories; newly recognized are hyperextensional passive continental margins leading to exhumation of subcontinental mantle that may have triggered voluminous fluid migration and mineralization, possibly including Au;
- Oceanic-divergent, or 'constructive' plate boundaries; Cyprus-class Cu–Zn sulphides and gold; the active Cheoeum Au–Sn vent field;
- Convergent ('destructive') plate boundaries (ANNEX Fig. 5); Kışladağ porphyry Au in western Anatolia, Turkey; giant Lihir epithermal Au in Papua New Guinea (ANNEX Fig. 6); Fruta del Norte epithermal Au–Ag deposit in Ecuador;
- Orogeny, sutures and terrane accretion; the Himalayas– Tibet metallogenic domain; 'collisional gemstones' ruby and jade; orogenic gold deposits; collisional, magmatic– hydrothermal giant Au–Cu deposit Telfer in Western Australia; Muruntau in Uzbekistan (an explosive Aumineralized breccia column originating in the mantle);
- Collision, assemblage, stasis and breakup of megacontinents and supercontinents. A part of orogenic gold deposits, formed by fluids derived from metasediments, may be directly related to collision and welding of supercontinents; an example is the great Altai metallogenic gold province of the Central Asian Orogenic Belt, which became part of Pangea (Aibai et al 2021).

Metallogenic models ('Metallogenic models') are complex schemes built from modules that comprise data, scientific knowledge and information from all geoscientific disciplines. Parts may be hypothetical. In this review, the source of gold and related elements ('Sources of gold') is arguably the least proven element of the system. In principle, the hypothesis of a crustal metamorphogenic dehydration source of gold (the 'metamorphogenic model': Phillips and Powell 2010; Gaboury 2019) is broadly supported, but a proof for all individual deposits is not available. A rare case is *Otago* (New Zealand), where ore-forming elements (Au, Ag, As, Sb, Hg, Mo, W) are depleted in higher-grade rocks relative to unmetamorphosed protolith samples. The same suite of elements is enriched in the island's orogenic gold deposits (Pitcairn et al 2014) that contain a total of approximately 580 tonnes of gold (past production and resources).

Observation and hard data do not yet fully support the widely accepted assumption that the source of gold may be metasomatized, hydrated or 'fertilized' mantle in a subduction setting (Groves et al 2020; Griffin et al 2013; Hronsky et al. 2012; Richards 2009; Sillitoe 2008). In the Lihir region (PNG), mantle xenoliths with metasomatic veins (ANNEX Fig. 6, inset magnifying lens) that originated by subduction zone-related metasomatism and contain phlogopite, amphibole, pyroxene, garnet, magnetite and Fe-Ni sulphides, and high concentrations of fluid-soluble elements (e.g. alkalis, S, Cu, Zn, Rb, U, Pb, large ion lithophile and light rare earth elements) are up to 800 times enriched in ore metals (Cu, Au, Pt and Pd) relative to normal depleted arc mantle (McInnes et al 2001). Mantle-derived dykes may provide clues. Geochemistry (e.g. mantle-derived noble gas compositions in fluid inclusions: Liu et al. 2021a, b, c) yields information about the involved processes, and geophysics such as seismics, marine magnetotelluric (MT) and controlled source electromagnetic sounding (Chesley et al 2021) can help to image the slab and altered rock masses. Higher resolution and more power of discrimination are, however, desirable.

We suggest that in the metallogenic subduction zone factory, at high temperature and at upper-mantle pressures, a supercritical state of hydrous melts and fluids is more common than generally admitted ('Mobilizing the gold: supercritical hydrous melts and fluids'). This should be seen together with the many possible configurations of hot (1400 °C) asthenosphere intruding into slab breaks or through slab windows, or replacing delaminated masses (ANNEX Fig. 5). Supercritical fluid/melts have water-like viscosity and possess very high H<sub>2</sub>O activity, which endows them with a great power of dissolution or metasomatism (Thomas et al 2019). Also, they may explain many observations of over-pressure such as the gold-rich 4-km-high auriferous breccia pipe of Muruntau in Uzbekistan. Mantle plumes may also be a heat source and a means of fertilization (Li et al 2021; Wyman 2020; Tassara et al 2017).

A review of current exploration methods is given in 'Metallogeny in present-day industry sources' that commences with a brief summary of the metallogenic analysis of the giant metallogenic gold domain of the North and South American Cordilleras (Sillitoe 2008). The role of non-ore alteration thousands of metres above Cu–Au porphyries is addressed and exemplified by reporting the remarkable discovery history beneath a lithocap in Chile (Sillitoe et al 2016). In their reports to regulating authorities, companies refer to metallogeny but rarely discuss how it was employed (SEDAR 2021). One of the global leaders is Geoscience Australia (2021), and we relate some of its activities. Geochemical mapping in China yields interesting tools for discovery, such as high-density (HGM) (1 sample/km<sup>2</sup>) to super-low-density (SLGM) (1 sample/180 km<sup>2</sup>) and ultra-low-density sampling of stream sediments (ULGM) (1 sample/1600 km<sup>2</sup>). One important result of work in the Altai gold province is that commonly used pathfinder elements such as As, Sb, and Hg often display a statistically independent behaviour and their application in gold exploration is questionable (Liu et al 2021a, b, c).

Among geophysical exploration methods, the increasing role of *magnetotellurics* (MT) in deep exploration is of greatest interest. Nowadays, Australian exploration companies particularly favour EM (electromagnetics) and SAM (subaudio magnetotellurics). We provide some introductory notes, case studies and references. Especially remarkable is the compilation and interpretation of long-period magnetotelluric (MT) and geomagnetic depth sounding (GDS) data across western Victoria and south-eastern South Australia. The data image the electrical resistivity of the crust and mantle, which depends on past thermal and fluid processes. The project area ( $500 \times 800$  km) encloses the giant *Victorian gold province* hosting the renowned Bendigo and Ballarat fields (Heinson et al 2021).

A complex plate tectonic setting (ANNEX Fig. 6) was resolved by Brandl et al (2020), who synthesized published and previously unreleased multimethod data from ship-based multibeam and seismic studies, satellite gravimetry, geochemistry and geochronology, explaining the formation of the giant *Lihir/Ladolam* gold deposit ('Metallogeny and plate tectonics'/ 'Metallogeny in gold exploration practice').

In 'The role of metallogeny in mineral system analysis', the mineral system approach to exploration, prospectivity mapping and mineral potential evaluation are highlighted (Skirrow et al 2019). The authors describe the methods used, fully worked out and explained in great detail, based on the example of iron oxide Cu–Au (IOCG) mineral prospectivity mapping by Geoscience Australia. For its central role in this section, the Cu–U–Au–Ag–REE *Olympic Dam* IOCG deposit in Australia is presented in more detail (ANNEX Fig. 9).

The term 'mineral system' is used in two ways: (i) as an ore-generating system in geological settings (such as Pitcairn's et al. 2014 'gold conveyor belt' in New Zealand) and (ii) as an intellectual construct, abstraction or generalization of the first for application in exploration. We propose that the first (i) should better be called a 'metallogenic or minerogenic system', whereas the second (ii) retains its present denomination 'mineral systems model'. The first is holistic metallogeny in space and time, at all scales from the microprobe to the cosmos. The second (ANNEX Fig. 10) uses the first as a knowledge base but defines borders and selects critical system components (proxies for properties, processes and features) that can be detected; its main task is mapping the coincidence of favourable components (such as the conductivity of enriched subduction-related mantle wedges or subcontinental lithospheric mantle). The proposed differentiation describes the relation between metallogenic and mineral system models.

#### Conclusions

Science and practice of metallogeny ultimately serve to supply mineral raw materials that are needed for a dignified life of humankind. Earth has a much larger endowment of mineral resources than is often claimed. Proponents of impending 'limits to growth' have been proved wrong by scientific arguments (Wellmer and Scholz 2018, 2017), and indeed, by the mining industry that reliably satisfies global requirements. There is no reason to assume a shortage of raw materials, if the mining sector is allowed to do its work.

This paper is a call for the appreciation of metallogeny as the holistic science of ore formation, and in that role, as a fundamental toolbox for exploration. The body of metallogenic knowledge grows at a quick pace. Like human ingeniousness, this growth is unlimited.

Future resources of many minerals and ores will be buried beneath cover. Already now, exploration has many tools for the discovery of these deposits. Yet, we may expect that the detectability of distal or weak pointers such as geochemical halos or geophysical signals will continue to grow. Innovative deep Earth imaging will yield ample raw materials. Better scientific understanding of the geodynamics of the early Earth (lid tectonics?) might greatly improve greenfield discovery.

The Earth's mantle will attain a central role in future exploration for deep (~3300 m) hidden ore deposits sourced from the lower crust or mantle, similar to the current exploration for ultra-deep hydrocarbon sources in oil and gas search. Alike to subsalt oil and gas traps, predicting favourable preservation sites of ore bodies through time will increase in importance.

Greenfield area selection might be facilitated if fertile sectors of subduction zones can be identified by features such as metasomatized mantle and translithospheric up-flow architecture. Scanning subduction zones for favourable locations might be considered a contribution to the current trend of 'precompetitive' geoscience data sets being made available by state geological surveys, allowing the exploration industry to take advantage of novel methods of data processing and interpretation similar to the *Deep Earth Imaging program* (CSIRO 2021). This program aims at developing holistic joint analysis of seismic, magnetotelluric and potential field methods, boosting discovery for the next generation of exploration.

We expect that Sillitoe's (2008) dictum 'the most fundamental questions of all relate to the concepts of metallogenic inheritance and provinciality as explanations for the metal distribution patterns' will be answered by skilled use of metallogenic tools and models for exploration, such as the mapping of fertilized mantle, of structures allowing up-flow of melts and fluids, and of hidden traps containing exploitable concentrations of minerals and metals.

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Competing interests The author declares no competing interests.

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