An introduction to *Recent Advances in Understanding Gold Deposits: from Orogeny to Alluvium:* the importance of multi-method approaches and developing a characterization

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Abstract: Gold occurs in many settings but the dynamic nature of Earth's crust means overlapping and overprinting deposit styles are common. Characterization of mineralization from an early stage becomes important particularly where the mineralization is complex, in order to maximize exploration and project development success, and mining productivity. Various techniques are used at different stages of a project to characterize gold deposits. This Special Publication *Recent Advances in Understanding Gold Deposits: from Orogeny to Alluvium* offers a cross-section of some specific techniques to investigate a variety of gold deposit types. In this Introduction, we briefly compare the most common gold deposit types, summarize the techniques used to investigate them and discuss some of the most important outstanding questions regarding understanding gold deposits. This is followed by a summary of each paper in this Special Publication. Whilst the 15 papers in this book can only showcase some of the many approaches available, they do highlight both the breadth of the available techniques and their utility in deposit characterization. Several papers include suggestions for avenues for fruitful further research, including a paper suggesting a new approach to classifying orogenic gold deposits, and a paper describing archaeological applications of natural gold analyses.

Comparison of the most common gold deposit types and the tools for their characterization

Gold remains a key financial commodity but, in addition, several hundreds of metric tonnes of gold is needed annually for industrial applications, most important of which are electronic components and medicine (Corti and Holliday 2004). Gold mineralization is hosted in a variety of geological settings, from oceanic arcs to orogenic belts including their forelands and back-arc basins, as well as in alluvial (placer) sediments (Sillitoe 2020; Table 1 and references therein). Gold mineralization styles are classified in many ways and most models and classifications are both controversial and show overlapping characteristics with each other (Table 1). Recognition of the likely mineralization type can, however, be important as the mineralization type can dictate the exploration approach, and some mineralization types have been shown to be more likely to form an economic deposit (e.g. Singer and Kouda 1999; Frimmel 2008). Although genetic models assigned to a single occurrence tend to be both controversial and change over time as understanding of the mineralization evolves, those classified as 'orogenic gold' and (palaeo)placer have historically formed the majority of economic deposits; with porphyry (Cu–)Au, including related skarn deposits and epithermal Au, and Carlin-type deposits (disseminated gold deposits hosted in basinal sediments, typically carbonates) each forming less than 10% of historical production (Frimmel 2008; Fig. 1). However, the dynamic nature of the Earth's crust, particularly within mobile belts, typically results in various deposit types spatially overlapping or overprinting each other (**Liu *et al.* 2021**; **Mesquita *et al.* 2022**). Such overlaps can make understanding an individual deposit or a metallogenic district very challenging: characterizing the process(es) that formed a primary (hard-rock) deposit, or the detailed geometries in a changing river system for an alluvial deposit, typically requires a range of techniques for even a relatively basic characterization.

The need for a detailed characterization increases as the project becomes more advanced: whilst a fairly rudimentary characterization may suffice during the early exploration stages, an increasingly detailed understanding of, for example, the ore

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Table 1. *Summary and comparison of the most typical gold deposit types*

	Trap/mineralization type	Host type	Tectonic setting	Crustal palaeodepth	Temperature of ore-forming fluids	Mineralogical and/or alteration zonation	Syn-ore magmatism	Other typical metals/elements	Fluid type	Fluid CO_2 content	Fluid salinity (NaCl equiv.)
Orogenic gold	Quartz ± carbonate veins and breccias in lower-order structural traps (veins, faults, shear zones, fold hinges) near major crustal faults; typically showing evidence of progressive deformation and multiple fluid pulses (e.g. 1)	Variable metamorphic and magmatic rocks (e.g. 1)	Orogenic belts: late to post-peak metamorphism; form typically, but not always, during the late stages of the orogeny (2)	Variable: <5 km to >15 km; typically 5–7 km (2; 3)	Variable but up to 650–700°C; typically *c.* 350°C (2; 3; 4)	Alteration not systematic: any alteration and its type depends on the effective chemical gradient between fluid and host; nugget effect common in gold grade (1)	Can occur but no universal association with magmatism in time or space (1)	As, B, Bi, Sb, Te, W; low base-metal contents (1)	Aqueous-carbonic, 'metamorphic' fluids injected during multiple seismic cycles (1)	5–20 mol% (1)*	3–7 wt% (1)
Reduced intrusion-related gold systems (RIRGS)[†]	Variable: disseminated ore to breccias and stockwork, sheeted veins or skarns (6, 7, 8)	Continental margin volcano-sedimentary rock sequences (6)	Orogenic back-arc or foreland weakly extensional/transtensional setting (6, 8)	Typically 5–7 km (8)	>350°C proximal to intrusion; 150–200°C distally (7, 8)	Common zoning from proximal Au–W skarns & Au–As veins & dissemination, to distal Au–Pb–Zn (–W–Bi) veins; proximal carbonate-feldspar alteration (6)	Yes: diverse but usually felsic, relatively reduced, alkaline, volatile-rich plutons with low ferric: ferrous ratios of <0.3; some can be more mafic (monzodioritic) (6, 8)	Bi, Te, W, As; typically low in base metal sulfides e.g. Zn, Pb, Mo, Sn, Sb, Ag; Cu very rare (6, 7, 8)	Reduced magmatic fluids, typically carbonic (6, 7)	Variable but often CO_2-rich (6, 7)	Usually low, <10% (6, 7)
Oxidized intrusion-related gold systems (Porphyry Au (-Cu) systems)[†]	Typically in breccias and veins, stockwork and dissemination; also in fracture zones, sheeted veins, skarns/replacement ore distal to intrusion. Major deformation post-deposition rare (9). Au grades usually low (<1.5 g t^{-1}; e.g. 10)	Accretionary wedge or back-arc basinal sedimentary rocks (9)	(Locally) extensional sites in continental and island volcanic arcs at convergent margins; usually pre-collisional, syn-subduction (9)	Typically 1–2 km (9)	500–700°C proximal to intrusion; <350°C distally (9)	Yes: zoned alteration, albeit often overprinting by successive magmatic fluids: proximal potassic to propylitic, intermediate pyrite-rich phyllic, to outer argillic zones in the epithermal parts of the system (9)	Yes: typically crustal melts of intermediate composition, low-K calc-alkaline, oxidized, magnetite-rich, sulfur-poor; not highly fractionated granitic magmas (9, 10). In composite intrusions, high grades usually with early magmas only (9, 10)	Cu very common and often dominant; Zn, Ag, Pb, Mo, Te; occasional PGEs; low As and Hg except in the most proximal epithermal parts of the system (9)	Oxidized magmatic fluids (9)	25–30 mol% in intial magmatic fluids (9)	40–60 wt% in initial magmatic fluids; 5–20 wt% in later fluids* (9)

Carlin-type	Anticlinal traps and similar structural culminations within reactive, permeable calcareous host rocks capped by non-reactive siliciclastics (5)	Non-metamorphic calcareous and pyritic sedimentary rocks (5)	N/A: traps form along orogenic thrust fronts but mineralization post-orogenic extension and/or strike slip (5)	<5 km (5)	*c.* 180–240°C (5)	Not systematic (5)	Probably none, although some of the fluids may have magmatic origins (5)	As, Sb, Tl, Hg, Ba, F; low base metal and Ag contents; some U (5)	Aqueous-carbonic from a variety of sources ± fluid mixing (5)	<4 mol% (5)	2–3 wt% (5)
Epithermal deposits Au(-Ag) (low-, intermediate- and high-sulfidation types: LS/IS/HS)†	100 m-scale fault- and fracture-controlled veins; low- and intermediate-sulfidation types can be very rich with >30 g t^{-1} Au; colloform banding and vugs very common (10)	Volcanic host but fluids derived from buried intrusion(s) of variable compositions (10)	Volcanic arcs and orogenic belts (10)	<1 km	200–300°C (10)	Yes: pervasive silicification and argillic alteration (10)	Yes; igneous intrusions at depth; HS and IS above shallow intrusions; LS above deeper intrusions of up to 10 km depth (10)	Ag common; base metals occur in many IS and HS type deposits; LS types related to alkaline magmas can be high in Te (10)	Vapour-rich magmatic fluids: HS fluids acidic; IS and LS fluids near-neutral (10)	Variable (10)	Usually low especially in LS but can be higher in IS/HS (10)
Gold-rich VMS deposits	Disseminated to massive sulfide lenses and stockwork feeder zones; typically strongly deformed in later orogenic events (12)	Syngenetic replacement or direct precipitation onto seafloor (12)	Rifted magmatic arcs and immature back-arc basins with submarine volcanism (11)	Relatively shallow-water seafloor or near-seafloor (12)	>400°C but drops quickly upon boiling on seafloor (12)	Usually advanced argillic but chloritic to white mica zoned alteration can occur (10, 11, 12)	Yes: Tholeiitic to calc-alkaline bimodal volcanism with shallow underlying intrusions (12)	Cu, Zn, Ag, Sb, Hg common (11, 12)	Magmatic (11)	Variable (13)	High-salinity original magmatic fluids (13)
Fluvial placer deposits	Physical deposition of detrital particles controlled by variations in hydrodynamic setting at all scales (14)	Fluvial sediments (15, 16)	Various, according to interplay of geological and geomorphological setting (15, 16)	Contemporary erosion level	N/A	N/A	N/A	Can be significant: governed by compositional characteristics of source (17)	N/A	N/A	N/A

*Unmixing due to depressurization can lead to separation of high v. low saline fluids.

†Note that skarn gold deposits are here considered to be a sub-type of the porphyry and RIRGS deposit groups because their formation is intimately associated with fluids derived from the intrusions interacting with carbonitic host rocks (e.g. Sillitoe 2020); on the other hand, epithermal deposits are presented separately as, although also intimately associated with magmatic intrusions, their characteristics are more varied (e.g. Sillitoe 2020).

References: (1) Goldfarb and Groves (2015); (2) Groves *et al.* (1998); (3) Goldfarb *et al.* (2001); (4) Gebre-Mariam *et al.* (1995); (5) Cline *et al.* (2005); (6) Thompson *et al.* (1999); (7) Baker (2002); (8) Hart (2007); (9) Sillitoe (2000); (10) Sillitoe (2020); (11) Hannington *et al.* (1999); (12) Dubé *et al.* (2007); (13) Galley *et al.* (2007); (14) Slingerland (1984); (15) Garnett and Bassett (2005); (16) Boyle (1979); (17) Chapman *et al.* (2021*a*).

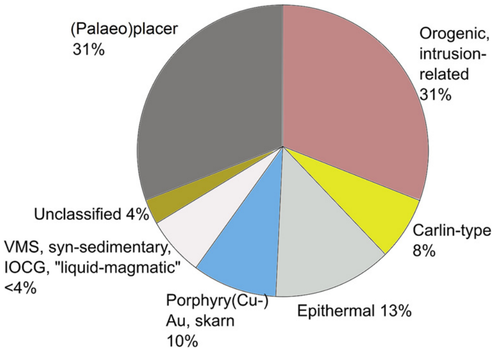

Fig. 1. Relative significance of different gold deposit types in terms of global production between 1984 and 2006. Reserves and resources are combined. Modified from Frimmel (2008).

paragenesis and mineralogy, geological structure and 3D geometry, rock mechanical and geochemical properties, and tectonic context is needed at the resource estimate and, subsequently, mine and processing planning stages (Table 2). The cornerstones of exploration remain fundamentally unchanged and basic lithological and structural mapping, rock (*in situ* or boulders), stream or soil sediment geochemistry, and possibly some geophysics such as airborne gravity and magnetic data, if available, are still an essential part of the toolbox. However, as ore deposits in general are getting more difficult to find and develop, exploration is increasingly carried out using more advanced tools and approaches tailored for the specific expected deposit type (e.g. Wood and Hedenquist 2019). This induces an increased need to characterize any observed mineralization as early as possible, requiring advanced expertise in geological thinking and the ability to synthesize and visualize multiple, often complex datasets, and the ability to robustly formulate and test hypotheses (Wood and Hedenquist 2019; Davies *et al.* 2021). Therefore, developing a deposit characterization, geological expertise, and the ability to approach an exploration problem similarly to a research question, goes hand-in-hand with successful exploration efforts. Collaborations between academics conducting applied research and industry can, in this context, provide a very valuable, relatively low-cost resource to provide valuable insights into characterization.

Modern techniques such as remote sensing and microanalytical techniques are increasingly being used in all stages of a project from exploration to target development and mine planning (Table 2). For initial large-scale (regional) exploration, the more traditional geophysical tools such as gravity and magnetics are now complemented by other remote-sensing techniques, for example satellite imagery, including hyperspectral data, or high-resolution light detection and ranging (LiDAR) data, often aided by computer-based analysis using geographical information system (GIS) or stress modelling packages (Groves *et al.* 2000; Krupnik and Khan 2019; Lypaczewski *et al.* 2019; Murray *et al.* 2019; Wood and Hedenquist 2019). For field (prospect-scale) exploration, portable geochemical analysis tools such as portable X-ray fluorescence instruments (pXRF) and near-infrared/short-wave infrared (VNIR-SWIR) spectrometers have enabled real-time first-pass analysis of soil and rock samples. Machine learning techniques are still being developed, but research so far shows promising results in potential applicability to interpreting complex and multi-scale datasets used in ore exploration (Nwaila *et al.* 2020; Shirmard *et al.* 2022). Machine learning may become particularly important, for example, when exploring for buried deposits whose only surface expression may be a subtle alteration halo, the recognition of which requires a powerful capacity to calculate mathematical patterns in multi-variant data (Shirmard *et al.* 2022).

Once the project is more advanced and drilling commences, the traditional geochemical and litho-structural data collection from drill core can be supplemented by various more advanced downhole geophysical and imaging techniques and by, for example, hyperspectral imaging of drill core, whilst computerized and directional drilling has enabled greater accuracy (Mutton 2000; Krupnik and Khan 2019; Wood and Hedenquist 2019). In terms of the more detailed characterization of the mineralization, the traditional transmitted and reflected light microscopy techniques are now supplemented by an array of microanalytical techniques that can greatly help in the characterizing, for example: the mineral paragenesis and the association of the ore minerals; detailed geochemical properties including zoning of both the ore and the gangue sulfides and silicates; and the possible sources of the fluids and metals. The recognition that natural gold is frequently a highly heterogeneous material at all scales has presented challenges to compositional characterization (Chapman *et al.* 2021*a*) but also opportunities in terms of refining our ability to identify gold from specific deposit types (e.g. Chapman *et al.* 2018, 2022). Last, but not least, structural, 3D geometric and stress modelling of gold deposits has been successfully used to mitigate the ‘nugget effect’ that is common particularly in orogenic gold deposits (e.g. Holyland and Ojala 1997; Table 1). The term ‘nugget effect’ is used to describe the heterogeneous distribution of gold grade, particularly in vein-hosted deposits where large volumes of the vein system are barren or very low-grade, interrupted by smaller high-grade volumes. The heterogeneous distribution of the grade poses a significant challenge to

Table 2. *Typical analytical approaches in gold exploration, research and mining at different stages of the project*

	Lithological and structural mapping	Stream and soil geochemistry	Geophysics and remote sensing*	Rock geochemical whole-rock assays	Reflected and/or transmitted light microscopy	Drilling*	Geomechanical and geotechnical modelling	3D geological modelling	Microanalytical techniques†
Prospecting	(x)	(x)	(x)	x	(x)				
Early exploration	x	x	x	x	x	(x)		(x)	(x)
Advanced exploration/scoping	x	x	x	x	x	x		x	x
Resource evaluation/feasibility study			(x)	x	x	x	x	x	x
Processing planning, metallurgical testing				x	x		x		x
Mine planning and development	x			x		x	x	x	(x)
Mine operation	x			x	x	x	(x)	x	(x)

*These approaches can include hyperspectral imaging to understand the spatial patterns in mineralization and/or alteration (e.g. Krupnik and Khan 2019).
†Examples of microanalytical techniques include SEM = scanning electron microscope SEM which includes techniques such as cathodoluminescence (CL), electron backscatter diffraction (EBSD), energy dispersive spectroscopy (EDS), and backscattered electron imaging (BSE); mass spectometry techniques, e.g. ICP-MS and LA-(ToF)ICP-MS; electron probe microanalyser EPMA; secondary ion mass spectrometry (SIMS); X-ray computed tomography (HRXCT).

exploration and resource estimate as any sampling and data analysis carry significant inherent uncertainty due to the nugget effect. Thus, continuous advances in computing power should enable increasingly efficient structural and geometric modelling of gold and other metal occurrences.

As mentioned earlier, an ongoing and evolving systematic characterization of a mineralization is an important part of the exploration and target development process. A large body of research utilizing a variety of approaches has significantly added to the available data and detail in recent years, advancing the understanding of gold deposits and their formation. However, detailed characterization remains problematic in most cases, and the issues have not changed much from those outlined by Groves *et al.* (2003). That is: (1) incomplete genetic models and classifications for most gold deposits; (2) non-unequivocal fluid and metal sources; (3) incomplete understanding of fluid migration, focusing, trapping and precipitation mechanisms at all scales, including the causes for the nugget effect in gold-bearing veins; and (4) the precise role and importance of both magmatism and CO_2-rich fluids. In addition, the signatures in many gold deposits are complex and likely result from overlapping deposit types, formed at different time during the geological history, and unravelling these requires a very detailed understanding of the deposit and the regional geology (**Liu *et al.* 2021**; **Mesquita *et al.* 2022**). Finally, the realization that gold solubility is too low to account for the very high grade gold deposits via the traditional models invoking gold transportation as sulfur or, in certain cases, chloride complexes in aqueous crustal hydrothermal fluids (e.g. Pokrovski *et al.* 2014) has added new questions about, and suggestions for, the transport and precipitation mechanisms for gold (nanoparticles and colloids; Petrella *et al.* 2020; Prokofiev *et al.* 2020). The additional tools available to us in the past approximately 20 years have, indeed, highlighted the complexity of gold deposits, and one could argue the new data have provided more new questions than new answers. For example, Hastie *et al.* (2021*a*) highlighted the potential importance of local transport and coarsening of gold via a dissolution–reprecipitation process. Such a remobilization–reprecipitation process, whilst explaining many features that have puzzled researchers, also raises new questions, for example regarding the mechanisms of such processes; what is the exact significance of these processes for gold enrichment; and what are the implications for deposit classification as such processes influence mineral microgeochemistry and are also likely to obscure any original mineral associations and textural features? All in all, there is still much fruitful research to be done in understanding gold deposits.

Content of this volume

This Special Publication provides a cross-section of various approaches that can be used to understand and classify gold deposits. The papers are divided here according to their approach.

The first five papers use multiple and regional-scale datasets to understand the larger-scale context of gold mineralization, including two papers discussing problems with the currently widely accepted genetic models on orogenic gold deposits (**Liu *et al.* 2021**; **Mortensen *et al.* 2022**; **Zhao *et al.* 2021**; **Babedi *et al.* 2022**; **Mesquita *et al.* 2022**). These five papers are examples of approaches that are commonly conducted by academic researchers to give useful background information feeding into the relatively early stages of exploration, i.e. they contribute to the understanding of the wider mineralization context with respect to the geological evolution of a specific area or within a genetic model framework.

The next four papers showcase specific case studies on gold deposits that have been classified as orogenic gold, using a variety of techniques (**Alexandre and Fayek 2021**; **Combes *et al.* 2021*a***; **Perret *et al.* 2021**; **Smith *et al.* 2021**). The papers use a combination of structural and 3D imaging techniques (including 3D CT scanning), scanning electron microscopy (SEM) and electron microprobe (EPMA) and laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS), elucidating their efficiency in gaining a more detailed understanding of a deposit. The approaches exemplified by these papers are commonly used at a more advanced stage of an exploration project where a more detailed understanding of the deposit is required, i.e. when resource estimation and processing planning are initiated.

The final section is dedicated to papers showcasing studies of gold in the surficial environment. The first five papers (**Chapman *et al.* 2021*b*, *c***; **Combes *et al.* 2021*b***; **Leal *et al.* 2021**; **Masson *et al.* 2021**) look into alluvial (placer) gold utilizing a variety of techniques such as EPMA, SEM, LA-ICP-MS and X-ray microtomography, and show how detailed characterization of alluvial gold can assist both hard-rock gold deposit targeting and interpreting soil sample data. The sixth paper in this section discusses the archaeological applications of gold alloy studies (**Standish *et al.* 2021**). In this very interesting paper, the authors critique the current approaches to archaeological provenance studies of gold and propose a two-stage approach to such studies.

Large-scale processes, models and multi-variate datasets

Due to the complexity of most gold deposits, many of the contributions highlight the need to compile an extensive, multi-variate, multi-scale dataset to understand a deposit or a district. This need arises partly from the ambiguity of the meaning of results, and partly from the fact that many deposits show evidence of multiple mineralization episodes, progressive deformation, dissolution–reprecipitation processes, and/or overprinting deposit types. In this Special Publication, several papers address analysis of large-scale processes and overprinting relationships via complex datasets and/or multi-data approaches.

One of the most contested models is that for 'orogenic gold deposits' (OGDs), originally defined by Groves *et al.* (1998) and subsequently modified and reviewed by, for example, Groves *et al.* (2020). The first paper in this Special Publication by **Mortensen *et al.* (2022)** discusses whether the presently accepted genetic models for 'orogenic gold' should be modified to account for Phanerozoic OGDs. The original OGD models were developed based on Precambrian, mostly Archean, deposits, and **Mortensen *et al.* (2022)** note the different prevailing tectonic styles and sediment and seawater geochemical characteristics, particularly in the Archean. They argue that there are several characteristics in Phanerozoic OGDs that are not commonly seen in Precambrian OGDs, such as: (i) evidence for rapid exhumation during mineralization; (ii) dominance of siliciclastic sediments commonly rich in organic material as host rock, as opposed to volcanoclastic, usually graphite-poor rocks; (iii) in many cases, lack of a syn-mineralization, crustal-scale steep structure that is an inherent feature in Precambrian OGDs; (iv) the dominance of disseminated, rather than obviously structurally controlled, mineralization in some Phanerozoic OGDs; (v) evidence that the gold may be remobilized from early diagenetic disseminated pyrite within the sedimentary rocks in the general vicinity of the deposit, rather than sourced from great depths; and (vi) their typically much smaller volumes although the high average grades in many Phanerozoic OGDs still render them economic (see also **Babedi *et al.* 2022** in this Special Publication who suggest that their 5500 spot analyses of pyrite trace element data across several deposits show a systematic problem with the OGD classification in general; and **Smith *et al.* 2021**, who demonstrate multiple fluid sources in their case study 'orogenic gold deposit', a feature that they argue is not compatible with the OGD model). **Mortensen *et al.* (2022)** divide Phanerozoic OGDs into four groups: (1) Crustal-Scale Fault group, which is the group most closely resembling the Precambrian OGDs; (2) Sediment-Hosted group, often hosted by carbonitic rocks with both disseminated gold and local structurally controlled mineralization formed within compressional stress regimes; this group also typically shows a 'carbonate spotting alteration' that **Mortensen *et al.* (2022)** argue is unique to this group; (3) the Forearc group, where gold is hosted in extensional (i.e. dilational) veins within the sedimentary rocks of an active forearc; and (4) Syn- and Late-Tectonic Dispersed group, where gold is strongly lithology-controlled and occurring in dilational vein arrays formed within active collisional or transpressional orogens. The authors also provide a preliminary comparison of lead isotopes between the suggested sub-types: although published Pb isotope data from Phanerozoic OGDs is still sparse, there seem to be some differences between the proposed sub-types (Fig. 2). Further research is, however, needed in order to distinguish whether or not Phanerozoic OGDs can be distinguished based on their Pb isotope signatures or, indeed, other characteristics. Whilst this sub-classification of OGDs, including the need for one, is likely to prove controversial, this paper provides an important insight into the complexity and varied nature of OGDs in general.

The second paper in this section highlights the utility of trace element analysis of sulfides (via techniques such as EPMA and LA-ICP-MS). This approach has become widely applied to Au mineralization in recent years (e.g. Meffre *et al.* 2016; Gourcerol *et al.* 2018; Augustin and Gaboury 2019; Fielding *et al.* 2019; Godefroy-Rodríguez *et al.* 2020) and has started to produce valuable insights into our understanding of hydrothermal processes, mineral deposition mechanisms and Au deportment. **Babedi *et al.* (2022)** in this Special Publication present a large compilation of over 5500 multi-element spot analyses of pyrite across a broad suite of Au deposit types, which they submit to multi-variate meta-analysis. This work shows that the pyrite trace element data can be related to a particular deposit class, e.g. porphyry, low- and high-sulfidation epithermal and Carlin-style mineralization. In particular, specific Au–As concentration ranges in pyrite (**Babedi *et al.* 2022**) are relatively sensitive to different geological conditions. This suggests a relationship between the concentration of these trace elements and the geological processes occurring in these different settings. Interestingly, pyrite from orogenic Au deposits shows Au and As concentrations which overlap almost all other deposit types, suggesting a potential systematic problem with the classification of this deposit class. **Babedi *et al.* (2022)** highlight the non-trivial nature of interpreting these trace element data, with a critical assessment of the relationship between various trace elements (As, Se, Te, Ni, and Co) and temperature of formation. These variations, as the paper explores, cannot be wholly attributed to a single physical condition such as temperature and are instead influenced by a range of physico-chemical variables (f_{S2}, f_{O2}, pH) and hydrothermal processes that would provide fertile ground for further research.

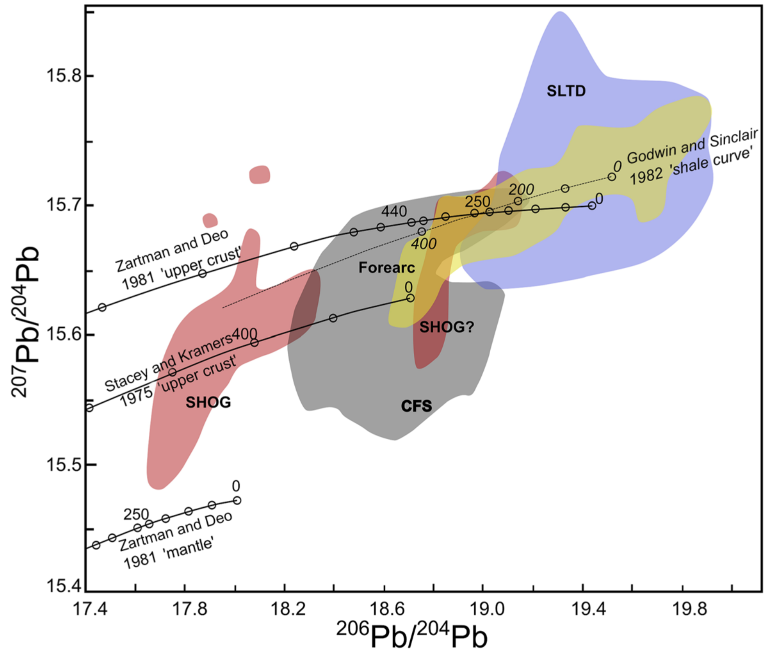

Fig. 2. Lead isotope analyses from different Phanerozoic OGDs, compiled and modified from **Mortensen *et al.* (2022)** with data from Farquhar and Haynes (1986), Godwin *et al.* (1988), Thorpe (2008), Mortensen *et al.* (2010), Bailey (2013), Huston *et al.* (2017). Note that global data are still sparse and further research is needed into the significance of lead isotopes with respect to Phanerozoic OGDs: therefore, the differences between the data from the various suggested sub-types needs to be taken with caution. Key: **CFS,** Crustal-Scale Fault type. Data from Sierra Nevada Foothills Belt, California; and Bridge River-Bralorne district, British Columbia. **Forearc,** Forearc type. Data from Otago Schist Belt, NZ; and Klondike district, Yukon. **SHOG,** Sediment-Hosted Orogenic Gold type. Data from Victoria gold field, Australia; South Cariboo, British Columbia; and Meguma Belt, Nova Scotia. The South Cariboo dataset shows distinctly higher $^{206}Pb/^{204}Pb$ ratios than the other deposits classified as SHOG by **Mortensen *et al.* (2022)**: the reason for this was not speculated in **Mortensen *et al.* (2022)** but, considering the significant overlap between these deposits and particularly the Forearc type lead isotope signatures, we suggest that a re-examination of this district classification may be in order. **SLTD,** Syn- and Late-Tectonic Dispersed type. Data from White Gold district, Yukon; and North Cariboo district, British Columbia.

The third contribution showcases how globally significant metallogenic provinces are commonly intensely geologically complex and may have experienced multiple episodes of orogenesis, magmatism and mineralization. **Liu *et al.* (2021)** describe complex overprinting of a Permian-aged porphyry system by apparently orogenic veins in the Changshagou Au deposit in the Eastern Tianshan orogen. This study utilizes textural observations, fluid inclusion analyses and stable and radiogenic isotopes to compare the geological conditions of the two events, highlighting the importance of employing multiple analytical techniques in the study of complex Au mineral systems. **Liu *et al.* (2021)** present convincing textural information combined with field studies and Re–Os dating of pyrite to make a strong argument for the two overprinting systems. It is instructive to note, however, that when examining $\delta^{34}S$ and paired $\delta^{18}O$ and δD isotope data from the porphyry and orogenic systems, there is no discernible difference between the two events. Stable isotope data alone, without the geological context, would therefore not have revealed the complexity of this multi-stage ore system.

Another example of multiple, overlapping mineralization episodes and the usefulness of large datasets comes from **Mesquita *et al.* (2022)**. They investigate multiple gold deposits and occurrences within the poorly exposed and only partially mapped Paleoproterozoic Alta Floresta district in the Amazonas Craton, Brazil, using a combination of both published and new structural data, chlorite and white mica geothermobarometry, and alteration assemblages. Based on an extensive analysis, they refine the previously published deposit classifications and confirm that there are at least two, probably three, distinct styles and ages of gold mineralization: an older 'orogenic' type mineralization succeeded and, in places, overprinted by younger Au–Cu porphyry type and/or an Au–Ag epithermal type. Particularly, the orogenic gold type shows distinct structural controls, alteration styles, and PT conditions of alteration compared to the other deposit types in the area. The paper demonstrates the value of not only investigating large datasets but also the value of detailed investigations into the alteration associated with the deposit.

Apart from direct investigations of deposits, it is also useful to understand the preservation potential in a given district. The fifth paper in this section by **Zhao *et al.* (2021)** combines $^{40}Ar/^{39}Ar$, AHe and ZHe thermochronology and apatite and zircon (U–Th)/He ages from Katebasu orogenic gold deposit in the western Tianshan Gold Belt, China, with thermal modelling to quantify the regional post-mineralization cooling and exhumation history. Their results suggest a three-phase cooling history with at least two distinct phases of exhumation. They calculate that 10–12 km of erosion has occurred since the Carboniferous, including at least 0.8 km of the mineralized 'roof' of the district having been removed by the uplift and erosion. They conclude that the preservation potential of particularly any Carboniferous shallowly emplaced meso- to epizonal systems such as porphyry and epithermal deposits may, therefore, have been significantly affected by the exhumation; this has clear implications for the exploration strategies employed for gold mineralization in the region. On the other hand, the authors suggest that the large erosion depth may be beneficial for forming placer deposits in the area, although to date only some small placer deposits have been found.

'Orogenic' gold deposit case studies

Several deposit-specific case studies in the Special Publication highlight the importance of detailed quantitative analysis to understand the evolution of a specific deposit at the more advanced stage of an exploration project.

The first paper in this section, by **Combes *et al.* (2021*a*)**, suggests a polyphase mineralization model of the Yaou Deposit, French Guiana. The deposit is structurally controlled with the gold hosted in shear zones and quartz–carbonate veins that formed during progressive deformation, but the authors show some evidence that suggests that at least some of the gold was remobilized from metasediment-hosted primary pyrite within the host rocks. The progressive enrichment of the deposit was possibly a process that was driven by the polyphase deformation, similarly to that suggested by Hastie *et al.* (2021*b*), for example. The gold enrichment may have occurred without additional external input of gold, although more research is needed to confirm if that was the case. Either way, this paper is another reminder of the importance of a multi-method approach linking macro- and meso-scale observations with grain-scale analysis, and that gold remobilization and proximal re-precipitation is likely to be a common phenomenon that may significantly affect the interpretation of the deposit type. Gold remobilization is, in other words, one key process that is presently only partially understood despite its potentially far-reaching implications for both deposit enrichment and characterization.

The second paper in this section is by **Perret *et al.* (2021)**. They highlight the need to understand the structural characteristics of an area in order to robustly model the ore body geometry and structural controls on grade distribution, thereby mitigating the nugget effect commonly affecting vein gold deposits in particular. The particular novelty of this paper is showing how field structural data can be linked with grain-scale geochemical and microstructural information, utilizing high-resolution X-ray computed tomography (HRXCT), electron backscattered diffraction (EBSD), and LA-ICP-MS. Their study area of Galat Sufar South gold deposit in NE Sudan is a complexly deformed deposit with prolonged, progressive deformation producing multiple gold mineralization events during the Neoproterozoic East African–Antarctic Orogeny. The host rocks show a penetrative folding at various scales and subvertical stretching, features that are replicated at micro-scale, including in the 3D geometry of the gold grain aggregates. The authors link these structural 3D geometries with the gold mineralization and the geometry of the ore shoots in general. The paper shows particularly nicely how gold mineralization progresses in time and space and how grade distribution in deformed deposits is closely linked to the 3D structural evolution. Especially the HRXCT technique has enabled a detailed 3D examination of the gold grade within the samples, enabling the authors to robustly link the mineralization geometry with the structural features. HRXCT is still under-utilized in ore geology research and this paper highlights the potential of this technology, as part of a wider toolkit, to provide key insights into grade control.

The study by **Smith *et al.* (2021)** of the Nalunaq Au deposit in Greenland employs microthermometry and LA-ICP-MS of fluid inclusion as well as X-ray photoelectron spectroscopy of sulfides and weathering products to explore the hydrothermal history of mineralization. The study shows that the Nalunuq deposit does not conform to the standard models of orogenic gold systems (e.g. Groves *et al.* 2020) in that the data presented provide compelling evidence for multiple fluid sources (magmatic, metamorphic, and potentially meteoric are all inferred) and mineralization in the hypozonal environment. This case study further contributes to the discussions elsewhere in this volume (**Babedi *et al.* 2022**; **Mortensen *et al.* 2022**) around the appropriateness, or otherwise, of a single model for nominally 'orogenic' Au deposits.

The final paper in this section showcases how understanding the chronological evolution of a deposit can help in developing a more detailed deposit characterization. A geochronological and stable isotopic investigation of the True North Au deposit in Manitoba, Canada by **Alexandre and Fayek (2021)** reveals a significant time gap between the development of the structures around the deposit (2.7 Ga) which have been previously assumed to control the deposit; and the age of mineralization which occurred later in two pulses at 2.48 and 2.44 Ga, respectively. The authors observe that the timing of these post-kinematic mineralization events correlates very closely with the pulsed emplacement of the Matachewan Large Igneous Province, implying that this magmatic event, rather than the structure, was driving the mineral system. This study serves to illustrate the importance of high-resolution geochronology applied to ore and alteration phases in understanding both the evolution of individual deposits, but also in probing the limitations of established genetic models.

Gold in the surficial environment

A significant proportion of this book highlights recent advances in our understanding of the heterogeneity of natural gold and implications for studies of gold liberated and transported by erosional processes. Studies of gold particles within surficial sediments may be divided into (i) those which address physical characteristics, whereby the progressive deformation of gold particles during transport is related to transport distance (e.g. Townley *et al.* 2003; **Masson *et al.* 2021**), and (ii) the much larger body of work that addresses compositional characteristics of gold alloy to either establish the relationship between lode gold and associated placers or to define specific compositional signatures associated with gold from specific deposit types (e.g. **Chapman *et al.* 2021*b***, 2022; **Liu *et al.* 2021**). A third approach to alluvial gold studies it its usage as indicator mineral: **Chapman *et al.* (2021*c*)** review our current understanding on this. Overall, this Special Publication provides a comprehensive collection of contributions that address fundamental questions in interpreting observations of gold particle heterogeneity and compositional datasets.

The first paper in this section addresses the morphology of placer gold particles as a potential indicator of distance to source: **Masson *et al.* (2021)** provide a review of the various approaches that have been proposed, all of which interpret shape indices derived from particle dimensions. A case study of placer gold in Quebec compares the definition of morphology via various shape indices to the more sophisticated 2D and 3D data obtained using SEM photogrammetry and X-ray microtomography, respectively. The authors propose a workflow in which the more straightforward 2D characterization is augmented by 3D shape analysis for selected particles within the target population.

The second paper, by **Chapman *et al.* (2021*b*)**, critically evaluates the contribution of authigenic gold in placers, considering both potential biogenic and chemical processes of gold accretion. The validity of interpreting chemical and mineralogical features of placer gold particles to illuminate the nature of their source is dependent upon the preservation of those compositional characteristics during liberation form the hypogene source and subsequent transport in the surficial environment. In the last 20 years a large body of work has demonstrated that biogenic processes can fix 'new gold' onto preexisting gold particle surfaces, thereby causing mass enhancement. Some authors have suggested that this process generates substantial particle growth (e.g. Reith *et al.* 2010), a hypothesis that resonates with a widely held perception that gold 'grows' in placers, as discussed in Boyle (1979). If true, widespread redistribution of gold in the surficial environment has major implications for targeting gold placers, and also undermines methodologies that seek to illuminate aspects of hypogene gold via study of placer gold particles. Evaluation of analyses and visual inspection of polished sections of over 40 000 gold particles from localities worldwide allowed the authors to conclude that the overwhelming majority of placer localities contain gold of a purely detrital origin, but gold particle growth by supergene processes can occur in specific environments where circumneutral groundwater facilitates both gold and silver transport as thiosulfate complexes. In contrast, biogenic process contribute to only the outer few microns of the particle surface and their potential to modify and indeed generate new gold in the surficial environment is generally overstated.

At present it remains unclear whether the supergene enrichment processes implied at some localities are replicated in other localities globally. In the third paper in this section, **Combes *et al.* (2021*b*)** characterize gold particles from different regolith units in French Guiana. They note gold particles whose form and composition indicate they have been released via weathering from adjacent decomposing veins, while other grains have experienced fluvial transport. Supergene gold was interpreted as a minor component, resulting from liberation of microscopic gold from sulfide decomposition. The study provides valuable insights on the importance of characterizing the mode of occurrence of gold within regolith profiles for the interpretation of soil surveys undertaken during exploration campaigns.

By and large, therefore, the overwhelming evidence indicates that the compositional characteristics of hypogene gold particles are preserved during transfer and residence in the surficial environment. This insight provides the platform for the fourth contribution in this section, where **Chapman *et al.* (2021*c*)** discuss the potential for an indicator mineral methodology based on detrital gold. The paper collates information from extensive studies of gold from different deposit types in terms of alloy compositions determined by electron microprobe and the assemblage of opaque inclusions revealed within polished sections of populations of gold particles from the same locality. Whilst detrital gold is, of course, a clear indicator for gold deposits (McClenaghan and Cabri 2011), the presented methodology may be used to distinguish between mineralization types, thereby both aiding the characterization of a known occurrence, or to infer yet undetected mineralization in the area. As discussed in this paper, specific gold signatures have been identified for gold from alkalic Cu–Au porphyries, calc alkalic Cu–(Mo)–Au porphyries, gold associated with redox-controlled U deposits and gold associated with ultramafic intrusions; and all of these signatures may be distinguished from those associated with gold found in occurrences classified as orogenic gold. Two avenues for future work are established; the first applying laser ablation inductively-coupled-plasma time-of-flight mass spectrometry (LA-ICP-ToF-MS) to map trace element distribution in polished gold particle sections, and the second to develop algorithms and machine-learning approaches by which deposit-specific gold signatures may be recognized and applied in an exploration context.

The fifth paper in this section builds on the methodology outlined in **Chapman *et al.* (2021*c*)** and shows how our ability to recognize generic compositional signatures of gold from different deposit types is dependent upon the breadth of data available. **Leal *et al.* (2021)** undertook a study of gold in the Iberian Variscan belt to provide the first substantial dataset describing gold from a granite-dominated terrane. The characteristics of gold from both *in situ* and alluvial settings is considered together with mineralogical studies of heavy mineral concentrates co-collected with gold particles. The relatively pronounced Cu signature of the gold provides a clear platform for comparison with results of other studies of gold from other granite terrains as these become available, and provides a platform for defining an additional indicator system for granite-greisen Sn–W mineralization.

Our final contribution is from **Standish *et al.* (2021)** who provide a critical evaluation of using gold as an archaeological provenancing tool, using methodologies that rely on compositional data alone. There is considerable overlap between aspects of placer geology, mineral exploration and those geoarchaeological studies that seek to establish sources of gold used in antiquity. Contemporary exploration is frequently informed by the position and density of current artisanal workings and the principle that placer deposits are spatially related to their source applies equally to mining in any period (e.g. **Leal *et al.* 2021**). Various archaeological studies have sought to take advantage of regional variation in natural gold composition to correlate signatures of natural gold with those of gold artefacts. Their aim is to establish provenance and thereby illuminate wider societal implications for trade and cultural exchange. The critique provided by **Standish *et al.* (2021)** is based upon the challenges that face meaningful characterization of natural gold due to the compositional heterogeneity both within and between gold particles from the same locality. In addition, compositional signatures are almost inevitably modified by metalworking or smelting, including deliberate additions of other metals. However, these anthropogenic processes do generate heterogeneous microfabrics in artefacts that may be characterized and interpreted using methodologies developed for natural gold. The authors advocate a two-stage approach to gold provenance studies comprising an initial characterization of ores and artefacts using Pb isotope signatures (because these are regionally specific and unaffected by fabrication processes) and a more detailed compositional study with a regional focus. The paper clearly demonstrates the value of expertise generated in the geological sector to related disciplines.

Summary and acknowledgements

This Geological Society of London Special Publication *Recent Advances in Understanding Gold Deposits: from Orogeny to Alluvium* offers a cross-section of approaches and techniques, at different scales, to characterize gold deposits. Whilst the papers in this Special Publication can only showcase some of the many techniques and approaches available to both academics and industry involved in ore geology, they do highlight both the breadth of the available techniques and their utility to deposit characterization at various stages of an exploration project. Some of the most important outstanding questions regarding understanding and characterizing gold deposits remain partly unanswered whilst new questions have emerged: several papers include suggestions of avenues for fruitful further research, including a paper suggesting a new approach to classifying orogenic gold deposits, and a paper describing archaeological applications of natural gold analyses.

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