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The genesis of gold mineralisation hosted by orogenic belts: A lead isotope investigation of Irish gold deposits

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ABSTRACT

Lead isotope analyses have been performed on 109 gold and 23 sulphide samples from 34 Irish gold occurrences, including 27 placers, and used to shed light on the sources of mineralising fluids and metals associated with gold mineralisation hosted by orogenic belts. The Pb isotope ratios of lode and placer gold range from $^{206}Pb/^{204}Pb$ = 17.287–18.679, $^{207}Pb/^{204}Pb$ = 15.382–15.661, and $^{208}Pb/^{204}Pb$ = 37.517–38.635, consistent with the Pb isotopic data on previously reported Irish sulphide mineralisation. There is no evidence that gold mineralisation is associated with distinctive source regions, and it appears to have been derived from similar sources to those responsible for the widespread sulphide mineralisation in Ireland. It is inferred that the principal controls on the Au mineralisation are structural and not related to the distribution of Au in their source rocks. The range of Pb isotope ratios favours the interaction of multiple source reservoirs predominantly during the Caledonian Orogeny (c. 475–380 Ma). Underlying basement was the primary control on two key sources of Pb. Gold occurrences located to the south-east of the Iapetus Suture are characterised by Pb compositions that derive predominantly from the Late Proterozoic crustal basement or overlying Lower Palaeozoic sediments, whilst those located north-west of the Iapetus Suture are characterised by less radiogenic Pb signatures derived predominantly from Late Proterozoic or older crustal basement. A third source, relatively enriched in radiogenic Pb, also played a role in the formation of a number of Irish gold occurrences, and may have been associated with syn- to post-orogenic intrusives. Magmatic processes may therefore have played an important role in the formation of some orogenic gold occurrences.

1. Introduction

Gold mineralisation hosted by low grade metamorphic facies, often in proximity to syn- to post-orogenic intrusives, and located within collisional orogenic belts, is commonly referred to as 'orogenic' (e.g. Groves et al., 2003; Goldfarb et al., 2005). Such deposits are globally important mineral resources, however their classification has proved problematic because a number of uncertainties regarding their genesis remain. These include the source(s) of the ore fluids and metals and the role of granitoid magmas which are commonly encountered within this tectonic environment (Groves et al., 2003; Goldfarb et al., 2005). Both 'intrusion related gold' (e.g. Goldfarb et al., 2005) and gold derived from the porphyry epithermal environment (e.g. Seedorf et al., 2005; Simmonds et al., 2005) can also contribute to the overall gold inventory of an orogenic belt. This study primarily focuses on 'orogenic' gold but acknowledges that different fluids may have varying influence at different localities.

Tomkins (2013) identified metamorphic rocks and felsic-intermediate magmas as the two possible sources of gold-bearing fluids. Metamorphic rocks are usually seen as the most likely of the two (Goldfarb et al., 2005; Phillips and Powell, 2010), and the presence of ethane (C_2H_6) in fluid inclusions within orogenic gold mineralisation led Gaboury (2013) to highlight the potential of deeply buried carbonaceous–pyritic metasedimentary rocks. However Yardley and Cleverley (2013) recently questioned the role of metamorphic fluids in orogenic mineralisation on the grounds that fluid release is slow and yet mineralisation forms very quickly. These authors proposed that magmatic fluids may be more important in the formation of orogenic gold than previously recognised. In addition, they suggested that periods of rapid uplift may generate the requisite conditions for orogenic gold formation in instances where there was no magmatic activity.

The lead isotope signature of an ore mineral reflects the composition and age of the geological source(s) of the lead, and acts as a proxy for the source(s) of the principal ore constituents. Lead isotope analysis is frequently used in studies of gold mineralisation worldwide, however

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most investigations rely on analyses of sulphide minerals associated with vein gold mineralisation (e.g. Curti, 1987; Arias et al., 1996) and only a few studies included analyses of gold particles (Eugster et al., 1995; Pettke and Frei, 1996; Kamenov et al., 2013). Recent development of an accurate and reproducible procedure for lead isotope analysis on gold now allows this technique to be widely applied directly to both vein gold and to placer deposits, and provides a more rigorous approach to the study of gold (Standish et al., 2013). A lead isotope study of placer and lode gold grain populations using this new technique therefore has the potential to provide new perspectives on the sources of ore fluids and metals involved in gold mineralisation hosted by orogenic belts.

Numerous (>100) gold occurrences are present in Ireland (Maclaren, 1903; McArdle et al., 1987; Stanley et al., 2000), the majority of which can be classified as orogenic based on their tectonic settings (e.g. Chapman et al., 2000a; Stanley et al., 2000). Furthermore, most available information (e.g. Wilkinson and Johnston, 1996) is consistent with emplacement of mineralisation by 'typical' CO_2-rich and Cl-poor orogenic fluids which generate gold rich and base metal poor mineralisation (Ridley and Diamond, 2000). A large-scale lead isotope study of Irish gold mineralisation therefore provides an excellent opportunity to better understand the genesis of orogenic gold.

Lead isotope analysis has rarely been performed on gold or gold-bearing mineralisation in Ireland, although O'Keeffe (1986) and Parnell et al. (2000) performed analyses on associated sulphides from the Clontibret and Cavanacaw deposits respectively and Standish et al. (2013) presented data for two Irish placer occurrences. A number of notable studies have employed the technique to investigate other Irish mineral deposits, principally Lower Palaeozoic hosted Early Caledonian massive sulphide mineralisation and Palaeozoic hosted Carboniferous and Variscan Pb–Zn and Cu mineralisation (e.g. Boast et al., 1981; Caulfield et al., 1986; O'Keeffe, 1986; LeHuray et al., 1987; Dixon et al., 1990; Kinnaird et al., 2002; Everett et al., 2003). This wealth of Pb isotope data provides a valuable dataset that can be used to help interpret the isotopic signature of gold from different localities.

This paper presents the first large-scale Pb isotope study performed directly on gold mineralisation. The data relate to 34 Irish gold deposits, the majority of which are consistent with the tectonic setting of orogenic gold. This is followed by a discussion focusing on the key sources of Pb associated with Irish gold mineralisation, and the role of syn- to post-orogenic intrusive magmatic rocks.

2. Geological setting

2.1. The geology of Ireland

The geology of Ireland (Fig. 1) reflects a long and complex history. In the context of this study, the main formations can be summarised as Precambrian, Lower Palaeozoic, Upper Palaeozoic and post-Variscan.

2.1.1. Precambrian basement

The Precambrian basement of Ireland can be simplified to two distinct units: the north-west terrane (NWT) and south-east terrane (SET). The NWT (Laurentian) is formed of Dalradian (Neoproterozoic) and pre-Dalradian (Lewisian and Grenvillian) lithologies and may be further divided into the Grampian, the Midland Valley, the Southern Uplands and the Mayo (sub)terranes (Fig. 1), whilst the SET (Avalonian) is formed of Late Proterozoic rocks (Max and Long, 1985; Daly, 2001). The NWT and SET were brought together as the Iapetus Ocean closed during the Caledonian Orogeny, c. 475 Ma to c. 380 Ma (Holdsworth et al., 2000; Chew and Stillman, 2009). At present the Iapetus Suture (solid black line Fig. 1) runs approximately from the Shannon estuary in the south-west to Balbriggan on the east coast (Todd et al., 1991).

2.1.2. Lower Palaeozoic

Cambrian, Ordovician and Silurian rocks overlie the Precambrian basement across much of Ireland. They are exposed in four key regions: the Longford Down Inlier of the Southern Uplands terrane (Ordovician to Silurian); southern Co. Mayo (Ordovician to Silurian); the Leinster Massif of south-east Ireland (Cambrian to Silurian); and as numerous inliers in southern central Ireland (Silurian). They consist of ocean floor (Iapetus) and turbidite sequences (greywackes, mudstones, shales, siltstones and sandstones) with interbedded basic and mafic volcanics (Stillman and Williams, 1978; Morris, 1987; Max et al., 1990; Aherne et al., 1992; Thompson et al., 1992). These units were affected by Caledonian deformation and metamorphism, the peak of which occurred c. 470 Ma, and were the result of a series of collisions between Iapetus crust and associated island arcs, and the Laurentian and Avalonian continents. The Grampian Orogeny (c. 470 Ma), an early phase of the Caledonian Orogeny, specifically refers to the collision between an oceanic island arc and the margin of the Laurentian continent (Fettes et al., 1985; Powell and Phillips, 1985; Chew et al., 2010; Cooper et al., 2011). A suite of syn- to post-orogenic intrusions associated with the Grampian Orogeny (dating to c. 475–460 Ma) are located in the north and west of Ireland, and includes the Tyrone Igneous Complex plutons and the Oughterard Granite of Connemara (Chew and Stillman, 2009).

2.1.3. Upper Palaeozoic

Devonian sediments are primarily found in the Munster Basin of south-west Ireland, although sequences are also exposed further north. Terrestrial Old Red Sandstone (ORS) facies dominate with placer and fluvial sequences, whilst marine facies began to develop by the late Upper Devonian (Clayton et al., 1980; MacCarthy, 1990). Syn- to post-orogenic intrusions (for example, the Donegal, Leinster, Newry and Corvock granites) associated with the final closure of the Iapetus Ocean and the late stages of the Caledonian Orogeny (also known as the Acadian Orogeny) were emplaced during the Silurian and Early Devonian, c. 430–380 Ma (O'Connor, 1975; O'Connor and Brück, 1978; Halliday et al., 1980; Murphy, 1987; O'Connor, 1989; Chew and Stillman, 2009). The late Upper Devonian marine transgression continued into the Lower Carboniferous when shale and siltstone deposits from the Lower Tournaisian were overlain by thick limestone sequences that host important Pb–Zn deposits (LeHuray et al., 1987; Banks et al., 2002; Wilkinson, 2003). Metamorphism and mineralisation associated with Late Devonian to Carboniferous crustal extension ceased with the onset of the Variscan Orogeny (Meere, 1995; Kinnaird et al., 2002). This was the result of the closure of the Rheic Ocean and the collision between the continents of Laurasia (which included the old Laurentian and Avalonian land masses) and Gondwana, and was associated with deformation, low grade metamorphism and further episodes of mineralisation (Cooper et al., 1986; Graham, 2001; Kinnaird et al., 2002). The collision itself is most likely to have occurred during the Upper Carboniferous to Lower Permian, c. 320–270 Ma (Graham, 2001).

2.1.4. Post-Variscan

Post-Variscan rocks are relatively rare in Ireland. Permian, Triassic, Jurassic and Cretaceous sequences are found in north-east Ireland's Rathlin Trough and Lough Neagh–Larne Basin (McCann, 1988, 1990; Naylor, 1992), whilst Permo-Triassic lithologies have been recorded in Co. Cavan (Kingscourt Graben) and the Wexford Outlier; Jurassic sediments have been identified in the Cloyne Syncline of Co. Cork; and Upper Cretaceous lithologies are present in Co. Kerry (Ballydeenlea Outlier; Naylor, 1992). Tertiary igneous complexes relating to the rifting of North America and Eurasia and the opening of the Atlantic Ocean are present in north-east Ireland (Jolley and Bell, 2002; Stevenson and Bennett, 2011). The vast basaltic lavas of Co. Antrim date to this period (Lyle, 1980; Lyle and Preston, 1993), whilst the Mourne granites of Co. Down were also emplaced at this time (McCormick et al., 1993; Stevenson and Bennett, 2011).