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Introduction to the Special Publication ‘Recent Advances in Understanding Gold Deposits: From Orogeny to Alluvium’: the importance of multi-method approaches and developing a characterisation

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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. Characterisation of mineralisation from an early stage becomes important particularly where the mineralisation is complex, in order to maximise exploration and project development success, and mining productivity. Various techniques are used at different stages of a project to characterise 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; summarise 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 characterisation. 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.
Introduction: Comparison of the most common gold deposit types and the tools for their characterisation

Gold remains a key financial commodity but, in addition, several hundreds of tons of gold is needed annually for industrial applications, most important of which are electronic components and medicine (Corti and Holliday, 2004). Gold mineralisation 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 mineralisation 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 mineralisation type can, however, be important as the mineralisation type can dictate the exploration approach, and some mineralisation 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 mineralisation 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 historic 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: characterising 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 characterisation.

The need for a detailed characterisation increases as the project becomes more advanced: whilst a fairly rudimentary characterisation may suffice during the early exploration stages, an increasingly detailed understanding of e.g. the ore 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 characterise any observed mineralisation as early as possible, requiring advanced expertise in geological thinking and the ability to synthesise and visualise 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 characterisation, 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 characterisation.

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 such as satellite imagery, including hyperspectral data, or high-resolution LiDAR data, often aided by computer-based analysis using 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 ores 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 down-hole geophysical and imaging techniques and by e.g. hyperspectral imaging of drill core, whilst computerised and directional drilling has enabled greater accuracy (Mutton, 2000; Krupnik and Khan, 2019; Wood and Hedenquist, 2019). In terms of the more detailed characterisation of the mineralisation, the traditional transmitted and reflected light microscopy techniques are now supplemented by an array of microanalytical techniques that can greatly help in the characterising e.g. the mineral paragenesis and the association of the ore minerals; detailed geochemical
properties including zoning of both the ore and the gangue sulphides 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 characterisation
(Chapman et al., 2021) but also opportunities in terms of refining our ability to identify gold from
specific deposit types (e.g. Chapman et al., 2018; Banks et al., 2019; Chapman et al., 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
& Ojala, 1997; Table 1). 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 characterisation of a mineralisation is an
important part of the exploration and target development process. A large body of research utilising
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
characterisation remains problematic in most cases, and the issues have not changed much from
those outlined by Groves et al. (2003), i.e.: (1) incomplete genetic models and classifications for
most gold deposits; (2) non-unequivocal fluid and metal sources; (3) incomplete understanding of
fluid migration, focussing, 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 realisation that gold solubility is too low to
account for the very high grade gold deposits via the traditional models invoking gold transportation
as sulphur 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 ~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) highlighted the potential importance of local
transport and coarsening of gold via a dissolution-reprecipitation process. Such a remobilisation-

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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 exploration and resource estimate as any sampling and data analysis carry
significant inherent uncertainty due to the nugget effect.
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 to 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 here divided according to their approach.

The first five papers use multiple and regional-scale datasets to understand the larger-scale context of gold mineralisation, including two papers discussing problems with the currently widely accepted genetic models on orogenic gold deposits (Liu et al., 2021; Mortensen et al., 2021; 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 mineralisation 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., 2021a; Smith et al., 2021; Perret 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 stages 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., 2021a, 2021b; Masson et al., 2021; Combes et al., 2021b; Leal et al., 2021) look into alluvial (placer) gold utilising a variety of techniques such as EPMA, SEM, LA-ICP-MS and X-ray microtomography, and show how detailed characterisation 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.

Section 1: 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 mineralisation 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 e.g. 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 Archaean, deposits, and Mortensen et al. (2021) note the different prevailing tectonic styles and sediment and seawater geochemical characteristics, particularly in the Archaean. 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 mineralisation; 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-mineralisation, crustal-scale steep structure that is an inherent feature in Precambrian OGDs; iv) the dominance of disseminated, rather than obviously structurally controlled, mineralisation in some Phanerozoic OGDs; v) evidence that the gold may be remobilised from early diageneric 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 5,500 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 mineralisation 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 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 sulphides (via techniques such as EPMA and LA-ICP-MS). This approach has become widely applied to Au mineralisation in recent years (e.g., Meffre et al., 2016; Gourcerol et al., 2018; Augustin and Gaboury, 2019; Fielding et al. 2019; Godefroy-Rodriguez 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 5,500 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-sulphidation epithermal and Carlin-style mineralisation. 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 ($f_{s_2}, f_{o_2}$ pH) and hydrothermal processes that would provide fertile ground for further research.
The third contribution showcases how globally significant metallogenic provinces are commonly intensely geologically complex and may have experienced multiple episodes of orogenesis, magmatism and mineralisation. **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 utilises 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 $\delta D$ 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 mineralisation 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 Palaeoproterozoic 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 mineralisation: an older “orogenic” type mineralisation, 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)** combine $^{40}$Ar/$^{39}$Ar, AHe and ZHe thermochronology andapatite 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-mineralisation 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 mineralised “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 to the exploration strategies employed for gold mineralisation 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.

Section 2: ‘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. (2021a), suggests a polyphase mineralisation 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 remobilised 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 what has been suggested by e.g. Hastie et al. (2021). 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 remobilisation and proximal re-precipitation is likely to be a common phenomenon that may significantly affect the interpretation of the deposit type. Gold remobilisation is, in other words, one key process that is presently only partially understood despite its potentially far-reaching implications for both deposit enrichment and characterisation.

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, utilising high-resolution X-ray computed tomography (HRXCT), electron back-scattered diffraction (EBSD), and laser-ablation inductively-coupled plasma mass spectrometry (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 mineralisation 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 mineralisation and the geometry of the ore shoots in general. The paper shows particularly nicely how gold mineralisation 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 mineralisation geometry with the structural features. HRXCT is still under-utilised in ore geology research and this paper highlights the potential of this technology, as a part of a wider toolkit, to provide key insights into grade control.

The study by Smith et al. (2021) in this section of the Nalunaq Au deposit in Greenland employs microthermometry and LA-ICP-MS of fluid inclusion as well as X-ray photoelectron spectroscopy of sulphides and weathering products to explore the hydrothermal history of mineralisation. 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 mineralisation 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 characterisation. 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 mineralisation which occurred later in two pulses at 2.48 Ga and 2.44 Ga, respectively. The authors observe that the timing of these post-kinematic mineralisation events correlate 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.

Section 3: 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., Liu et al., 2021; Chapman et al., 2021a, 2022). A third approach to alluvial gold studies it its usage as indicator mineral: Chapman et al. (2021b) reviews 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 data sets.

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 characterisation is augmented by 3D shape analysis for selected particles within the target population.

The second paper, by Chapman et al. (2021a), critically evaluate 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 from 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 pre-existing 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 thiosulphate complexes. In contrast, biogenic processes 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. (2021b) characterise 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 sulphide decomposition. The study provides valuable insights on the importance of characterising 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. (2021b) 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 (McLenaghan and Cabri, 2011), the presented methodology may be used to distinguish between mineralisation types, thereby both aiding the characterisation of a known occurrence, or to infer yet undetected mineralisation in the area. As discussed in this paper, specific gold signatures have been identified for gold from alkalic Cu-Au porphyries, calc-alkaline 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 recognised and applied in an exploration context.
The fifth paper in this section builds on the methodology outlined in Chapman et al. (2021b) and shows how our ability to recognise 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 provide a platform for defining an additional indicator system for granite-greisen Sn-W mineralisation.

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 characterisation 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 characterised and interpreted using methodologies developed for natural gold. The authors advocate a two-stage approach to gold provenance studies comprising an initial characterisation 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 characterise 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 characterisation at various stages of an exploration project. Some of the most important outstanding questions regarding understanding and characterising gold deposits remain partly unanswered whilst new questions have emerged: 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.

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**Figure Captions**

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

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 is 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 subtypes 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 $^{206}\text{Pb}/^{204}\text{Pb}$ 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.

**Table Captions**

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

Table 2. Typical analytical approaches in gold exploration, research and mining at different stages of the project
| Trap/mineralisation 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 CO2 content | Fluid salinity (NaCl equiv.) |
|-------------------------|-----------|------------------|---------------------|----------------------------------|----------------------------------------|-------------------|--------------------------------|-----------|-----------------|-----------------------------|
| Orogenic gold           | 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 volcanic-sedimentary rock sequences (6) | 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 sulphides e.g. Zn, Pb, Mo, Sn, Sb, Ag; Cu very rare (6, 7, 8) | Reduced magmatic fluids, typically carbonic (6, 7) | Variable but often CO2-rich (6, 7) | Usually low, <10% (6, 7) |
| Type                      | Description                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | Examples                                                                                                                                                                                                                                                                                                                                                     |
|--------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Oxidised intrusion-related gold deposits (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; 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, oxidised, magnetite-rich, sulphur-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)  |  
|                          | Oxidised magmatic fluids (9)  |  
|                          |  
|                          | 25-30 mol% in initial 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 mineralisation 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-sulphidation 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 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 silification 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)  |  

** Note: LS/IS/HS refers to Low-Intermediate-High sulphidation types.
Gold-rich VMS deposits are typically strongly deformed in later orogenic events (12). Syngenetic replacement or direct precipitation onto seafloor (12) can lead to massive sulphide lenses and stockwork feeder zones. Rifted magmatic arcs and immature back-arc basins with submarine volcanism (11) can produce relatively shallow-water seafloor or near-seafloor (12) alteration. Usually advanced argillig 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 fluids can be significant: governed by compositional characteristics of source (17).

Fluvial placer deposits involve physical deposition of detrital particles controlled by variations in hydrodynamic setting at all scales (14). Fluvial sediments (15, 16) can vary according to interplay of geological and geomorphological setting (15, 16). Contemporary erosion level N/A. Can be significant: governed by compositional characteristics of source (17).

Table 1

| Gold-rich VMS deposits | Disseminated to massive sulphide 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) | Usually advanced argillig 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 depressurisation can lead to separation of high vs. 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., 2021a.
|                          | 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)                                         | (x)       | (x)                                      | (x)                    | (x)                       |
| Early exploration        | x                                   | x                           | x                              | x                                 | x                                           | (x)       | (x)                                      | (x)                    | (x)                       |
| Advanced exploration/ scoping | x                                   | x                           | x                              | x                                 | x                                           | x         | x                                        | x                      | x                         |
| Resource evaluation/ feasibility study | (x)                                 | x                           | x                              | x                                 | x                                           | x         | x                                        | x                      | x                         |
| Processing planning, metallurgical testing |                                  | x                           | x                              | x                                 | x                                           | x         | x                                        | x                      | x                         |
| Mine planning and development | x                                   |                              | x                              | x                                 | x                                           | x         | (x)                                      | (x)                    | (x)                       |
| Mine operation           | x                                   |                              | x                              | x                                 | (x)                                         | x         | (x)                                      | (x)                    | (x)                       |

*These approaches can include hyperspectral imaging to understand the spatial patterns in mineralisation 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).
Figure 1
Figure 2