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Tectono-magmatic controls of post-subduction gold mineralisation during late Caledonian soft continental collision in the Southern Uplands-Down-Longford Terrane, Britain and Ireland: A review

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ABSTRACT

The Southern Uplands-Down-Longford Terrane (SUDLT) within the British Caledonides hosts several economically significant gold occurrences, including a 45 km-long gold trend in central Ireland that includes the proven deposit at Clontibret. However, the region is relatively underexplored for gold and the well-constrained geology and tectonic history of the terrane provide a firm geological framework for investigating the roles of tectonic, magmatic and metamorphic processes in gold mineralisation during the transition from subduction of oceanic lithosphere to soft (thin-skinned) continental collision. The SUDLT is an Ordovician-Silurian fore-arc accretionary complex that evolved into a foreland basin fold-and-thrust-belt during continental collision in earliest Devonian times. Comparable terranes in Phanerozoic orogenic belts globally host significant orogenic gold deposits. However, the SUDLT exhibits a very low metamorphic grade and mineralisation exhibits similarities with orogenic, intrusion related and post-subduction porphyry gold systems.

Gold in the SUDLT predominantly occurs as a lattice constituent of arsenopyrite and pyrite within quartz-carbonate veins and disseminated within phyllic and propylitic potassic alteration haloes around quartz-carbonate veins and some minor intrusions. Fluid inclusion data indicate that the gold was deposited from a low salinity mesothermal (~330 °C) carbonic fluid of mixed magmatic-metamorphic origin consistent with Caledonian orogenic conditions. Gold mineralisation occurred at shallow crustal depths of less than ~10 km and exhibits a broad spatial association with major NE-SW-trending Caledonoid shear-zones (D_1). Economically significant gold mineralisation in the SUDLT is most commonly hosted by transverse ~NW-SE- and ~N-S-trending fractures (D_3) constrained to between 418 and 410 Ma that cut anchizone-epizone facies volcaniclastic turbiditic metasedimentary host rocks. The mineralised D_3 structures cut, and are cut by, broadly coeval polyphase diorite and granodiorite intrusions. Gold mineralisation is associated with the early, dioritic I-type metaluminous oxidised phase of Trans Suture Suite magmatism that straddles the Iapetus Suture but predates the later emplacement of S-type granitic magma. The host structures were subsequently reactivated during Late Palaeozoic, Mesozoic and Cenozoic times and host younger base metal deposits (Pb-Zn, Cu, Sn, Sb).

Mineralisation occurred in Early Devonian times (~418 and ~410 Ma), following arrival of the Avalonian continental margin at the subduction trench at ~420 Ma, coeval with the onset of regional transtension, post-subduction lithospheric mantle delamination and K-lamprophyric and mafic to intermediate calc-alkaline magmatism. Gold in the SUDLT, therefore, provides a case study for relationships between post-subduction porphyry and orogenic gold mineralisation in soft continental collision zones. The transient geodynamic setting between subduction and transtension, common during soft continental collision, provided the critical elements of the mineralising system: a metasomatically fertilised mantle source; transient geodynamics; favourable lithospheric architecture for the rapid transfer of mass and energy from subcrustal to upper crustal levels; thin-skinned deformation and relatively low exhumation favours the preservation of mineral deposits in the upper crust.

1. Introduction

Phanerozoic orogenic belts host a significant proportion of gold deposits globally; predominantly classified as orogenic gold deposits (Böhlke, 1982; Groves et al., 1998). Examples include Ballarat-Bendigo in the Lachlan Fold Belt, Tasman Orogen, eastern Australia; Goldenville and Beaver Dam in the Meguma Terrane, Appalachian Orogen, Nova Scotia and Reefton in the Buller Terrane, South Island, New Zealand (Goldfarb et al., 2001). However, it is well-known that orogenic belts commonly also include other deposit types, with some shared characteristics, and classified as intrusion related gold systems (IRGS) (e.g. Fort Knox, Alaska; Salave, Spain; Mokrsko, Czech Republic; Muruntau in the southern Tien Shan, Central Asia and Vasilkovskoye in the Kipchak Arc, Kazakhstan (Dolgopolova et al., 2015; Thompson et al., 1999), and the more recently recognised post-subduction porphyry types (e.g. Çöpler, Central Turkey; Sari Gunay, northwest Iran; South Tibet; Hou et al., 2017, 2015; Richards et al., 2006). The classification of IRGS's and their differentiation from orogenic gold deposits is a long-standing problem due to many overlapping characteristics, shared geodynamic settings and conditions of formation (Groves et al., 1998; Hart, 2007; McCuaig and Hronsky, 2014; Thompson et al., 1999; Tomkins, 2013). The problem is compounded by an ongoing debate

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over metamorphic versus magmatic sources of gold, hydrothermal fluids and sulphur in orogenic deposits (Phillips and Powell, 2009; Pitcairn et al., 2006; Tomkins, 2013). Fluid inclusion and stable isotope data for individual orogenic gold deposits are commonly ambiguous, or indicate mixing between metamorphic and magmatic fluid sources and/or equilibration with country rocks (Phillips and Powell, 2009; Tomkins, 2013). For example, at Tyndrum, Scotland (Hill et al., 2013); Round Hill, New Zealand (de Ronde et al., 2000), Loulo, Mali (Lawrence et al., 2013), Ashanti Belt, Ghana (Mumin et al., 1996; Treloar et al., 2014). Some studies indicate a magmatic origin for the mineralising fluids (e.g. Massawa, Senegal; Treloar et al., 2014) while others suggest fluid of purely metamorphic origin (e.g. Otago and Alpine Schists, New Zealand; Pitcairn et al., 2006). More recently it has been recognised that some gold deposits in post-subduction and collisional orogenic settings closely resemble porphyry gold deposits that are generally understood to have formed in shallow sub-volcanic environments in the fore-arc regions of active magmatic arcs (Hou et al., 2017, 2015; McCuaig and Hronsky, 2014; Richards, 2009; Sillitoe and Thompson, 1998).

Establishing a genetic model for gold deposits in orogenic belts, individually and globally, has also been compounded by the challenges of unravelling the intrinsically complex geodynamic histories of such regions (Groves et al., 2003). The British and Irish Caledonides (Fig. 1) represent a potentially fertile but relatively underexplored gold belt and provide an exceptionally well-studied example of a Phanerozoic orogen and a firm geological framework in which to study the tectonic and magmatic controls of mineralising systems in orogenic settings, including the sources of heat, fluids and metals. Caledonian gold mineralisation in the Southern Uplands-Down-Longford Terrane (SUDLT) in southern Scotland and Ireland (Figs. 1 and 2) is relatively poorly explored and has been interpreted in terms of both orogenic (Goldfarb et al., 2001; Lusty et al., 2012) and porphyry gold models (Boast et al., 1990; Brown et al., 1979; Charley et al., 1989; Duller et al., 1997; Leake et al., 1981; Steed and Morris, 1997). The age and origin of hydrothermal vein gold mineralisation in the Grampian Terrane, situated to the northwest of the SUDLT in Scotland and Northern Ireland (e.g. Tyndrum and Curraghinalt; Fig. 1), is better-studied, but remains controversial (Graham et al., 2017; Hill et al., 2013; Rice et al., 2016).

This paper, synthesises the available data, from a range of mainly local studies of gold mineralisation in the SUDLT, to contribute to the wider understanding of gold metallogenesis in Britain and Ireland. We find that gold mineralisation occurred at shallow crustal levels and low metamorphic grade during a period of soft collision and post-subduction lithospheric mantle delamination accompanied by regional transtension, high heat flow and polyphased bimodal K-lamprophyric and granitoid magmatism (Leake et al., 1981; Miles et al., 2016). We assess the sources of magma, mineralising fluids, sulphur and gold and find that gold mineralisation was related to a relatively early phase of hydrous, metaluminous, oxidised, dioritic, I-type magmatism (Brown et al., 2008; Miles et al., 2014). This magma had a metasomatically hydrated and fertilised subcrustal source (Graham et al., 2017) and could have carried gold and sulphur from depth, to be released into an exsolved magmatic-hydrothermal fluid phase at shallow levels, similar to porphyry and intrusion-related gold systems (IRGSs). Magmatic-hydrothermal fluid mixed with fluid that was probably generated by low grade metamorphic dewatering of the country rocks. We consider that soft, thin-skinned, continental collision provided the critical elements of the mineralising system, enabling sufficient flux of mass and energy to form gold deposits at shallow crustal levels (McCuaig and Hronsky, 2014).

2. Data sources and methodology

Here we review and synthesise, for the first time, the available data for all of the known bedrock gold occurrences in order to critically evaluate the nature, conditions, timing and the regional-scale tectonic and magmatic controls of mineralisation. A brief overview of gold mineralisation in the SUDLT is given in Lusty et al. (2012). However, the aim of the work of Lusty et al. (2012) was to provide a geospatial model for orogenic gold rather than critically evaluate the evidence for alternative deposit types and the tectono-magmatic controls of mineralisation. We bring together geochemical, isotopic and fluid inclusion data from several studies into the origins of mineralising fluids and metals at individual gold-bearing localities in the SUDLT (e.g. Boast et al., 1990; Duller, 1990; Lowry et al., 1997; Naden and Caulfield, 1989; Steed and Morris, 1997). We also make use of legacy commercial exploration reports and government records of mineral exploration (MEIGA Reports) combined with press-releases, PhD Theses and historical literature (Atkinson, 1619; Lapworth, 1878; Peach et al., 1899; Porteous, 1876). Several reports of the Mineral Reconnaissance Programme (MRP) carried out by British Geological Survey in the 1970s-1990s were important sources for this work in addition to digital datasets provided by the Irish and British Geological Surveys including the BGS Mineral Occurrence Database, G-Base regional stream sediment geochemistry, 'Tellus' geochemical datasets for Northern Ireland and BGS and GSI digital geological mapping. Geochemical survey data were analysed in GIS and compared with other geological data to identify spatial relationships. Whole-rock geochemical data for Caledonian minor igneous intrusions in the Southern Uplands were provided by the British Geological survey, screened and plotted on tectonic discrimination diagrams for potassic igneous rocks following the method of Müller and Groves (2016).

3. Geological setting

The SUDLT is part of the Caledonide Orogenic Belt (Fig. 1) which comprises various terranes assembled during successive phases of deformation associated with progressive closure of the Iapetus Ocean between 470 and 420 Ma (Mid Ordovician to Early Devonian time; Fig. 3) (Dewey and Strachan, 2003; McKerrow et al., 2000; Miles et al., 2016). The SUDLT is bounded by the Southern Uplands Fault to the northwest and by the buried Iapetus Suture to the southeast (Figs. 1, 2 and 4) (Leggett et al., 1979a; Phillips et al., 1976). Terranes to the southeast belonged to the Avalonian microcontinent; terranes to the northwest represent the Laurentian active margin. Avalonian crust to the southeast of the Suture is represented by the Leinster-Lakesman Terrane in northern England, the Isle of Man and central Ireland (Fig. 1). To the northwest lie the Midland Valley Terrane and the Grampian Highlands Terrane (Bluck et al., 1992). The Midland Valley Terrane comprises a Middle Ordovician volcanic arc that collided with the Laurentian margin (Grampian Highlands) during the Middle Ordovician Grampian event of the Caledonian Orogeny (Fig. 3) (Cooper et al., 2011; Oliver, 2001).

Controversy over the tectonic interpretation of the Southern Uplands-Down-Longford Terrane is now resolved (Stone, 2014); it represents an Ordovician accretionary complex in the northwest that passes stratigraphically upwards into a Silurian foreland basin fold-and-thrust-belt in the southeast (Stone, 2014). The SUDLT, therefore, documents the final closure of Iapetus at around 420 Ma (earliest Devonian) when the Avalonian margin reached the subduction trench. The low metamorphic grade (sub-greenschist facies), and relatively weak deformation of the terrane indicates that the rocks were not deeply buried and that the final closure of Iapetus in this region resulted in thin-skinned, soft collision (Merriman and Roberts, 2000; Miles et al., 2016).

The tectonostratigraphy of the SUDLT is well documented and discussed in detail elsewhere (Barnes et al., 1987; Floyd, 2001; Leggett et al., 1979a; McKerrow, 1987; Stone, 2014). The SUDLT has an area of around 20 000 km^2 in the British Isles (Fig. 2). The succession comprises anchizonal-epizonal, meta-volcaniclastic sedimentary rocks dominated by greywacke turbidites, deposited in a deep marine basin over a period of ~75 Ma in Ordovician and Silurian times, from ~495

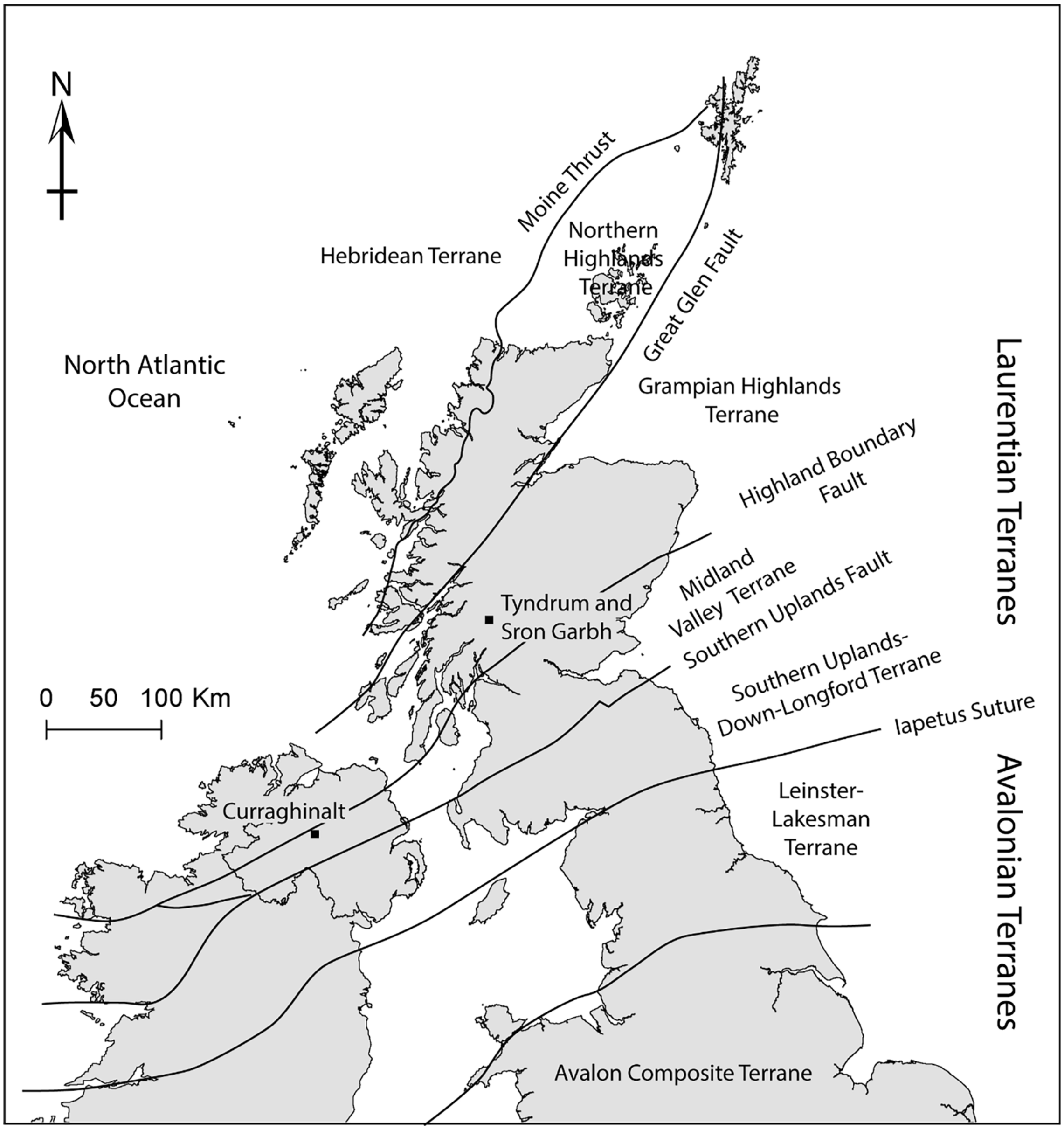


Fig. 1. Map of the main tectonostratigraphic terranes and boundaries recognised in Northern Britain and Ireland based on Bluck et al. (1992).

to ~420 Ma (Fig. 3) (Anderson, 2004; Floyd, 2001; Merriman and Roberts, 2000; Oliver, 1978; Oliver et al., 2003). Bedding predominantly youngs to the NW throughout the terrane (Craig and Walton, 1959). However, progressively younger units crop out from northwest to southeast at the terrane scale (Lapworth, 1878; Peach et al., 1899) due to top-to-the-southeast thrust imbrication (Fig. 4) (Anderson and Cameron, 1979; Stone et al., 1987). The thrust faults strike ~NE-SW, generally subparallel to bedding (Fig. 5). Together with bedding, cleavage and fold axes, these originally low-angle thrust faults are now subvertical to steeply-dipping (Fig. 4). They developed during fore-arc accretion and resulted in top-to-the-south thrust-imbrication and stratigraphic repetition (Anderson, 2001; Mitchell and McKerrow, 1975). The major strike-parallel faults demarcate numerous fault-bounded tectonostratigraphic units ('tracts') (Craig and Walton, 1959).

Within each tectonostratigraphic unit, hemipelagic black pyritic argillite (Moffat Shale) passes stratigraphically upwards into a succession of turbiditic greywacke beds (Leggett, 1980, 1979; Leggett et al., 1979a). The age of the Moffat Shale and the oldest overlying turbidites is, in general, diachronous across the terrane, becoming younger from northwest to southeast (Fig. 4) (Leggett et al., 1982, 1979a; McKerrow et al., 1977), consistent with south-eastward progradation of trench-fill sediments derived from the accretionary complex over northwest subducting Iapetus oceanic lithosphere (Mitchell and McKerrow, 1975). The terrane has traditionally been divided into three 'belts' (Fig. 2) (Anderson, 2004, 2001; Stone, 2014). The Northern Belt is predominantly composed of Ordovician turbidites, mainly greywackes of Caradoc to Ashgill age (458–444 My) and is separated from the Central Belt by the Orlock Bridge Fault (Fig. 2). The Central Belt is composed mainly of Llandovery greywackes and is separated from the mainly Wenlock age greywackes of the Southern Belt by the Laurieston Fault in Scotland and its continuation in Ireland as the Cloughy Fault (Fig. 2) (Anderson and Cameron, 1979; Oliver et al., 2003).

To the southwest, in central Ireland, the terrane is buried beneath unconformably overlying shallow-marine shelf carbonates of Lower Carboniferous age (Figs. 2 and 4) (George, 1958; Guion et al., 2000; Lewis and Couples, 1999; Mitchell, 2004). A much thinner Carboniferous succession comprising volcano-sedimentary rocks is preserved within narrow NW-SE and N-S trending fault-bounded half-graben within the terrane (Fig. 2). These basins contain thick Permo-Triassic

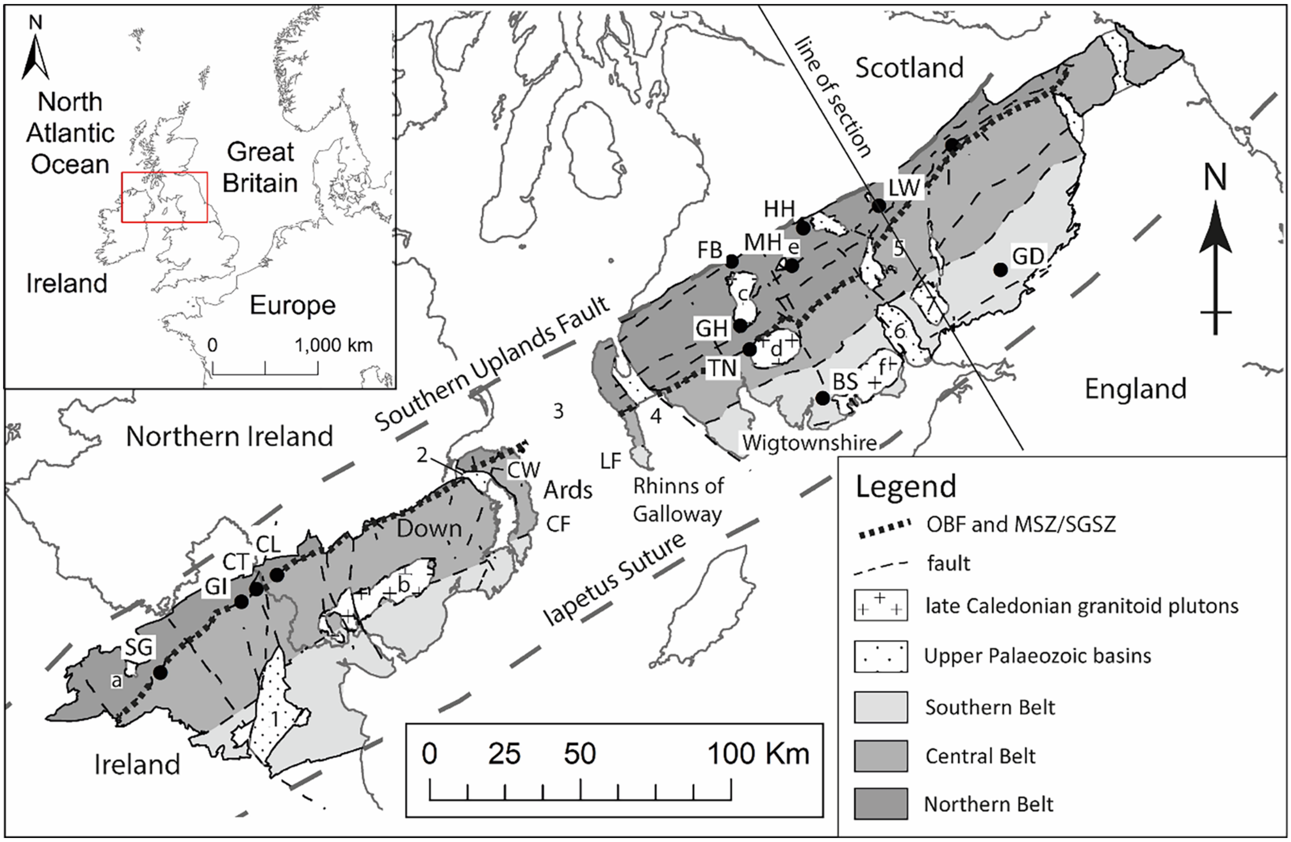


Fig. 2. Map of the Southern Uplands-Down-Longford Terrane showing features and locations referred to in the text: BS: Black Stockarton; CL: Clay Lake; CT: Clontibret; CW: Conlig-Whitespots; FB: Fore Burn; GD: Glendinning; GH: Glenhead; GI: Glenish; HH: Hare Hill; LW: Leadhills-Wanlockhead; MH: Moorbrock Hill; SG: Slieve Glah; TN: Talnotry and Fleet. Permo-Carboniferous volcano-sedimentary basins: 1: Kingscourt; 2: Strangford; 3: North Channel; 4: Stranraer/Luce; 5: Thornhill; 6: Dumfries; 7: Langholm. Caledonian plutonic complexes: a: Crossdoney; b: Newry; c: Loch Doon; d: Fleet; e: Cairnsmore of Carsphairn; f: Criffel-Dalbeatie. Named structures: CF: Cloughy Fault; LF: Laurieston Fault; MSZ/SGSZ: Moniaive Shear Zone and Slieve Glah Shear Zone; OBF: Orlock Bridge Fault. Based upon data provided by the British Geological Survey - Licence No. 2015/162 ED © NERC. All rights reserved.

volcano-sedimentary successions, composed of basic lavas and terrestrial red sandstone (Anderson et al., 1995; Caldwell and Young, 2013a; Coward, 1995; Pringle and Richley, 1931).

Ordovician rocks, predominantly cropping out in the Northern Belt of the SUDLT (Fig. 2), represent a fore-arc subduction-accretion complex as proposed by Dewey (1969) and Mitchell and McKerrow (1975). The sedimentary rocks did not sample any coeval magmatic arc, indicating probable amagmatic subduction (Miles et al., 2016; Phillips et al., 2003). Younger metasedimentary rocks of the Central and Southern Belts of the SUDLT were deposited following the arrival of the Avalonian continental margin at the subduction trench at ~420 Ma and represent a foreland fold and thrust belt (Fig. 3) (Hutton and Murphy, 1987; Stone, 2014; Stone et al., 1987). Deposition in the SUDLT was terminated by the end of Wenlock times (422 Ma), followed by magmatism, uplift and emergence (Fig. 3) (Barnes et al., 1987; Dewey and Strachan, 2003; Kemp, 1987; Miles et al., 2016; Stone, 2014). Clockwise transection of folds by cleavage indicates a change from orthogonal accretion to transpressional deformation at around this time, and prior to 418 Ma (Fig. 3) (Anderson, 1987; Dewey and Strachan, 2003). Early Devonian exhumation and erosion of up to 20 km was accompanied by terrestrial deposition of the Old Red Sandstone Group within transtensional basins controlled by sinistral strike-slip and normal faults (Anderson et al., 1995; Bluck, 1984; Coward, 1995; Dewey and Strachan, 2003; Leeder, 1982). Transtension between 420 and 405 Ma was accompanied by the onset of lamprophyric and calc-alkaline magmatism (Fig. 3) (Miles et al., 2016). It is important to emphasise that Caledonian calc-alkaline magmatic rocks of northern Britain and Ireland straddle the suture zone and post-date final closure of Iapetus by up to 40 Ma (Miles et al., 2016).

4. Structure

The structure of the terrane is remarkably uniform (Figs. 2, 4 and 5): The 'Caledonoid' structural grain (D_1) is defined by the predominantly NE-SW strike of the generally subvertical to steeply-dipping turbidite beds, exhibiting tight to isoclinal asymmetrical folds (F_1), strike-parallel faults and subparallel slaty cleavage (S_1), best developed in fine-grained argillaceous lithologies (Figs. 4 and 5) (Anderson, 2001; Barnes et al., 1987; Stringer and Treagus, 1980). D_1 faults are subvertical to steeply-dipping back-rotated thrusts that predominantly downthrow to the south and have been reactivated by strike-slip. F_1 folds are generally tight to isoclinal, predominantly highly asymmetrical upright folds with ~NE-SW trending axes having variable plunge and exhibit ~SE-vergence (Fig. 5) (Anderson, 2001; Barnes et al., 2008, 1987; Stone et al., 2012; Stringer and Treagus, 1980).

D_1 structures reflect deformation due to tectonic development of the accretionary complex during northwards underthrusting and accretion of Iapetus oceanic lithosphere in an active forearc setting (Dewey and Strachan, 2003; Leggett et al., 1979b; McKerrow et al., 1977). Argillaceous rocks of the Moffat Shale Group acted as the principal decollement during D_1 thrusting (Barnes et al., 1995; Leggett et al., 1979a). In the younger, southeasterly units the S_1 cleavage obliquely transects F_1 folds with a clockwise sense by $< \sim 20°$ reflecting a progressively non-orthogonal relationship between the principal compressive stress and the orientation of bedding, indicating a change from orthogonal to oblique subduction during arrival of the Avalonian margin at the

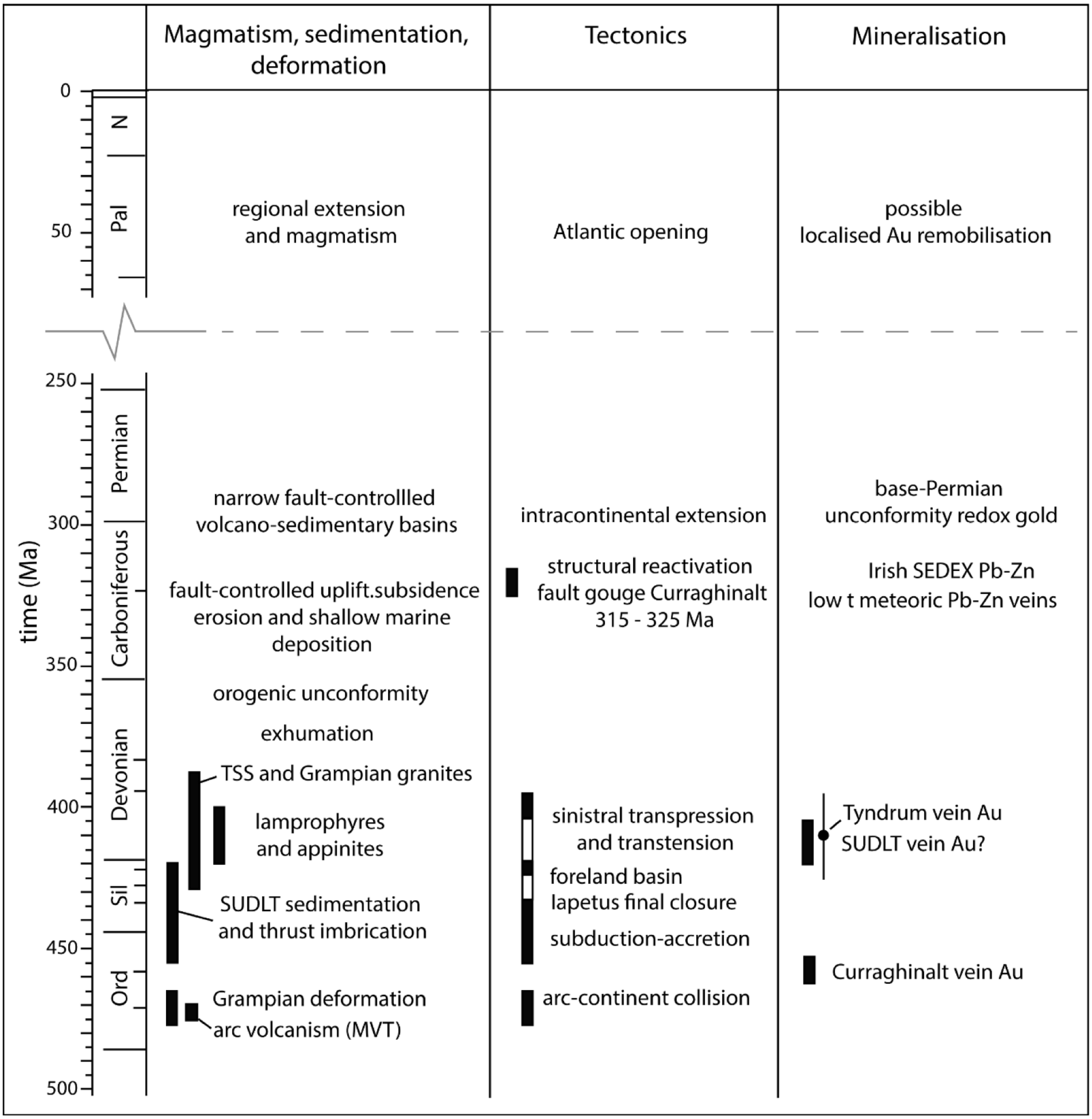


Fig. 3. Chronology of geological events relating to Caledonian Orogeny and hydrothermal mineralisation in Northern Britain and Ireland. See text for details. Timescale after Gradstein et al. (2012). Probable age of SUDLT vein Au based on this review. Grampian events and Curraghinalt mineralisation after Rice et al. (2016). SUDLT sedimentation and deformation and Iapetus final subduction after Oliver et al. (2003). Late Caledonian deformation and TSS magmatism after Miles et al. (2016). Tyndrum vein gold after Hill et al. (2013) and Rice et al. (2012). Carboniferous deformation at Curraghinalt: Rice et al. (2016); Carboniferous Irish Pb-Zn deposits: Banks et al. (2002), Hitzman (1995); Permian basins and redox gold: Leake et al. (1998, 1996), Lusty et al. (2011), Mitchell (1992) and Ruffell and Shelton (2000); Palaeogene magmatism and remobilisation; Cooper et al. (2012), Leake et al. (1998).

subduction trench in Early Silurian time (Fig. 3) (Anderson, 2004, 1987; Anderson and Cameron, 1979; Dewey and Strachan, 2003; Stone et al., 2012; Stringer and Treagus, 1980).

The Moniaive Shear Zone (MSZ) in Scotland and its continuation, the Slieve Glah Shear Zone (SGSZ) in Central Ireland (and Figs. 2 and 4), is a zone up to 5 km wide of enhanced ductile deformation sub-parallel to the regional Caledenoid structural grain (Phillips et al., 1995). It dips steeply NW and marks the boundary between the Northern and Central Belts (Anderson and Oliver, 1986; Oliver, 1978; Phillips et al., 1995) (Anderson and Oliver, 1986; Oliver, 1978; Phillips et al., 1995). The MSZ/SGSZ is cut by, and locally bounded on its northern side by the Orlock Bridge Fault (OBF) (Anderson and Oliver, 1986; Barnes et al., 1995). In central Ireland the SGSZ hosts several gold occurrences including the potentially significant Clontibret deposit (Fig. 2) (Cruise and Farrell, 1993; Lusty et al., 2012). Within the shear zone, Silurian greywackes of the Gala Group exhibit pervasive linear and planar fabrics including mylonite, extensional crenulation cleavage and stretching lineation with a consistently sinistral sense of shear (Phillips et al., 1995; Stone, 1996). Sinistral deformation on the MSZ post-dates D_1 and probably represents strike-slip reactivation of an over-steepened major tract-bounding fault during Wenlock times (Barnes et al., 1995). The superposition of brittle structures upon the ductile fabrics of the shear zone indicates that sinistral strike-slip deformation accompanied progressive exhumation through the brittle-ductile transition zone (Phillips et al., 1995).

F_1 folds and S_1 cleavage are deformed locally by gently to moderately inclined open to close folds (F_2) with gently to moderately inclined axial surfaces and associated crenulation cleavage (Barnes et al.,

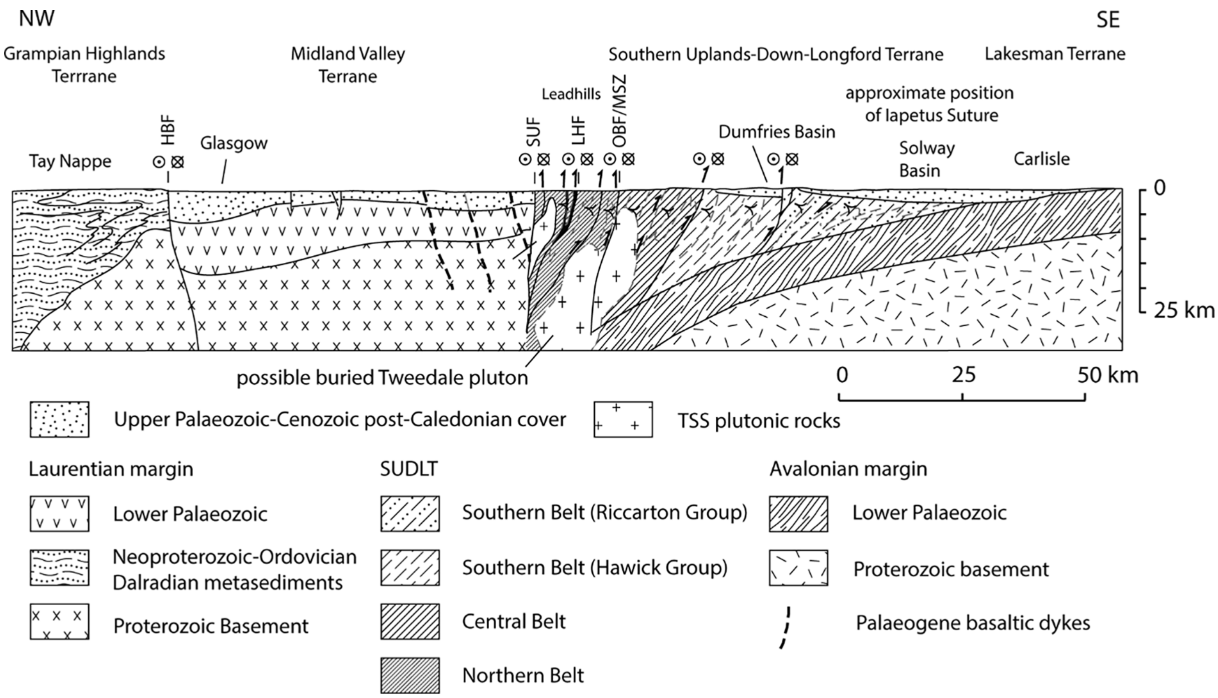


Fig. 4. Simplified cross-section of the Southern Uplands-Down-Longford terrane and neighbouring units in Southern Scotland. Modified from 1:625 000 Scale Bedrock Geology Map UK North, NERC/BGS (Floyd et al., 2007).

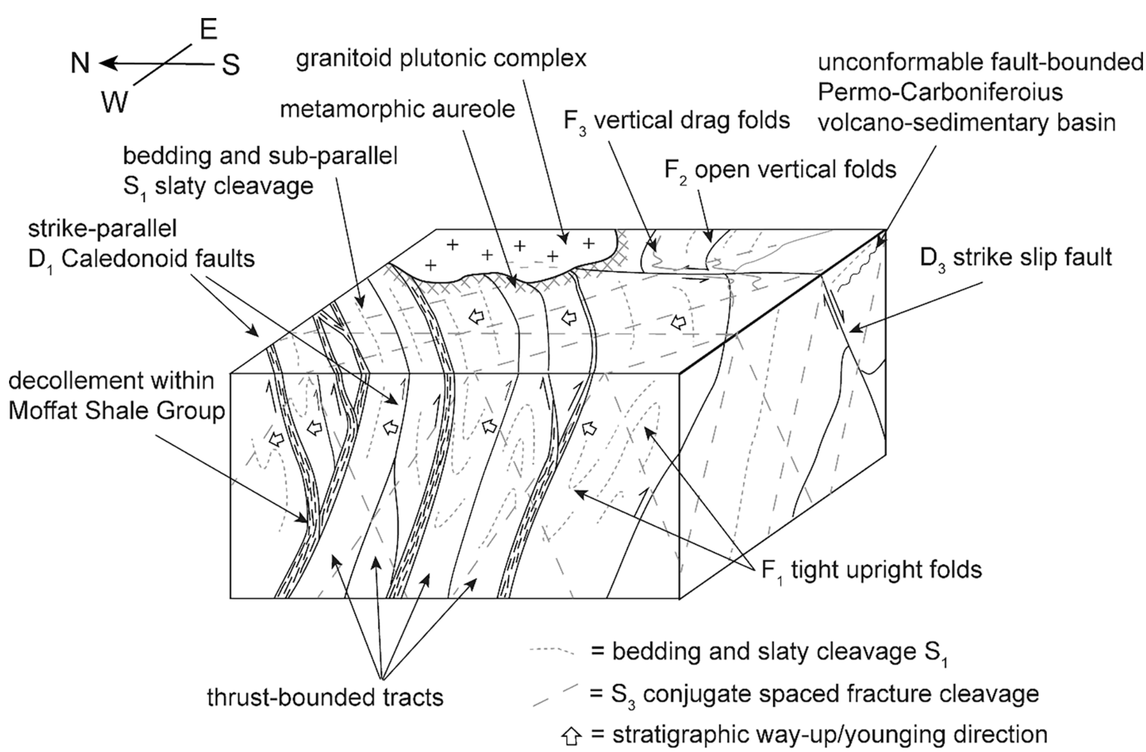


Fig. 5. Schematic block diagram showing generalised structural and tectonostratigraphic relationships within the SUDLT based on the work of Anderson (2001) and Anderson and Cameron (1979).

1987). F_2 structures are generally weakly developed (Fig. 5).

Two orientations of steeply inclined faults and associated spaced fracture cleavage are developed transverse to the NE-SW trending D_1 regional structural grain (Fig. 5) (Anderson and Cameron, 1979). These structures represent D_3 and strike NW-SE (110°-150°) and ~N-S (170°-030°) (Fig. 6) (Stone, 1995; Stone et al., 2012) and host the gold and base metal mineralised lodes e.g. Sb-Au lodes at Clontibret, Fore Burn, Hare Hill and Glendinning (Boast et al., 1990; Charley et al., 1989; Duller et al., 1997; Morris, 1984) and Pb-Zn veins at Leadhills-Wanlockhead (Temple, 1956; Wilson and Flett, 1921) and Conlig-Whitespots (Moles and Nawaz, 1996; Woodrow, 1978) (Figs. 2, 5, 6, 7). Some of the transverse faults exhibit breccia zones ~1 m thick with stockworks and vein-filled fractures (Anderson, 1987; Moles and Nawaz, 1996; Morris, 1984; Temple, 1956). Dextral subhorizontal slickensides

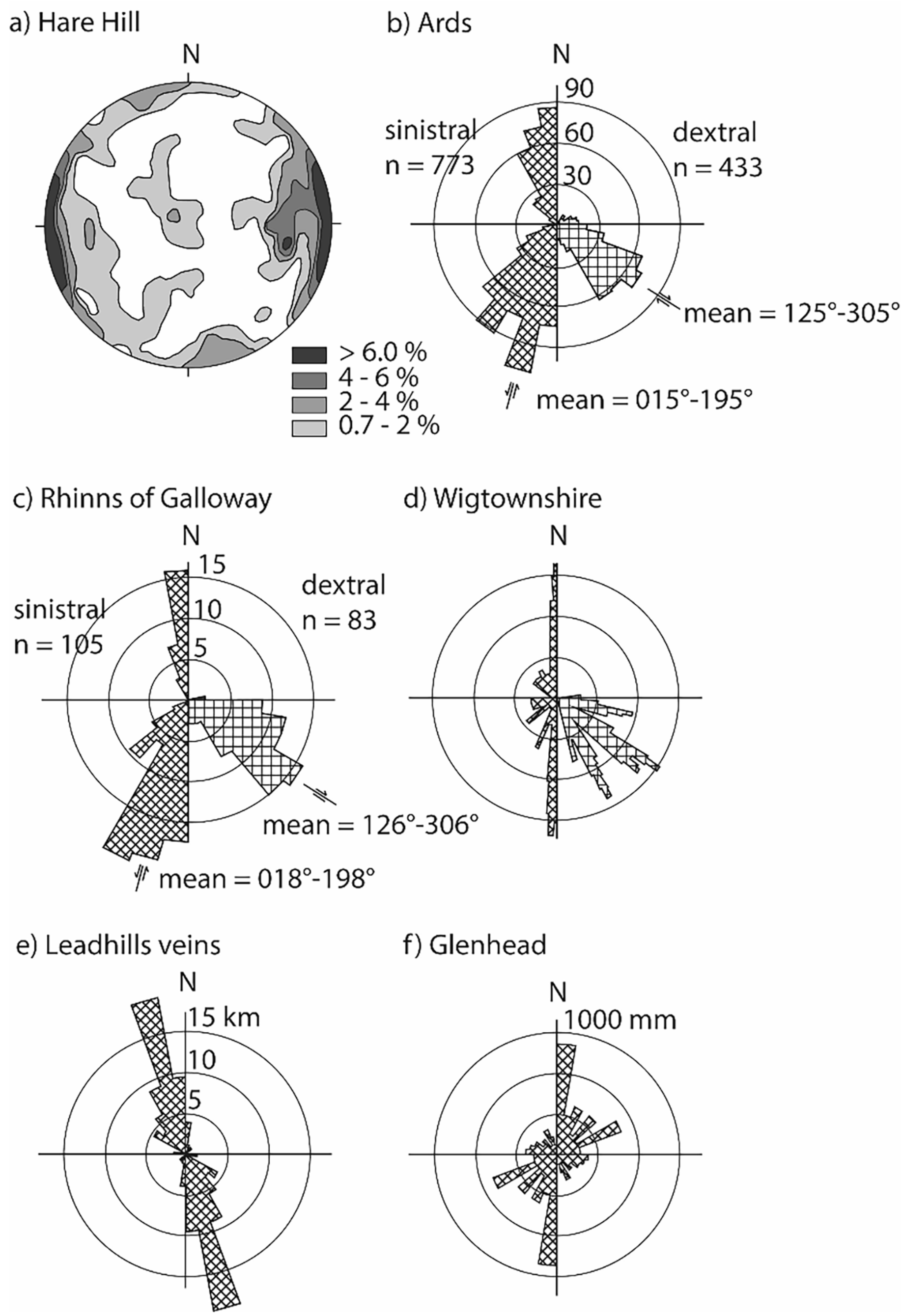


Fig. 6. Structural data. (a) poles to veins at Hare Hill after Boast et al. (1990); (b–d) strike orientations of dextral and sinistral D_3 strike-slip faults, see Fig. 2 for locations; (b) Ards peninsula, Co. Down, Anderson et al. (1995); (c) Rhinns of Galloway, Stone (1995); (d) Wigtownshire, Barnes (2008); (e) Pb-Zn veins at Leadhills-Wanlockhead, Temple (1957); (f) veins and fractures at Glenhead, Leake et al., 1981.

are dominant on the NW-SE striking faults whereas sinistral sub-horizontal slickensides are dominant on the N-S faults (Fig. 6). Limited lateral offset is exhibited across transverse D_3 faults. Steeply plunging D_3 folds of D_1 cleavage are developed adjacent to D_1 and D_3 faults, indicating that D_1 faults were reactivated by D_3 sinistral strike-slip motion (Anderson and Cameron, 1979; Stone et al., 2012; Stringer and Treagus, 1980).

5. Magmatism

The metasedimentary country rocks of the SUDLT are intruded by several large calc-alkaline granitoid plutons (Fig. 2) ranging in age from 408 ± 2 to 395 ± 2 Ma (Brown et al., 2008; Halliday et al., 1980; Stephens and Halliday, 1984; Thirlwall, 1988) and swarms of Early-Devonian (418–400 Ma; Rock et al., 1986), mainly calc-alkaline mafic K-lamprophyres plus appinite, monzonite, granodiorite, felsic quartz-porphyry and microgranite dykes (Anderson and Cameron, 1979; Barnes et al., 2008; Brown et al., 2008; Leake et al., 1981; Leake and Cooper, 1983; Miles et al., 2016; Pidgeon and Aftalion, 1978; Read, 1926; Rock et al., 1986). The granitoid plutons of the Southern Uplands belong to the Trans Suture Suite (TSS) that includes all late Caledonian granitoids south of the Highland Boundary Fault (Brown et al., 2008; Miles et al., 2014, 2016). Rocks belonging to the TSS exhibit similar petrological and geochemical character and span the buried trace of the Iapetus Suture (Fig. 1) (Brown et al., 2008; Miles et al., 2016).

Recent U-Pb zircon ages show that the TSS was emplaced between

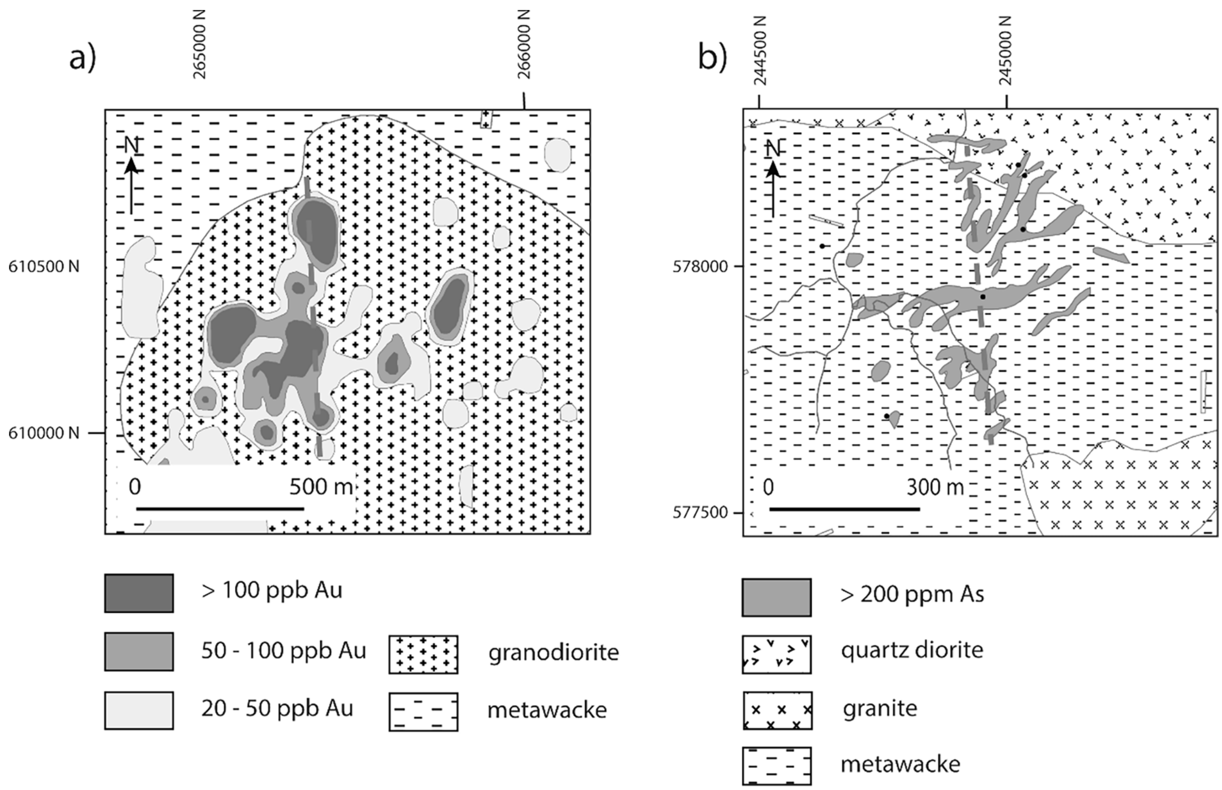


Fig. 7. Structural control of geochemical anomalies. (a) Au in bedrock at Hare Hill showing a dominant NE-SW Caledonoid pattern with weaker intersecting ~N-S anomalies (Boast et al., 1990). (b) arsenic anomaly map of Glenhead Burn showing concordant NE-SW anomalies intersected by a ~N-S discordant trend (Leake et al., 1981).

426 and 387 Ma, broadly coeval with granitoids in the Grampian Highlands (Fig. 3), indicating a possible common origin (Miles et al., 2016). K-lampropyre dykes dated 400 and 418 Ma (K-Ar method) are, likewise, broadly coeval (Fig. 3) (Anderson, 1987; Rock et al., 1986) and some granitic bodies exhibit lamprophyric enclaves (Brown et al., 2008).

Geophysical evidence for buried large plutons in the Tweedale area (Fig. 4) suggests that the volume of TSS late Caledonian granitoid intrusions in the SUDLT is likely to be greater than currently estimated (Miles et al., 2016). Magmatism is therefore likely to have had a substantial influence on the thermal regime and the activity of fluids, sulphur and metals in the SUDLT during early Devonian times.

The granitic plutons are generally zoned, with older, more mafic dioritic rims and younger, more silicic granitic cores (Brown et al., 2008; Halliday et al., 1980; Stephens and Halliday, 1984). The outer zones have more metaluminous I-type compositions whereas the cores have more peraluminous S-type compositions (Brown et al., 2008). For example, the Criffel-Dalbeattie Pluton (Fig. 2) is concentrically zoned with outer, early I-type hornblende granodiorite enveloping a core of S-type two-mica granite (Stephens, 1992; Stephens et al., 1985). The proportion of Caledonian S-type relative to I-type granitoids generally increases southwards from the Grampian Highlands to the Lakesman Terrane (Brown et al., 2008). The Cairnsmore of Fleet Pluton (Fig. 1) is a two-mica granite pluton with S-type chemical and isotope characteristics (Brown et al., 2008). The Loch Doon Plutonic Complex is a zoned I-type dioritic to granitic complex with ferric/ferrous ratio between ~0.66 and 2.88. In each of these plutons isotopic ratios and REE abundances vary systematically from the outer to the inner zones, indicating an increased input of crustal material through time (Brown et al., 2008). Initial $^{86}Sr/^{87}Sr$ ratios (0.705 to 0.708) together with $\delta^{18}O$ (8 to 12‰) and ƐNd values (−3.4 to −0.6) for Southern Uplands plutons indicate the same magmatic source as for the north of England (Brown et al., 2008). Pb isotopes match those of the Ordovician Skiddaw Group in the Lake District, indicating melting and assimilation of Avalonian crust but not SUDLT rocks (Brown et al., 2008).

The ages of the granitic plutons show that magmatism occurred on both sides of the suture zone during regional transtension immediately following the termination of Iapetus subduction (Fig. 3) (Miles et al., 2016). Isotopic characteristics of the TSS plutons indicate a source in Avalonian crust that was underthrust beneath the Iapetus Suture, including a component comparable to pelites of the Skiddaw Group (Fig. 4) (Miles et al., 2016). The lamprophyres and appinites were probably sourced in sub-continental mantle previously metasomatised by subduction prior to collision (Graham et al., 2017; Miles et al., 2016). Recognition of coeval mantle-derived lamprophyric and crustal S-type granitic melts supports the role of magmatic heat advection in generating anatectic granites (Brown et al., 2008). The hydrous granitoid magmas most probably indicate a metasomatically hydrated mantle source, likely to be also enriched in sulphide and metals. Comparable orthomagmatic auriferous PGE-sulphide mineralisation within an appinite-dolerite intrusion at Talnotry is found at Srón Garbh in the Grampian Terrane and in the northernmost Northern Highlands Terrane (Graham et al., 2017) and demonstrates that at least some of the more primitive magmas have transported gold, PGE's, Cu and Ni from the lower crust or mantle and have become saturated with respect to sulphide.

The most probable tectonic model to explain the post-subduction emplacement of these magmas on both sides of the suture zone is southwards-propagating delamination of the Avalonian sub-continental lithospheric mantle (Miles et al., 2016). Comparable post-subduction lithospheric delamination has been proposed elsewhere, for example, in the Eastern Mediterranean region on the basis of seismic tomography (van Hinsbergen et al., 2010).

Whole-rock geochemical data for Caledonian minor igneous intrusions in the Southern Uplands were provided by the British Geological Survey and screened to identify ultrapotassic rocks following the

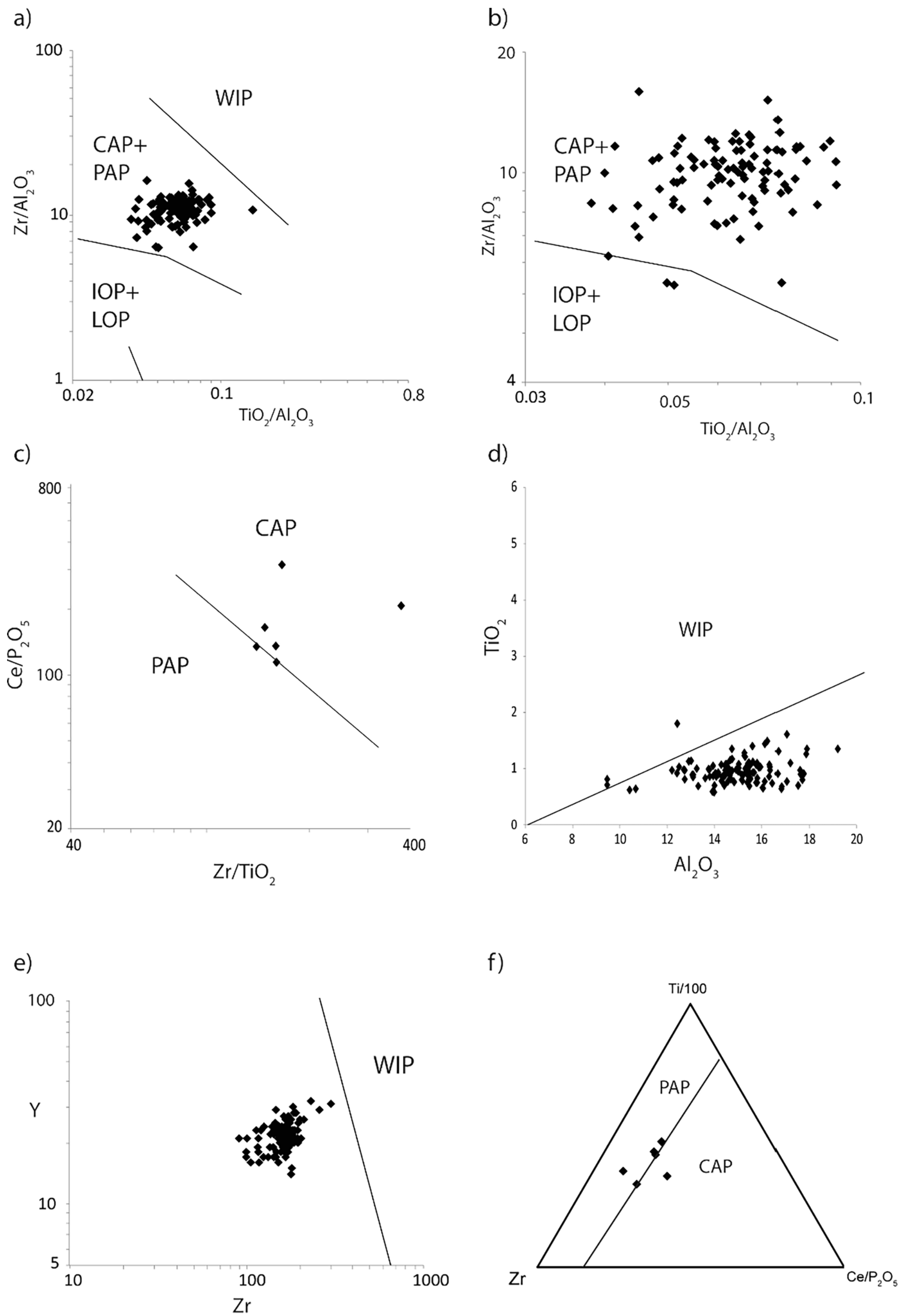


Fig. 8. Compositions of lamprophyric rocks of the SUDLT plotted on a hierarchical series of geochemical tectonic discrimination diagrams for potassic igneous rocks following Müller and Groves (2016). Geochemical data provided by BGS under licence IPR/191-244DX. Fields for potassic igneous rocks: CAP: continental arc; IOP: initial oceanic arc; LOP: late oceanic arc; PAP: post-collisional arc; WIP: within-plate.

parameters used by Müller and Groves (2016). Out of 357 samples, 116 fell within the range for ultrapotassic rocks. These results were then plotted on a hierarchical series of tectonic discrimination diagrams (Fig. 8) (Müller and Groves, 2016). These discrimination diagrams use incompatible immobile element ratios in order to minimise interference by the effects of fractionation, alteration, weathering and inter-laboratory differences.

The diagrams show that none of the samples are within-plate potassic igneous rocks (Fig. 8a, d and e) but represent a post-collisional or continental margin volcanic arc and not a juvenile or mature oceanic arc (Fig. 8b). Only 6 of the ultrapotassic samples were analysed for cerium and could therefore be plotted on the Ce/P_2O_5 versus Zr/TiO_2 diagram (Fig. 8c) to separate post-collisional from continental margin volcanic arc ultrapotassic rocks. Four of the samples fall clearly within the field for continental arc and 2 fall just inside the field for post-collisional arcs. It is important to note that on Fig. 8c there is overlap between continental and post-collisional arcs. The Ti/100-Zr- Ce/P_2O_5 diagram (Fig. 8f) provides better separation between continental margin and post-collisional arcs and on this diagram, with the exception of one sample, the lamprophyres fall mainly in the post-collisional arc field. This analysis provides geochemical evidence that lamprophyric and coeval TSS granitoid magmatism occurred within a post-collisional arc setting. Structural relationships, mineral assemblages and fluid inclusions described below indicate that this was the context of gold mineralisation.

6. Timing of magmatism and deformation

Minor intrusions cutting the Slieve Glah Shear Zone in Ireland indicate that compressional D_1 deformation on the shear zone occurred prior to ~400 Ma (Anderson and Oliver, 1986). In County Down and Galloway a change from foliated to unfoliated lamprophyre dykes, together with clockwise-transecting cleavages, indicates that orthogonal accretion switched to sinistral transpression at ~400 Ma (Fig. 3) (Anderson, 1987; Barnes et al., 2008, 1986; Dewey and Strachan, 2003; Miles et al., 2016; Stone, 1995). A maximum age for the initiation of the transverse strike-slip faults (D_3) is provided by broadly contemporaneous lamprophyre dykes in Galloway dated between ~400 and ~418 Ma (K-Ar method) that are in some cases cut by, and in others contained by the faults (Anderson, 1987; Barnes et al., 1986; Rock et al., 1986). In places the dykes are brecciated and exhibit the same sense and magnitude of displacement as the country rocks, indicating pre-kinematic intrusion (Anderson, 1987; Barnes et al., 1986). In other cases, the dykes follow D_3 faults, cut breccia zones and exhibit apparent displacements in the opposite sense to the country rocks, indicating post-kinematic intrusion (Anderson, 1987; Barnes et al., 1986). The dykes are best exposed on the Galloway coast near Kirkudbright where they intrude ~420 My old Llandovery-Wenlock country rocks and are not found intruding the Criffel Pluton, dated at 410 ± 6 Ma (Barnes et al., 1986; Miles et al., 2014; Rock et al., 1986).

Within the contact metamorphic aureole of the Fleet Pluton, cordierite porphyroblasts have overgrown the early mylonitic fabric (D_1) of the Moniaive Shear Zone (Phillips et al., 1995). However, the porphyroblasts have been deformed by subsequent reactivation of the shear zone (Miles et al., 2014). Recent U-Pb zircon geochronological evidence for the Fleet Pluton indicates that the reactivation of the Moniaive Shear Zone occurred between two intrusive phases at ~410 and ~387 Ma (Miles et al., 2014, 2016). In northern England and Wales clockwise-transecting transpressive regional cleavages mark the onset of Acadian transpression at ~404 Ma (Fig. 3) (Miles et al., 2016). The locations and geometries of the granitoid plutons appear to be influenced by D_1 and D_3 structures (Fig. 2). For example, the Cairnsmore of Carsphairn Pluton (410.4 ± 4 Ma, Rb-Sr method; Thirlwall, 1988) crops out near the intersection of the Leadhills fault and the NNW-SSE trending Luke's Stone Fault. Strong ~N-S elongation (Fig. 1) of the Loch Doon Plutonic Complex (408 ± 2 Ma, K-Ar method; Stephens and Halliday, 1984) together with locally developed internal ~N-S foliation and asymmetrical vertical drag folds in contact metasedimentary country rocks indicates syn-magmatic N-S sinistral shear (Leake et al., 1981).

Due to extensive fault reactivation, the minimum age of deformation on the transverse D_3 strike-slip faults is not known. However, regional borehole, geophysical, structural and stratigraphic data indicate that reactivation of the transverse D_3 faults occurred in Carboniferous, Permian and Palaeogene times under extensional regional stress fields (Anderson et al., 1995; Barnes et al., 2008; Caldwell and Young, 2013a; Cooper et al., 2012; Coward, 1995). For example, Carboniferous and Permian stratigraphic thickness variations across major ~N-S and ~NW-SE-trending faults indicate syn-tectonic sediment deposition continued within fault-controlled volcano-sedimentary basins in the East Irish Sea, Solway Firth, North Channel and Firth of Clyde and at Kingscourt, Strangford, Luce Bay, Stranraer, Dumfries, Thornhill, Sanquhar and Langholm (Fig. 2) (Anderson et al., 1995; Barnes et al., 2008; Caldwell and Young, 2013a; Coward, 1995; Kelling and Welsh, 1970; Mitchell, 1992; Oliver et al., 2003; Ruffell and Shelton, 2000; Stone, 1995; Stone et al., 1995). Thicknesses of Permo-Carboniferous volcanosedimentary successions in these basins together with contrasts in metamorphic grade across D_3 faults indicate vertical displacements in excess of 2 km (Anderson et al., 1995; McMillan and Brand, 1995; Stone et al., 1995). Carboniferous and Palaeogene dykes following transverse structures indicate likely reactivation at these times (Caldwell and Young, 2013b; Cooper et al., 2012). These observations accord with textural evidence from Ireland for Carboniferous hydrothermal (SEDEX) Pb-Zn mineralisation (Everett et al., 1999). It is likely that regional hydrothermal activity and Pb-Zn-Ag vein mineralisation was related to this tectonic reactivation (Fig. 3) (Baron and Parnell, 2005; Wilkinson et al., 1999). Caledonian gold could, therefore, potentially have been remobilised in Permian, Carboniferous and/or Palaeogene times. Permian and Palaeogene Au mobility is supported by evidence from the distribution and character of alluvial gold grains in the Thornhill and Leadhills areas (Leake et al., 1998; Leake and Cameron, 1996) and by atypical oxide-related lode-gold mineralisation in Western Ireland (Lusty et al., 2011). Detailed geochronological studies would clarify the timing of these events and their influence on regional gold metallogeny.

7. Gold mineralisation in the SUDLT

Detrital gold in drainage sediment is widespread in the SUDLT and more than 25 000 oz of alluvial gold was extracted historically from the Leadhills-Wanlockhead mining district alone prior to 1876 (Fig. 2) (Gillanders, 1976). No sufficient bedrock source has yet been identified for these alluvial deposits. However, gold concentrations are recorded in bedrock in eleven other areas in the SUDLT (Fig. 2). An economically important, 45 km-long gold trend, occurs in Central Ireland that incorporates the Clontibret deposit; estimated to contain at least 600 koz Au (Conroy Gold and Resources, 2011). Gold grades in excess of 50 ppm/m and 9.8 ppm are reported from Fore Burn (Charley et al., 1989) and Moorbrock Hill (Beale, 1984) respectively, both in southwest Scotland.

7.1. General description of gold mineralisation in bedrock

Gold mineralisation in the SUDLT occurs as veins that may be within, spatially associated with, or remote from known igneous intrusions. However, all of the known auriferous bedrock localities in the SUDLT (Fig. 2) exhibit similar sulphide mineral assemblages. Auriferous veins are generally < 10 cm thick and contain quartz ± subordinate carbonate together with sulphides (Allen et al., 1982; Boast et al., 1990; Brown et al., 1979; Duller et al., 1997; Leake et al., 1981; Morris et al., 1986). The sulphides associated with gold are principally arsenopyrite, pyrite and chalcopyrite and occur as veins and disseminations within the veins and sericitised wallrocks. At Clontibret gold grades are highest in the wall rocks (Morris, 1984; Morris et al., 1986; Steed and Morris, 1986). Native gold grains are generally rare in bedrock throughout the terrane. However, gold has been observed as small inclusions < 20 µm, locks < 50 µm and fracture fills within brecciated arsenopyrite and pyrite at Fore Burn and Glendinning (Boast et al., 1990; Charley et al., 1989; Duller et al., 1997) and grains < 10 µm were recovered from sericitised granodiorite at Hare Hill (Boast et al., 1990). Rare grains of particulate gold, generally < 10 µm were identified within quartz and pyrite but not arsenopyrite at Clontibret (Morris et al., 1986). At none of these localities was the abundance of gold grains sufficient to account for the corresponding gold grades, suggesting that the gold is predominantly sub-microscopic and most probably a lattice constituent of arsenopyrite and pyrite (Boast et al., 1990), i.e. 'refractory ore'.

Gold and geochemical pathfinder element anomalies in soil and bedrock predominantly exhibit ~NE-SW (D_1) and ~N-S trending (D_3) elongation and occur within metasedimentary rocks and within late Caledonian hypabyssal intrusions (Fig. 7) (Boast et al., 1990; Leake et al., 1981). The anomalies may correspond to zones of simple quartz veining, e.g. at Glenhead and Hare Hill (Boast et al., 1990; Leake et al., 1981), or to more complex zones of fracturing, brecciation and fault gouge containing veins and disseminations of quartz-sulphide mineralisation, e.g. at Clontibret, Glendinning, Duns and Moorbrock Hill (Beale, 1984; Duller et al., 1997; Morris, 1984; Steed and Morris, 1986).

Whether within, proximal to or remote from igneous intrusions, the gold-mineralised structures are consistently enveloped by distinctive zones of metasomatic phyllic (sericite) alteration with veinlets and

Table 1
Paragenetic sequence at Clontibret (after Morris, 1984).

Stage	1A	1B	2A	2B	3	4A	4B	5A	5B	6
quartz	X	X	X	X		X	X	X		
carbonate	X	X	X	X		X	X	X	X	
carbonaceous material	X	X								
pyrobitumen		X								
chlorite			X							
sericite				X						
pyrite	X	X	X	X	X	X	X			
arsenopyrite			X	X	X	X	X			
brecciation					X					
gold						X	X			
chalcopyrite						X				X
sphalerite						X		X	X	X
tetrahedrite						X	X			
stibnite							X	X	X	
marcasite									X	
boulangerite								X		
galena								X		X
ankerite										X
siderite										X

patches of disseminated sulphides including auriferous arsenopyrite and pyrite (Fig. 9) (e.g. Boast et al., 1990; Brown et al., 1979; Duller et al., 1997; Leake et al., 1981; Morris et al., 1986). Fragments of altered and mineralised brecciated wallrocks within fault breccia, e.g. at Clontibret, demonstrate reworking and a polyphase history of fluid flow and deformation of the lode zone (Morris et al., 1986). Detailed analysis of the lode zones at Clontibret has revealed a complex paragenetic

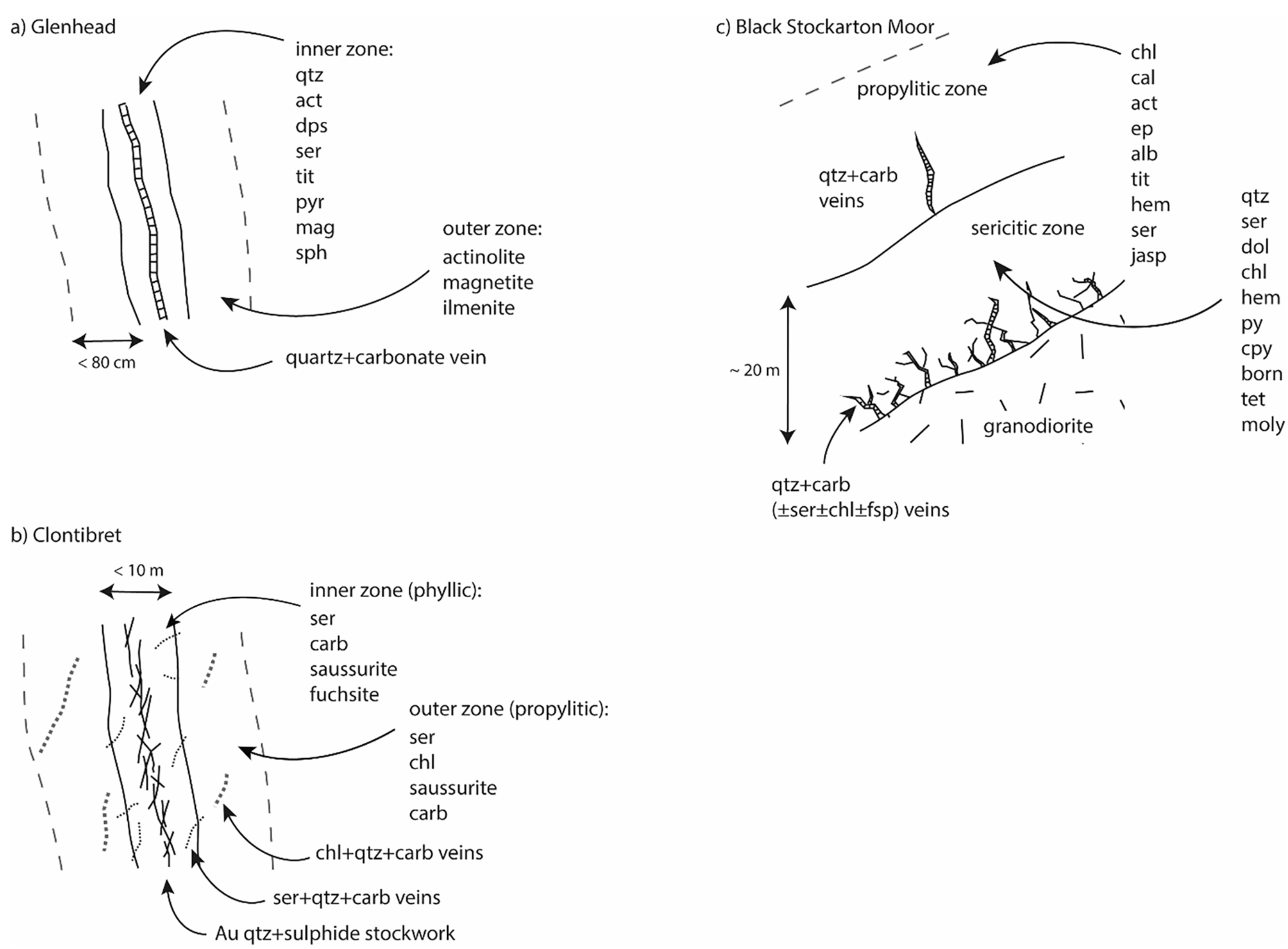


Fig. 9. Schematic representations of zoned alteration mineral assemblages at Glenhead, Clontibret and Black Stockarton Moor based on descriptions in Leake et al. (1981), Brown et al. (1979) and Morris (1984).

Table 2
Summary of published data for Au-mineralised localities in the Southern Uplands-Down-Longford Terrane. See text for details.

Deposit name	Host rocks	Lode structural control	Max reported bedrock grade	Alteration	Paragenesis	Proposed model	Fluid NaCl (wt%)	Th (°C)
Slieve Glah	Black shale (Moffat Shale)	135°	1 m @ 1.7 g/t			orogenic		
Glenish		135°	1 m @ 9.4 g/t			orogenic		
Clontibret	Turbiditic greywacke	170°	1 m @ 34.98 g/t	Zoned phyllic-propylitic, disseminated asp.	Qtz + carb + asp + py + cpy + sph + tet + sb + boul + marc	orogenic, magmatic-hydrothermal	2–4 (Steed and Morris, 1986)	170–340 (Steed and Morris, 1986)
Clay Lake	Black shale (Moffat Shale)	050°	5 m @ 3 g/t			orogenic		
Fore Burn	Microdiorite (TSS)	135°	0.9 m @ 50 g/t	Phyllic-propylitic, tourmaline, not zoned	Qtz + carb + asp + py	Epithermal/porphyry, intrusion-related		
Glenhead Burn	Turbiditic greywacke (Shinnel and Glenlee Fms.)	010°, 050°	1 m @ 8.8 g/t		Qtz + carb + asp + py	Epithermal/porphyry, intrusion-related		
Talnotry	Diorite (TSS)	135°, 050°			Qtz + carb + asp + py	orthomagmatic		
Moorbrock Hill	Granodiorite, black shale (TSS, Moffat Shale)	050°, 010°	9.8 g/t 10 m @4.85 g/t			orogenic		
Black Stockarton Moor	Granodiorite and turbiditic greywacke (Hawick Grp.)		Low grade anomaly	Zoned phyllic-propylitic		Epithermal/porphyry	Early, 4.4–11.7 Late, 6–22 (Lowry et al., 1997)	Early, 197–386 Late, 123–188 (Lowry et al., 1997)
Hare Hill	Granodiorite	010°, 050°	0.5 g/t	Phyllic-propylitic	Qtz + carb + asp + py	Orogenic, epithermal, intrusion-related	5.2–7.6 (Samson and Banks, 1988)	168–213 (Samson and Banks, 1988)
Leadhills-Wanlockhead	unknown	050°, 010°	2.25 g/t (spoil) 0.4 g/t (in-situ)				2–8 (Samson and Banks, 1988)	187–236 (Samson and Banks, 1988)
Glendinning	Turbiditic greywacke (Hawick Grp.)	010°	840 ppb (mineralised wallrock)	Zoned K-phyllic-propylitic	Ser + qtz + ank + sb + sphal + py + asp + gal + sem + tet etc.	Turbidite-hosted orogenic/magmatic-hydrothermal	0–3 (Duller et al., 1997)	250–300 (Duller et al., 1997)
Duns area	Turbiditic greywacke (Gala Grp.)	050°, 010°	5 g/t (top bedrock) 1.3 ppm (rock)	Phyllic-propylitic	Ser + qtz + py	Turbidite-hosted orogenic/magmatic-hydrothermal		

sequence with six generations of hydrothermal mineralisation in which gold is associated only with phases 4 and 5 (Table 1) (Morris, 1984; Morris et al., 1986). Complete paragenetic sequences have not been established for the other known gold-bearing localities. It is noted that, at Leadhills-Wanlockhead, gold in stream sediment is spatially associated with the traces of Pb-Zn veins (Gillanders, 1976; Porteous, 1876). Gold at Leadhills-Wanlockhead is thought to be associated with a relatively early generation of veins (Temple, 1956; Wilson and Flett, 1921), although specific data are lacking. Felsic dykes in the Leadhills area have yielded anomalous gold concentrations (Boast and Harris, 1984; authors unpublished data). Historical records suggest that gold-bearing veins in the Leadhills-Wanlockhead area possibly occur within deeply weathered saprolitic regolith (*sapper stone*) (Atkinson, 1619) and deeply weathered rock is identified in the area on BGS 1:10 000 scale maps and in the field (authors unpublished data).

Mineralisation at Black Stockarton Moor occurs within hydro-fractured and metasomatised rocks immediately above granodiorite sheets within a subvolcanic complex and represents a porphyry Cu (Au) type deposit (Brown et al., 1979). Remarkably similar geochemistry and hydrothermal alteration assemblages are also recorded at Clontibret, Glendinning, Fore Burn, Hare Hill and Glenhead Burn (Boast et al., 1990; Charley et al., 1989; Duller et al., 1997; Leake et al., 1981; Morris et al., 1986) indicating a common source of magmatic-hydrothermal gold-mineralising fluids is likely. These deposits have been interpreted as intrusion-related but have not been classed as porphyry-type due to the structural control of mineralisation, a lack of evidence for zonation of alteration and, for Glendinning, the lack of evidence of a proximal source intrusion (Boast et al., 1990; Charley et al., 1989; Duller et al., 1997; Leake et al., 1981; Steed and Morris, 1997).

7.1.1. Orthomagmatic Au-PGE mineralisation at Talnotry

The base of an appinite intrusion at Talnotry (Fig. 2) exhibits orthomagmatic polymetallic precious metal mineralisation (Power et al., 2004; Stanley et al., 1987) with inclusions of electrum (80% Au) within magmatic chalcopyrite (Power et al., 2004). Compositions and textures exhibited by the pyrrhotite-chalcopyrite assemblage indicate that monosulphide solid-solution crystallization led to enrichment of Ni, Cu, Pt, Pd, Au and As in the residual sulphide liquid (Power et al., 2004). A Cu and Au-rich phase subsequently crystallised to form discordant cross-cutting electrum-bearing chalcopyrite veins (Power et al., 2004). The PGE-enriched orthomagmatic sulphide deposit at Talnotry is a clear example of a magmatic igneous source of gold and indicates that late Caledonian magmas were capable of transporting and concentrating precious metals (Power et al., 2004). Comparable deposits of similar age are found in the Grampian Terrane at Srón Garbh and also in the Northern Highlands (Graham et al., 2017).

7.2. Lithological relations

7.2.1. Greywacke

Gold mineralisation in the SUDLT is concentrated in the Northern Belt, i.e. north of the OBF (Fig. 2) (Lusty et al., 2012). Two exceptions are Black Stockarton Moor and Glendinning, both located in the Southern Belt. However, to date neither of these localities have yielded Au concentrations greater than 0.84 ppm (Brown et al., 1979; Leake et al., 1981). Some units of the Northern Belt, e.g. the Portpatrick Formation, contain more andesitic and mafic detritus than those south of the OBF (Floyd, 2001; Stone et al., 1995). In addition, the Northern Belt exhibits a regional relative enrichment in As, Pb and Zn (Stone et al., 1995). The spatial correlation between gold mineralisation and more metalliferous metasedimentary units may indicate that metals were derived from the more mafic-rich greywackes of the Northern Belt or that the greywackes of the Northern Belt were more chemically reactive with metalliferous mineralising fluids than the rocks in the Central and Southern Belts (Lusty et al., 2012). However, gold does not exhibit a strong spatial association with the outcrop of any particular stratigraphic unit within the Northern Belt (Table 2) and significant Au anomalies are found within a range of lithologies including greywacke sandstone, carbonaceous black shale, major and minor dioritic, granodioritic and porphyrytic intrusions (Boast et al., 1990; Leake et al., 1981; Lowry et al., 1997; Morris et al., 1986; Naden and Caulfield, 1989). Greywacke sandstones hosting gold mineralisation occur at a range of stratigraphic levels from Middle Ordovician to Wenlock. For example, the Llandeilian Red Island Formation hosts the prospect at Glenish in central Ireland and the Silurian Hawick Group hosts auriferous As-Sb mineralisation at Glendinning (Conroy Gold and Natural Resources, 2015; Duller et al., 1997; Morris, 1983).

7.2.2. Black Shale

Black pyritic carbonaceous shale of the Moffat Shale Group is commonly the locus of D_1 shear zones that exert a primary control on the localisation of gold mineralisation in the terrane (Lusty et al., 2012). The Moffat shale is spatially associated with gold mineralisation in the Leadhills-Wanlockhead area, at Clay Lake and Slieve Glah in Central Ireland and at Moorbrock Hill (Fig. 2) (Beale, 1984; Conroy Gold and Natural Resources, 2014a,b). Discordant ~N-S mineralised faults and fractures within the Moffat shale are intruded by quartz microdiorites immediately south of Glenhead where they host auriferous sulphide bearing quartz veins (Leake et al., 1981). The Moffat Shale forms the main decollement in the SUDLT (Anderson, 2004), particularly in the Leadhills Imbricate Zone (Floyd et al., 2007) and is likely to be an important host rock, fluid conduit, possible source of sulphur and metals and a structural pathway for gold. In addition, carbon derived from the black shale during deformation and fluid flow is likely to have provided a ligand for gold transport and created a reducing environment promoting the stability of dissolved gold-sulphide complexes (Williams-Jones et al., 2009).

7.2.3. Igneous rocks

A spatial correlation between hydrothermal metalliferous mineralisation in the SUDLT and the outcrops of large plutons has been suggested (Lowry et al., 1997; Naden and Caulfield, 1989) but is not ubiquitous and notable exceptions include alluvial gold at Leadhills, Glendinning and the Central Irish gold trend including Clontibret (Lusty et al., 2012). An association with minor intrusions has also been suggested (Brown et al., 1979; Charley et al., 1989; Duller et al., 1997; Leake et al., 1981). Greywacke turbidites are hornfelsed in the vicinity of Clontibret indicating a probable buried intrusion and geophysical data support the possibility of unexposed intrusions here and at Glendinning, Stobshiel and Leadhills (Duller et al., 1997; Leake et al., 1996; Morris et al., 1986; Shaw et al., 1995; Steed and Morris, 1997). Relationships between minor intrusions, metasomatic alteration and gold mineralisation have been demonstrated at several of these localities, e.g. Glenhead (Leake et al., 1981), Black Stockarton Moor (Brown et al., 1979), Fore Burn (Allen et al., 1982; Charley et al., 1989) and Leadhills (Boast and Harris, 1984). At some of the gold-bearing localities, intensely K-altered felsic intrusions are found, as would be expected for porphyry-gold and intrusion-related gold systems (Allen et al., 1982; Berger et al., 2008; Boast et al., 1990; Brown et al., 1979; Charley et al., 1989; Leake et al., 1981; Rose, 1970; Sillitoe, 1991; Sillitoe and Thompson, 1998).

Gold mineralisation occurs in the I-type diorite Cairnsmore of Carsphairn Pluton (Moorbrock Hill) (Beale, 1984) and in the I-type dioritic margins of the Loch Doon Pluton (Glenhead Burn) (Leake et al., 1981), the Criffel Pluton (Black Stockarton Moor) (Brown et al., 1979), the Fleet Pluton (Leake et al., 1978; Lowry, 1991; Lowry et al., 1997; Power et al., 2004), the Newry Igneous Complex in County Down (Toal and Reid, 1986) and the Priestlaw Pluton Stobshiel and Duns area (Naden and Caulfield, 1989; Shaw et al., 1995) (Naden and Caulfield, 1989; Shaw et al., 1995) (Fig. 2).

Antimony-gold mineralisation at Hare Hill, with gold grades up to 5 ppm, is hosted within a moderate-scale late Caledonian slightly porphyritic biotite-hornblende granodiorite intrusion, ~1.6 km in diameter (Fig. 7) (Boast et al., 1990). The mineralisation occurs as discrete structurally controlled lodes corresponding to zones of faulting and veining with haloes of sericitic alteration and disseminated sulphides (Boast et al., 1990). Comparable relationships are evident at Moorbrock Hill, where gold grades up to 9.8 ppm occur within the dioritic Carsphairn igneous complex that intrudes Moffat Shale within the Leadhills Fault Zone (Beale, 1984; Dawson et al., 1977). Lamprophyric and felsic porphyritic dykes crop-out locally (British Geological Survey, 2005).

Two gold anomalies are identified at surface and in drill core within metasomatised Lower Devonian intermediate to acidic volcanic and subvolcanic intrusive igneous rocks at Fore Burn (Fig. 2) (Allen et al., 1982; Charley et al., 1989). The western anomaly corresponds to a NW-SE-trending lode zone with gold grades up to 50 ppm Au over 90 cm (Charley et al., 1989). The mineralised faults cut rhyodacites, tourmaline breccias and intermediate porphyries that exhibit intensive sericite alteration of possible subvolcanic origin and the mineralisation at Fore Burn is interpreted as epithermal (Charley et al., 1989). Fore Burn is located immediately north of the Southern Uplands Fault and may, therefore, be considered to lie just outside of the SUDLT *sensu stricto*. However, Fore Burn exhibits marked similarities to the other auriferous localities in terms of timing, host rocks, structure and mineral assemblages.

Numerous minor felsic porphyritic intrusions are spatially associated with alluvial gold concentrations in the Leadhills-Wanlockhead area (Boast and Harris, 1984; British Geological Survey, 2000; Leake et al., 1998). However, geochemical data for gold and pathfinder elements in bedrock at Leadhills-Wanlockhead are limited. The highest concentration of gold recorded in bedrock in the Leadhills-Wanlockhead area is from a felsic minor intrusion containing 413 ppb Au (Boast and Harris, 1984).

Greywacke turbidites are intruded by a subvolcanic complex of probable earliest Devonian age at Black Stockarton Moor (Fig. 2) (Brown et al., 1979). Turbidites immediately above granodiorite sills are hydro-fractured and quartz-veined and exhibit zoned metasomatic phyllic-propylitic alteration comparable to that seen at the other gold bearing localities (Fig. 9) (Brown et al., 1979). The fractured and metasomatised zones at Black Stockarton Moor have very low grade anomalous As-Au values (Brown et al., 1979). Although gold abundances so far recorded are very low, structural relationships and mineral assemblages are similar to the other localities and indicate comparable timing, P-T-X conditions and tectono-magmatic causes of metasomatism and mineralisation. Mineralisation and alteration at Black Stockarton Moor are most probably the result of the rapid release of magmatic-hydrothermal fluids at a shallow crustal level (Brown et al., 1979; Clarkson et al., 1975; Craig and Walton, 1959) and the deposit is interpreted as porphyry Cu (Au) type (Brown et al., 1979).

At Glenhead, the intensity of hydrothermal alteration in hornfelsed greywacke country rocks does not correlate with distance from the margin of the pluton, indicating that hydrothermal alteration and mineralisation were not coeval with and, therefore, not directly genetically related to plutonism (Leake et al., 1981). Xenoliths of altered country rock are found within the margins of the Loch Doon Plutonic Complex, indicating that metasomatic K-alteration preceded its emplacement (Fig. 10) (Leake et al., 1981). Two phases of gold mineralisation are identified at Glenhead: (1) Weak disseminated As-Au mineralisation, up to 0.14 ppm Au, is associated with the margins of concordant late Caledonian monzonite dykes (Leake et al., 1981); (2) Higher gold grades, up to 8.8 ppm Au, are associated with discordant ~N-S veins that cut the metawacke country rocks, minor intrusions and the early-formed dioritic margin of the pluton, indicating that gold mineralisation overlapped in time with the early stages of its emplacement (Fig. 10). These ~N-S veins have strong cm-scale post-metamorphic sericitic alteration haloes with disseminated sulphides (Leake et al., 1981). Concordant granodiorite intrusions at Glenhead exhibit no Au-As anomalies. Dyke emplacement and associated metasomatic alteration preceded emplacement of the granitoid plutons at Black Stockarton Moor and Glenhead at 397 ± 2 and 408 ± 2 respectively (Rb-Sr method) (Brown et al., 1979; Halliday et al., 1980; Leake et al., 1981). Taken together, these observations indicate that gold mineralisation post-dates the early stages of Caledonian magmatism and metamorphism but pre-dates the later stages of granitoid emplacement (Leake et al., 1981). However, in detail, relationships between deformation, magmatism and mineralisation are likely to be complex: gold mineralisation is likely to have been polyphased, but broadly coeval with magmatism and deformation.

7.3. Structural controls of gold mineralisation

With the exception of Black Stockarton Moor and Glendinning, located southeast of the OBF, the gold mineralised localities are spatially associated with major D_1 structures (Fig. 2) (Lusty et al., 2012). The NE-SW Caledenoid D_1 trend, therefore, exerts a primary structural control on the location of gold mineralisation (Lusty et al., 2012). However, at the prospect scale, the auriferous veins and lodes are mostly ~N-S trending (e.g. Clontibret, Glendinning, Glenhead) (Duller et al., 1997; Gallagher et al., 1983; Leake et al., 1981; Morris, 1984; Morris et al., 1986). Soil and deep overburden geochemical data for As and Au from Glenhead, Hare Hill and Moorbrock Hill exhibit a dominant ~NE-SW trend and a subordinate ~N-S trend (Beale, 1984; Boast et al., 1990; Leake et al., 1981). The soil geochemistry contrasts with geochemical and structural data from drill core from Glenhead and Hare Hill in which concordant ~NE-SW structures yield only weak Au anomalies (< 0.2 ppm Au), associated with As, and discordant ~N-S faults and fractures give stronger Au anomalies, up to 8.8 ppm (Leake et al., 1981) (Fig. 7). At Hare Hill and Glenhead ~N-S anomalies correspond to zones of sericite alteration containing quartz veins ~1 cm thick (Boast et al., 1990; Leake et al., 1981).

Localised D_2 structural anomalies could have focussed synchronous and/or subsequent hydrothermal activity. In the area of Glenhead Burn (Fig. 2) the regional strike swings to a more E-W orientation accommodated by near vertical folds in argillaceous rocks to the south (Leake et al., 1981; Stone and Leake, 1984) and is likely to have generated a deeply penetrating connected fracture system and enabled rapid ascent of hydrothermal fluids from depth. At Black Stockarton Moor the regional strike swings N-S forming a steeply-plunging sigmoidal monoform, possibly as a response to magmatic pressure from the Criffel-Dalbeattie Pluton (Brown et al., 1979). However, in other areas, e.g. Clontibret, D_2 structures are considered to be of little or no significance to gold mineralisation (Morris, 1984). Both D_2 and D_3 structures are likely to be related to the onset of regional transpression at 425 Ma (Miles et al., 2016).

At the deposit scale the lodes are most commonly controlled by transverse ~N-S to ~NW-SE trending (D_3) structures (Figs. 5, 6 and 7), e.g. Clontibret, Glenhead Burn, Hare Hill, Fore Burn and Glendinning (Boast et al., 1990; Charley et al., 1989; Duller et al., 1997; Leake et al., 1981; Steed and Morris, 1986). Abandoned mine plans from Leadhill-Wanlockhead (BGS data, with permission) indicate that the Pb-Zn mineralised structures that trend ~N-S dip steeply to the east, while those trending ~NW-SE dip steeply to the south-east. The lode zones at Clontibret are oriented ~140°/65°SW and are obliquely transected by ~N-S striking subvertical strike-slip faults containing muddy gouge up to several cm wide and fragments of mineralised and unmineralised rocks (Morris, 1984; Morris et al., 1986; Steed and Morris, 1986). Most of the Au-in-soil anomalies identified in central Ireland are elongate transverse to the dominant Caledonoid structural grain e.g. at Slieve Glah (Conroy Gold and Natural Resources, 2014b,c). Significant gold grades are found within ~N-S striking strike-slip faults within greywacke and intrusive igneous rocks at Glenhead (Figs. 2, 6 and 10) (Leake et al., 1981). A N-S trending top-of-bedrock Au, As and Sb anomaly at Hare Hill corresponds to a ~N-S trending zone of subvertical to steeply west-dipping veins within sericitised granodiorite

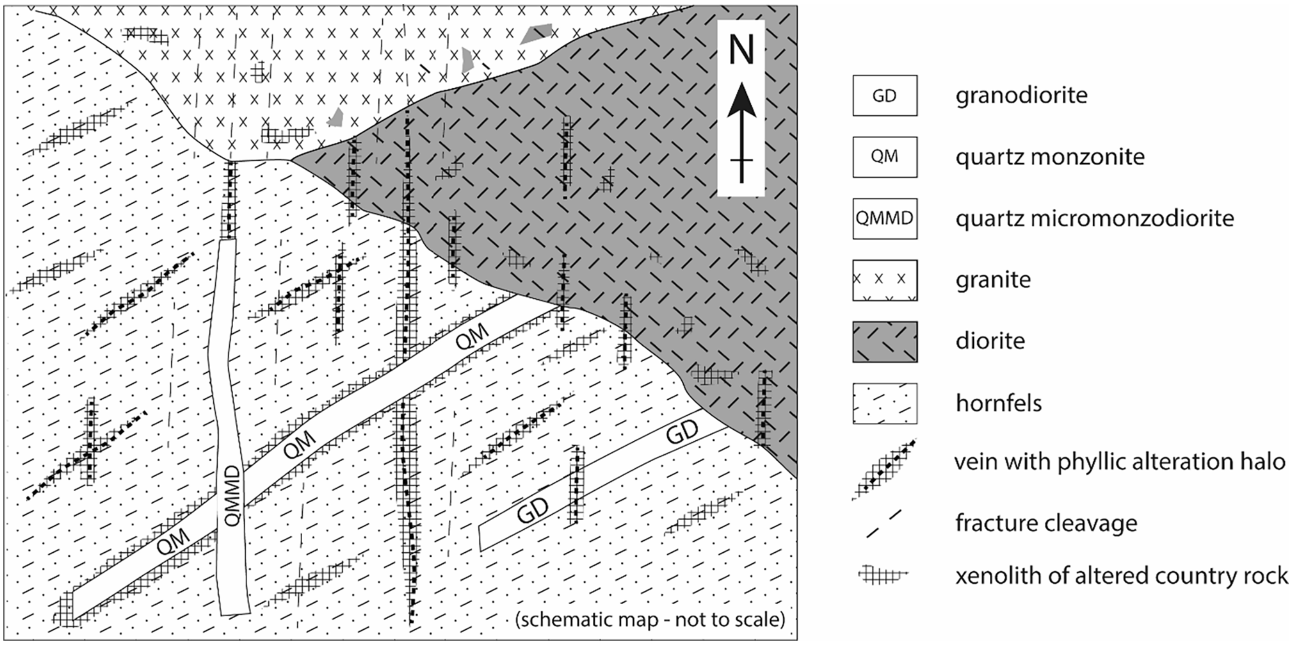


Fig. 10. Schematic map (not to scale) showing inferred cross-cutting relationships between country rocks, major and minor intrusions, alteration and veining at Glenhead based on work by Leake et al. (1981).

containing disseminated arsenopyrite. The zone is cut by subparallel late-stage Sb-Pb veins (Boast et al., 1990). The Glendinning Sb deposit with auriferous arsenopyrite is controlled by a 015°-trending fracture system (Duller et al., 1997). The two ore zones at Fore Burn correspond to ~NW-SE-trending fault zones with irregular quartz-carbonate-sulphide veins, stockworks and breccia (Charley et al., 1989).

The ~N-S structural control is also expressed more cryptically. For example, the alluvial gold field at Leadhills-Wanlockhead lies at the intersection between a ~N-S trending topographic lineament that extends from the fault-controlled Carbonifrous-Triassic Thornhill Basin, located ~7 km to the south, and the ~NE-SW trending Leadhills Fault (Leake et al., 1998; Temple, 1956; Wilson and Flett, 1921). Just north of Leadhills, the regional Eskdalemuir Dyke, of Palaeogene age exploits the ~NW-SE D_3 structural trend and intersects the Leadhills Fault and the ~N-S Thornhill trend (Leake et al., 1998; Macdonald et al., 2009). In addition, locally developed spaced cleavage with a strike of 110° corresponds to a relatively weak topographic lineament in the vicinity of the reputed historical gold workings at Bulmers' Moss near Leadhills (authors' unpublished data; Atkinson, 1619; Gillanders, 1976; Porteous, 1876). Alluvial gold concentrations are found in streams draining this area (Boast and Harris, 1984; Leake et al., 1998). A 110° trending topographic lineament intersects Hare Hill. The 110° trend is also weakly represented in As in soil anomalies at Glenhead (Fig. 7).

In summary, structural data indicate that, at the regional scale, the location of gold mineralisation is controlled by intersections between major NE-SW trending Caledonoid shear zones, such as the Leadhills Fault and Slieve Glah Shear Zone with significant N-S and/or NW-SE trending transverse D_3 faults. At some localities, for example in Central Ireland near Slieve Glah, at Glenhead, Hare Hill and possibly Moorbrock Hill, there is evidence at the prospect scale for ~NE-SW D_1 Caledonoid structural control of geochemical anomalies and gold grades. However, the predominant control of the orientation of mineralised lodes at the prospect scale appears to the subvertical to steeply-dipping transverse D_3 faults and fractures trending either ~N-S or ~NW-SE.

7.4. Associated hydrothermal alteration

All of the gold-mineralised localities, whether hosted by, associated with or remote from known igneous intrusions exhibit similar phyllic to propylitic alteration assemblages. Auriferous veins at all of the localities exhibit envelopes of sericitised rock indicating that gold mineralisation was accompanied by peak hydrothermal potassic alteration (Fig. 9). Other vein generations lacking alteration haloes may cut, or be cut by these veins, enabling recognition of pre-, syn- and post-alteration vein generations (Duller et al., 1997; Leake et al., 1981; Morris et al., 1986). Zones of alteration associated with disseminated or quartz vein-hosted auriferous sulphide mineralisation occur within metasedimentary and igneous host rocks and are up to 18 m wide (Boast et al., 1990; Morris et al., 1986).

Mineralogical zonation of potassic alteration assemblages is reported from Clontibret, Glendinning, Black Stockarton Moor and Glenhead Burn (Brown et al., 1979; Duller et al., 1997; Leake et al., 1981; Morris et al., 1986). At other localities, e.g. Hare Hill and Fore Burn, the same alteration mineral assemblages are preserved but without zonation (Boast et al., 1990; Charley et al., 1989). Zoned phyllic-propylitic alteration is clearly related to intrusion of granodiorite sheets and the release of a magmatic-hydrothermal fluid at Black Stockarton Moor, where zoned alteration is developed within hydrofractured metasedimentary rocks directly above porphyritic granodiorite sheets (Fig. 9) (Brown et al., 1979). Although established gold grades are very low at Black Stockarton Moor, very few Au determinations have been made. However, the relationships between alteration mineralogy and metasomatic enrichment of As, Sb and other pathfinder elements at Black Stockarton Moor are comparable to more richly gold-mineralised localities in the SUDLT (Brown et al., 1979; Duller et al., 1997; Leake et al., 1981; Morris et al., 1986; Shaw et al., 1995; Steed and Morris, 1986) indicating a common origin. Sericitic alteration at Black Stockarton Moor predominantly occurs within narrow zones around veins and above porphyritic granodiorite sheets (Brown et al., 1979). The sericitic zones are bleached and exhibit a pink colouration. The alteration assemblage comprises sericite, quartz, dolomite, muscovite and hematite developed pervasively with interstitial and replacive textures and filling veins (Brown et al., 1979). Orange colouration is locally associated with quartz-dolomite veins (Brown et al., 1979). The rocks in the sericitic zone contain abundant secondary pyrite, minor chalcopyrite and trace bornite, molybdenite, tennantite and arsenopyrite (Brown et al., 1979). Chalcocite, enargite, covellite and sphalerite occur throughout (Brown et al., 1979). In addition, zones and patches of argillic alteration are developed locally in which kaolinite replaces plagioclase (Brown et al., 1979). The propylitic alteration assemblage in the metasedimentary country rocks at Black Stockarton Moor comprises chlorite, calcite, actinolite, epidote, albite, titanite and hematite plus jasperoid and minor sericite (Brown et al., 1979). Quartz-carbonate veinlets and metasomatic replacement veins are locally developed containing secondary actinolite, epidote and albite (Fig. 9) (Brown et al., 1979). In igneous rocks, the propylitic alteration assemblage consists of chlorite, replacing primary mafic silicates; hematite replacing primary oxides, and disseminated epidote and minor sericite replacing plagioclase feldspar (Brown et al., 1979). The propylitic alteration zones contain secondary disseminated pyrite and minor veinlets of chalcopyrite (Brown et al., 1979).

Discordant N-S trending subvertical veins with prominent phyllic alteration haloes at Glenhead exhibit zonation with an inner core composed of quartz, actinolite, diopside, magnetite, pyrrhotite, sericite, pyrite and sphene surrounded by an envelope rich in actinolite, magnetite and ilmenite (Fig. 9) (Leake et al., 1981). Feldspars are sericitised and carbonated and mafic minerals are chloritised, sericitised and sulphidised. Actinolite from Glenhead Burn is comparable in composition to that in the propylitic alteration zone at Black Stockarton Moor, indicating similar conditions of hydrothermal alteration and mineralisation (Leake et al., 1981). At Fore Burn, intermediate to acidic volcanic and intrusive rock adjacent to the lode zones exhibit intense potassic alteration with the assemblage sericite, chlorite, tourmaline, carbonate, quartz and apatite. The lode zones and individual auriferous 4th generation veins exhibit zonation of phyllic and propylitic alteration assemblages at Clontibret (Fig. 9) (Morris et al., 1986; Steed and Morris, 1986). In the outer, propylitic zone, secondary sericite is abundant in the matrix and replacing feldspathic detrital grains. Mafic detrital grains are completely replaced by oxychlorite and saussurite (Morris et al., 1986). Pale green chlorite occurs interstitially in patches and microcrystalline carbonate, together with chlorite forms overgrowths and veinlets (Morris et al., 1986; Steed and Morris, 1986). The inner (phyllic) zone contains more abundant sericite and carbonate. Veins of sericite, quartz and carbonate are accompanied by secondary arsenopyrite and pyrite (Morris et al., 1986). Interstitial chlorite is absent and secondary oxychlorite replaces mafic grains and is, in turn, partially replaced by sericite, (Morris, 1984; Morris et al., 1986) indicating a progression of alteration from propylitic to sericitic reflecting increasing $a\mathrm{H_2O}$ and addition of potassium within the lode zone. In addition, detrital chromite grains exhibit haloes of bright green fuchsite (Cr-rich mica) (Steed and Morris, 1986).

In summary, the relationship between hydrothermal alteration and gold mineralisation, in conjunction with other lines of evidence, helps to constrain the geochemical and physical conditions of mineralisation. It demonstrates a clear association with late Caledonian calc-alkaline magmatism. Comparisons with other mineral deposits globally, along with established mineral deposit models indicate that gold mineralisation in the SUDLT was most probably related to magmatic-hydrothermal processes at shallow crustal levels, $< \sim 10$ km, comparable to the porphyry-epithermal spectrum of deposits (Berger et al., 2008; Brown et al., 1979; Richards, 2009; Richards et al., 2006; Steed and Morris, 1997). Furthermore, recognition of the association between gold mineralisation and peak potassic hydrothermal metasomatism is a useful aid to exploration for gold because it enables mineralised vein systems to be more easily identified and targeted.

7.5. Geochemistry

At all of the gold mineralised localities arsenic is sympathetically related to gold content and to indicators of potassic alteration (Fig. 11) (Boast et al., 1990; Duller et al., 1997; Leake et al., 1981; Morris et al., 1986). The association with arsenic reflects the abundance of auriferous arsenopyrite in which gold forms a lattice constituent (Duller, 1990; Duller et al., 1997; Leake et al., 1981; Morris et al., 1986). Gold concentrations up to 3000 ppm have been recorded in arsenopyrite from Glenhead Burn and up to 2500 ppm in arsenopyrite from Clontibret (Leake et al., 1981; Morris et al., 1986). Gold is also present in pyrite. The auriferous arsenopyrite-pyrite assemblage is spatially associated with the most intensive wall rock alteration (Duller et al., 1997; Leake et al., 1981; Morris et al., 1986) and is reflected by a close correlation between As and K_2O/Na_2O, e.g. at Clontibret (Fig. 11) (Duller, 1990; Duller et al., 1997; Morris et al., 1986; Steed and Morris, 1986). The inner, phyllic, zone of hydrothermal mineralisation and alteration at Glendinning, Clontibret and Hare Hill corresponds to a relative enrichment of SiO_2, K_2O, CaO, S and As. The outer, propylitic zone is depleted in Na, Fe, Mg relative to the surrounding unaltered rocks (Boast et al., 1990; Duller et al., 1997; Morris et al., 1986). The most significant chemical expression of alteration is the increase in K_2O/Na_2O with proximity to the lode zones (Fig. 11) (Duller et al., 1997; Morris et al., 1986). The increase in K_2O reflects the abundance of sericite. The inner zone of silicified and sericitised rock at Glendinning exhibits high CaO, SiO_2, As, Sb and S values (Duller et al., 1997). High S ($>$ 25 000 ppm) and As values correspond to zones of disseminated arsenopyrite and pyrite (Duller et al., 1997). The outer zone, up to 400 m wide is depleted in Na, Zn, Fe, Mn and Mg (Duller, 1990; Duller et al., 1997). The outer zone corresponds to a Na_2O depletion of up to 0.5%. The high K_2O concentrations reflect the increased abundance of sericite (Duller, 1990; Duller et al., 1997). A sharp decrease in MgO/CaO marks the transition between the phyllic and propylitic zones (e.g. Clontibret, Fig. 11) reflecting the addition of carbonate and the replacement of chlorite, feldspar and mafic minerals by sericite (Morris et al., 1986). Rubidium increases toward the lode in parallel with K_2O reflecting the presence of Rb as a lattice constituent in micas (Morris et al., 1986). Calcium also increases while MgO and FeO decrease with proximity to the lode zones at Clontibret and Glendinning (Duller et al., 1997; Steed and Morris, 1997). Gold-bearing pyrite + arsenopyrite mineralised samples from Clontibret are relatively enriched in Bi, Ni, Co, Cu and Zn. Bi is a minor constituent of arsenopyrite, Co and Ni are lattice constituents in pyrite and Cu and Zn are present as inclusions of tetrahedrite, chalcopyrite and sphalerite within pyrite (Morris et al., 1986).

Increased CaO is associated with mineralisation at some localities, e.g. Clontibret and Black Stockarton Moor (Brown et al., 1979; Morris et al., 1986). However, at other localities, for example Glendinning and Hare Hill, an inverse relationship is seen between CaO and S (Boast et al., 1990; Duller et al., 1997). This could possibly have resulted from the dissolution of carbonate by acidic sulphidic mineralising fluids. Carbonate dissolution could have enhanced porosity and focussed subsequent episodes of mineralisation (Duller et al., 1997). Decreasing Mn, Fe and Zn levels with proximity to the mineralised zone accompanied by increase in Ca, for example, at Black Stockarton Moor is comparable to zonal geochemical distributions above porphyry deposits, e.g. the Kalamazoo deposit (Chaffee, 1976). In the Duns area, Cu does not correlate with enrichments of Au, Sb or As indicating that the Ba-Cu and Au-As-Sb mineralising events occurred separately (Shaw et al., 1995). The same relationships are seen in limited data for Au, As, Sb and Cu at Black Stockarton Moor (Brown et al., 1979).

Stibnite mineralisation is localised within the lodes at Clontibret, Glendinning and Hare Hill. Antimony mineralisation is not accompanied by wall rock alteration at Clontibret and exhibits a poor correlation with K_2O/Na_2O (Fig. 11) indicating that stibnite mineralisation represents a separate event that may slightly post-date gold mineralisation (Morris et al., 1986). That some correlation is evident reflects the fact that Sb mineralisation occupies the same, previously mineralised lode zones (Morris et al., 1986). Highly elevated Zn values at Glendinning up to 1846 ppm occur within the mineralised fracture system due to sphalerite. However, away from the mineralised vein Zn is correlated with Pb and Sb but inversely with Ni, As and Co (Duller et al., 1997). This indicates the narrow zones of Zn enrichment reflect

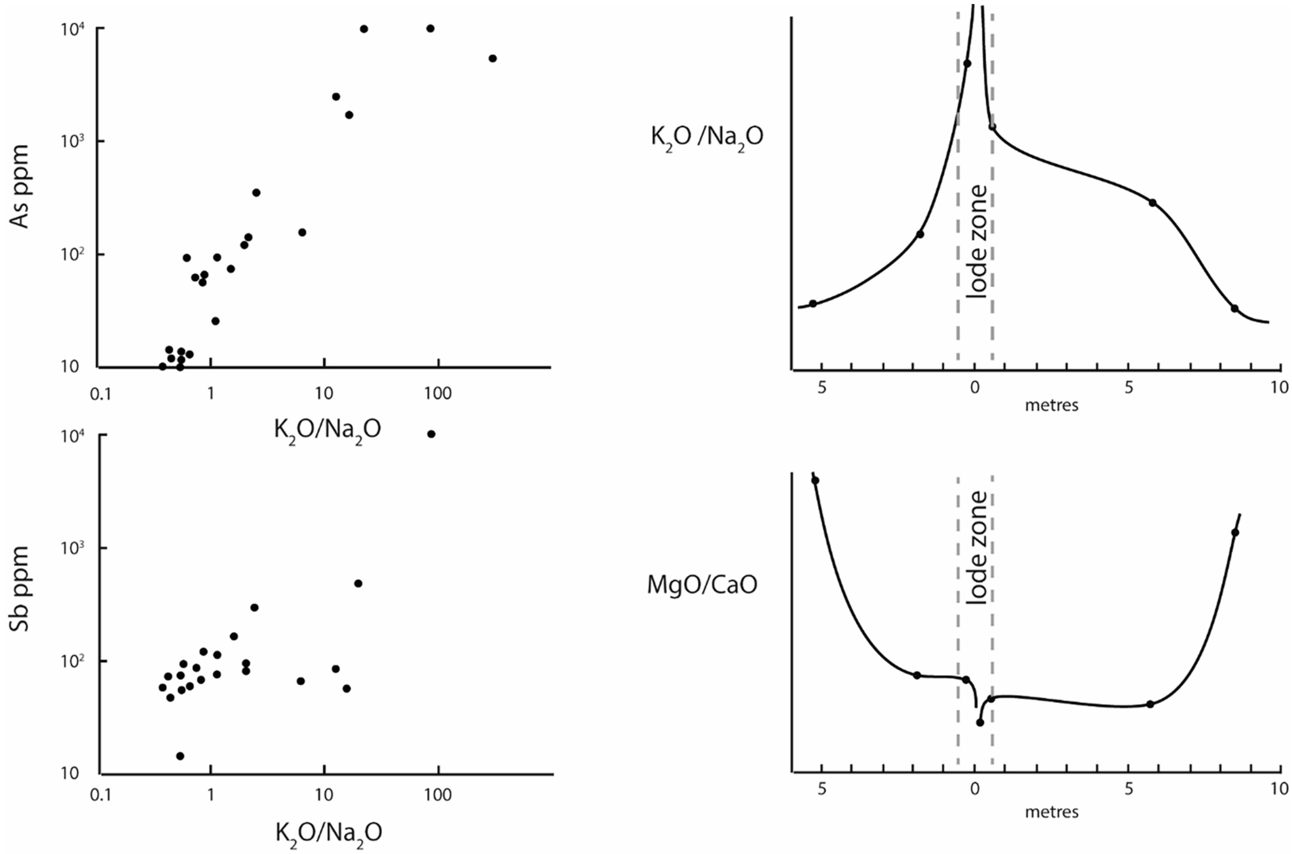


Fig. 11. Geochemical plots of rock samples from Clontibret: (a) As ppm vs K2O/Na2O, (b) Sb ppm vs K2O/Na2O, (c) K2O/Na2O 15 m profile across the main lode zone, (d) MgO/CaO 15 m profile across the main lode zone. After Morris et al. (1986).

late-stage sphalerite mineralisation superimposed on a wider zone of Zn depletion resulting from the early-stage As-Sb-Au mineralisation (Duller et al., 1997). However, the relationships of some elements are not consistent everywhere. For example, Zn is depleted in the lode at Glenhead, Black Stockarton Moor and Glendinning relative to background levels, but enriched at Clontibret; Mn is depleted in the lode zone relative to background levels at Glendining and Black Stockarton Moor but is enriched at Glenhead; Ni and Rb are also enriched at Clontibret but depleted at Black Stockarton Moor. These geochemical differences could reflect local differences in the degree of alteration and temperature due to the exhumed level of the mineralised system or distance from the mineralised lode or differences in primary lithology of the host rocks. For example, the Portpatrick Formation contains a relatively high proportion of pyroxene and spinel (Oliver et al., 2003) that would contain Pb and Zn respectively. Detailed, integrated mapping, isotopic and petrological studies could resolve these possibilities. In summary, the geochemical data are consistent with the mineralogical and structural evidence that gold mineralisation was associated with the peak of late Caledonian magmatic-hydrothermal potassic hydrothermal alteration.

7.6. Fluid inclusions

Two distinct mineralising fluids are recognised throughout the SUDLT at auriferous and base-metal (Cu, Pb, Zn) mineralised localities (Figs. 12 and 13, Table 3). The earlier quartz veins associated with gold mineralisation contain rare inclusions of a 2–3 phase carbonic fluid with high homogenisation temperatures (158–386 °C) and low salinity (0–11.7 wt% NaCl) interpreted as a metamorphic and/or magmatic fluid (Baron and Parnell, 2005, 2000; Moles and Nawaz, 1996). Veins containing auriferous arsenopyrite-pyrite and stibnite mineralisation at Clontibret contain three-phase fluid inclusions composed of aqueous liquid, CO_2 liquid and CO_2 vapour. Salinity of the aqueous phase is estimated to be between 2 and 4 wt% NaCl equivalent (Fig. 12) (Steed and Morris, 1986). Homogenisation temperatures from Clontibret are between 170 °C and 340 °C with a sharp peak at 290–300 °C (Steed and Morris, 1986). The calculated fluid temperature is ~330 °C based on an estimated minimum pressure of ~500 bars (Steed and Morris, 1986). At Glendinning fluid inclusions are rare in the early-stage arsenopyrite-quartz veins (Duller et al., 1997). Low-salinity (0–3 wt% NaCl equiv.), CO_2-rich, complex three-phase inclusions < 5 µm in diameter revealed temperatures in the range of 250–300 °C and periods of boiling, comparable to those estimated for Clontibret (Fig. 12) (Duller et al., 1997). Primary fluid inclusions in early quartz veins from Leadhills-Wanlockhead have low salinities in the range 2 to 8 wt% equivalent, some with very low salinities of 0.0 to 3.1 wt% equivalent (Figs. 12 and 13). Fluid homogenisation temperatures for early quartz veins at Leadhills-Wanlockhead are between 187 °C and 236 °C (Fig. 13) (Samson and Banks, 1988). Primary inclusions from greywacke-hosted veins at Black Stockarton Moor contain liquid and vapour with a salinity between 4 and 12% NaCl and homogenisation temperatures between 197 and 386° (Fig. 12) (Lowry et al., 1997). Primary fluid inclusions from intrusive-hosted veins at Black Stockarton Moor exhibited some remarkably high salinities (up to 52 wt% NaCl) and temperatures up to 468 °C (Lowry et al., 1997). Fluid inclusion data for veins from Moorbrock Hill, Hare Hill and Stobshiel contain carbonic 2- and 3-phase inclusions containing H_2O-CO_2-CO_2 vapour or H_2O + CO_2 vapour and exhibit low to moderate salinities in the range 0 to 9.24 equiv. wt% NaCl and have homogenisation temperatures between 190 and 250 °C (Naden and Caulfield, 1989), consistent with the data for the early vein stage from the other localities (Fig. 12). The properties of the relatively early fluid are consistent with a Caledonian magmatic-hydrothermal mineralising

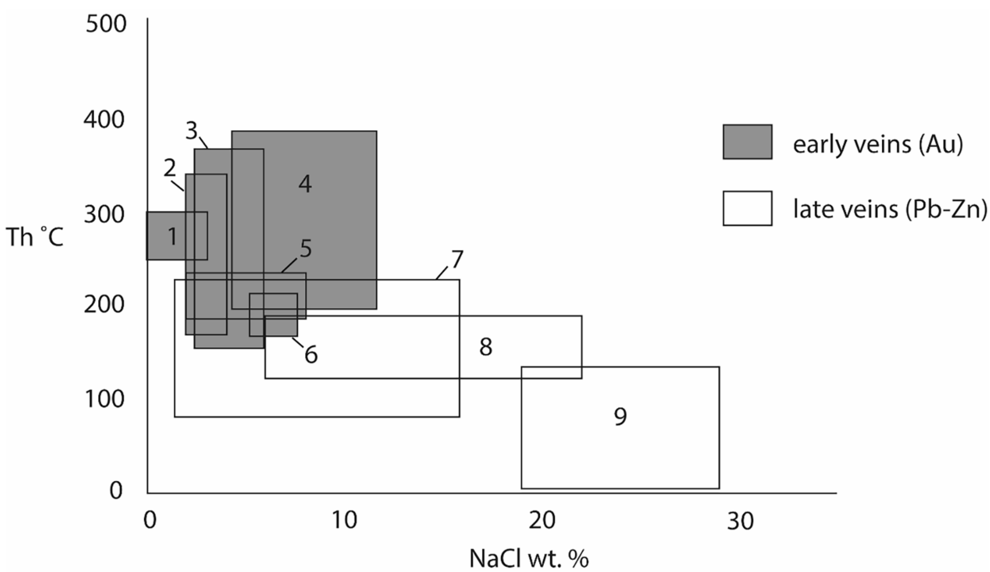


Fig. 12. Ranges of homogenisation temperature and salinity for fluid inclusions in early (Caledonian) auriferous veins and late Pb-Zn sulphide-bearing veins in the SUDLT. Ranges are based on published minimum and maximum values. However, available data are insufficient to plot individual data points. See Table 3 for data ranges and sources. Early veins: 1: Glendinning (Duller et al., 1997); 2: Clontibret (Steed and Morris, 1986); 3: Conlig-Whitespots and Castleward (Baron and Parnell, 2000); 4: Black Stockarton Moor (Lowry et al., 1997); 5: Leadhills-Wanlockhead (Samson and Banks, 1988); 6: Hare Hill (Samson and Banks, 1988); Late Pb-Zn veins: 7: Conlig-Whitespots and Castleward (Baron and Parnell, 2000); 8: Black Stockarton Moor (Lowry et al., 1997); 9: Southern Uplands (Leadhills-Wanlockhead, Woodhead, Hare Hill, Coldstream Burn, Blackcraig, Pibble and Enrick; Samson and Banks, 1988).

fluid that could have migrated along faults and fractures to form satellite deposits. The same type of fluid inclusions are identified in relatively early generations of veins at localities where gold has not been found, indicating that the gold-mineralising fluid flow event was widespread but generated only localised concentrations of gold. The relatively late, Pb-Zn sulphide veins throughout the SUDLT contain fluid inclusions with generally higher salinities and lower homogenisation temperatures (Figs. 12 and 13, Table 3) (Baron and Parnell, 2005; Samson and Banks, 1988). Late-stage quartz and dolomite from Conlig-Whitespots and Castleward (Fig. 2) contains two-phase H_2O-salt inclusions with salinities between 1.4 and 15.86 wt% NaCl equiv. and homogenisation temperatures 83 °C to 228 °C (Baron and Parnell, 2005). Inclusions in late-stage veins from Leadhills-Wanlockhead have lower homogenisation temperatures that range from 5 to 134 °C (Samson and Banks, 1988). Secondary inclusions from Black Stockarton Moor are CO_2-deficient, H_2O dominated, homogenise at 123–188 °C and have salinities up to 22 wt% equiv. NaCl (Fig. 12) (Lowry et al., 1997).

The data clearly reveal two distinct fluid types with distinct chemical compositions and representing markedly different physical conditions and, therefore, two distinct episodes of hydrothermal mineralisation (Figs. 12 and 13) (Baron and Parnell, 2005; Samson and Banks, 1988). These two fluids are recorded in gold-mineralised lodes within or genetically associated with late Caledonian igneous rocks and those within metasedimentary host rocks remote from any known igneous intrusions. Comparable distinct early and late mineralising fluids have also been identified in the Dalradian rocks of the Grampian Highlands Terrane, suggesting that these are more widespread, regional-scale hydrothermal events, not confined to the SUDLT (Baron and Parnell, 2000; Treagus et al., 1999; Wilkinson et al., 1999).

7.7. Sulphur isotopes

The total range of $\delta^{34}S$ values for hydrothermal sulphide mineralisation in the SUDLT is between −17.1 and +6.0‰ (Table 4). However, excluding values for Pb-Zn veins, Orchars and the Moffat Shale it is shown that sulphide associated with Caledonian gold concentrations in the SUDLT has a more restricted range between −4.9 and +6.0‰ (mean = +0.6‰) (Fig. 14). This range of values is significantly higher than, but overlaps with the $\delta^{34}S$ values for diagenetic sulphide in the Moffat Shale from Clontibret and Leadhills that range between −0.6 and −17.1‰ (mean = −8.4‰) (Fig. 14) (Anderson et al., 1989). Two samples of pyrite from unmineralised shale at Clontibret have $\delta^{34}S$ values of −15.1 and −15.7‰ (Fig. 14) (Anderson et al., 1989). The difference between the ranges for diagenetic sulphide for Leadhills and Clontibret is most easily explained if some of the samples of Moffat Shale from Leadhills were hydrothermally mineralised. This is considered likely, as pervasive deformation and veining

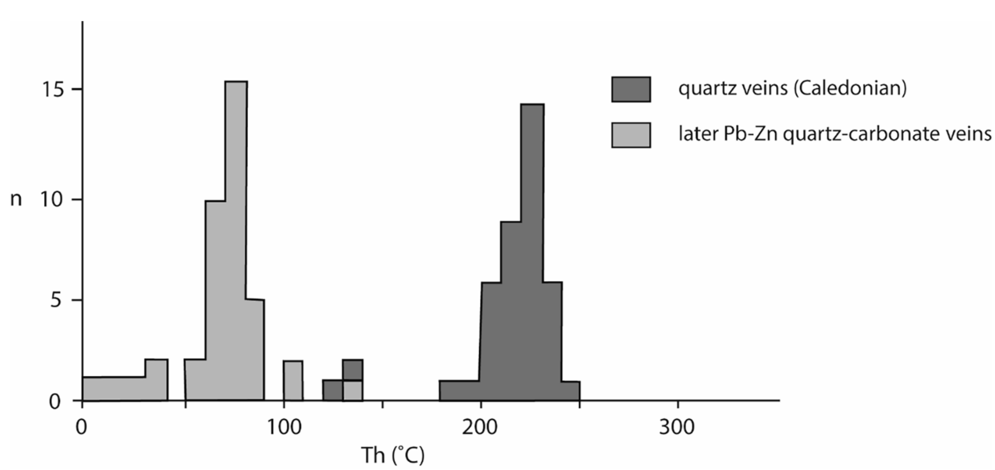


Fig. 13. Histograms showing homogenisation temperature data for fluid inclusions from 'early' (Caledonian) quartz veins and later Pb-Zn carbonate veins at Leadhills-Wanlockhead after Samson and Banks (1988).

Table 3
Summary of fluid inclusion data.

Early veins	NaCl min (wt%)	NaCl max (wt%)	t min (°C)	t max (°C)	Source
Clontibret	2	4	170	340	Steed and Morris (1986)
Glendinning	0	3	250	300	Duller et al. (1997)
Leadhills	2	8	187	236	Samson and Banks (1988)
Black Stockarton	4.4	11.7	197	386	Lowry et al. (1997)
Hare Hill	5.2	7.6	168	213	Samson and Banks (1988)
Castleward and Conlig	2.41	5.86	158	367	Baron and Parnell (2000)
late veins					
Southern Uplands	19	29	5	134	Samson and Banks (1988)
Black Stockarton	6	22	123	188	Lowry et al. (1997)
Castleward and Conlig	1.4	15.86	83	228	Baron and Parnell (2000)

are observed in the Moffat Shale in the Leadhills area (authors' unpublished data; Temple, 1956; Wilson and Flett, 1921), where it forms the decollement of the Leadhills Imbricate Zone and is, therefore, likely to have been the locus of hydrothermal fluid flow. This is supported by the observation that, at Clontibret, $\delta^{34}S$ values of hydrothermal sulphide within the lodes are consistently higher than for diagenetic pyrite in the unmineralised Moffat Shale (Fig. 14) (Steed and Morris, 1997).

$\delta^{34}S$ values for sulphide minerals from Orchars Vein within the Fleet pluton (Figs. 2 and 14, Table 2) are between −12 and −5‰; comparable with those for Pb-Zn veins at Leadhills-Wanlockhead (Anderson et al., 1989) and are, therefore, considered to reflect low temperature meteoric remobilisation during a significantly later episode of structural reactivation (Anderson et al., 1989; Baron and Parnell, 2000; Lowry et al., 1997; Lusty et al., 2011; Samson and Banks, 1988).

Excluding the Orchars Vein, the $\delta^{34}S$ values for sulphides in veins and wallrocks from gold-bearing localities in the SUDLT range between −4.9 and +6.0‰ (Fig. 14). With the exception of Clontibret and Glendinning, these data are from gold-bearing localities spatially associated with known significantly large intrusions. $\delta^{34}S$ values for gold occurrences spatially associated with known igneous intrusions fall in the range −4.9 to +2.8‰ (Fig. 14) (Lowry et al., 1997; Naden and Caulfield, 1989). Reported $\delta^{34}S$ values for Glendinning and Clontibret, taken together, exhibit an overlapping range from −3.95 to +6.0‰ (Fig. 14) (Duller et al., 1997; Steed and Morris, 1997). The narrow range of sulphide $\delta^{34}S$ from Glendinning, remote from any known intrusion, is very similar to that for a quartz vein at the contact of the Cairnsmore of Fleet granite and veins associated with intrusions at Cairngarroch Bay and Hare Hill (Fig. 2, Table 2) and overlap with the range of values for Clontibret, remote from any major intrusion. However, Clontibret exhibits a greater range of $\delta^{34}S$ that extends to higher values. Metasedimentary rocks are hornfelsed in the vicinity of Clontibret and minor Caledonian intrusions do occur, while Glendinning is in the area of the possible buried Tweedale Pluton, interpreted from gravity data (Stone et al., 2012).

Except for Black Stockarton Moor and Clontibret, the $\delta^{34}S$ values for hydrothermal pyrite from the gold-bearing localities fall within the upper part of the range for diagenetic pyrite in the Moffat shale (Anderson et al., 1989). However, the $\delta^{34}S$ range for hydrothermal sulphides indicates an external sulphur input, possibly of magmatic origin; either directly or by subsequent leaching of igneous rocks (Anderson et al., 1989; Duller et al., 1997; Lowry et al., 1997; Samson and Banks, 1988; Steed and Morris, 1997). This is supported by the observation that massive replacement sulphide in a diorite intrusion at Cairngarroch Bay exhibits more enriched $\delta^{34}S$ (mean −1.9‰) than arsenopyrite from associated quartz veins within the metawacke country rocks (mean −2.8‰) (Lowry et al., 1997). The overlapping ranges of diagenetic and hydrothermal S isotope values indicate that sulphides in the country rocks are likely to have dissolved in the circulating hydrothermal fluids (Lowry et al., 1997). Comparable S-isotope relations have been documented at Srón Garbh in the Scottish

Table 4
Summary of S-isotope data for mineralised localities described in the text.

Locality	Style	Mineral	$\delta^{34}S$ (‰)	Source
Glendinning	Disseminated (wallrock)	arsenopyrite	0.04	Duller et al. (1997)
Glendinning	Disseminated (wallrock)	pyrite	−2.81	Duller et al. (1997)
Glendinning	Microcrystalline (vein)	stibnite	−2.55	Duller et al. (1997)
Glendinning	Massive (vein)	stibnite	−2.81	Duller et al. (1997)
Glendinning	Granular (vein)	sphalerite	−2.74	Duller et al. (1997)
Hare Hill	(vein)	stibnite	−3.41	Duller et al. (1997)
Hare Hill		not-reported	−1.2	Naden and Caulfield (1989)
Hare Hill		not-reported	−4.9	Naden and Caulfield (1989)
Clontibret	(vein)	stibnite	−3.95	Duller et al. (1997)
Clontibret		stibnite	−2.7 to 0.2	Steed and Morris (1997)
Clontibret		arsenopyrite	−1.6 to 3.8	Steed and Morris (1997)
Clontibret		pyrite	−3.6 to 6.0	Steed and Morris (1997)
Clontibret		MFS	−15.7 to −15.1	Steed and Morris (1997)
Cairngarroch Bay		chalcopyrite	−3.2 to −1.34	Lowry (1991)
Cairngarroch Bay		pyrite	−2.7 to −1.32	Lowry (1991)
Fleet		arsenopyrite	−3.2 to −1.21	Lowry (1991)
Fleet		chalcopyrite	−1.82 to −1.12	Lowry (1991)
Fleet		pyrite	−2.59	Lowry (1991)
Orchars		chalcopyrite	−11.54 to −4.66	Lowry (1991)
Orchars		pyrite	−9.88 to −8.25	Lowry (1991)
Black Stockarton		pyrite	−0.06 to 2.8	Lowry (1991)
Black Stockarton		chalcopyrite	−0.96	Lowry (1991)
Leadhills	diagenetic	pyrite	−17.1 to −0.6	Anderson et al. (1989)
Leadhills	veins	galena	−10.3 to −8.1	Anderson et al. (1989)
Leadhills	veins	sphalerite	−5.9 to −5.1	Anderson et al. (1989)

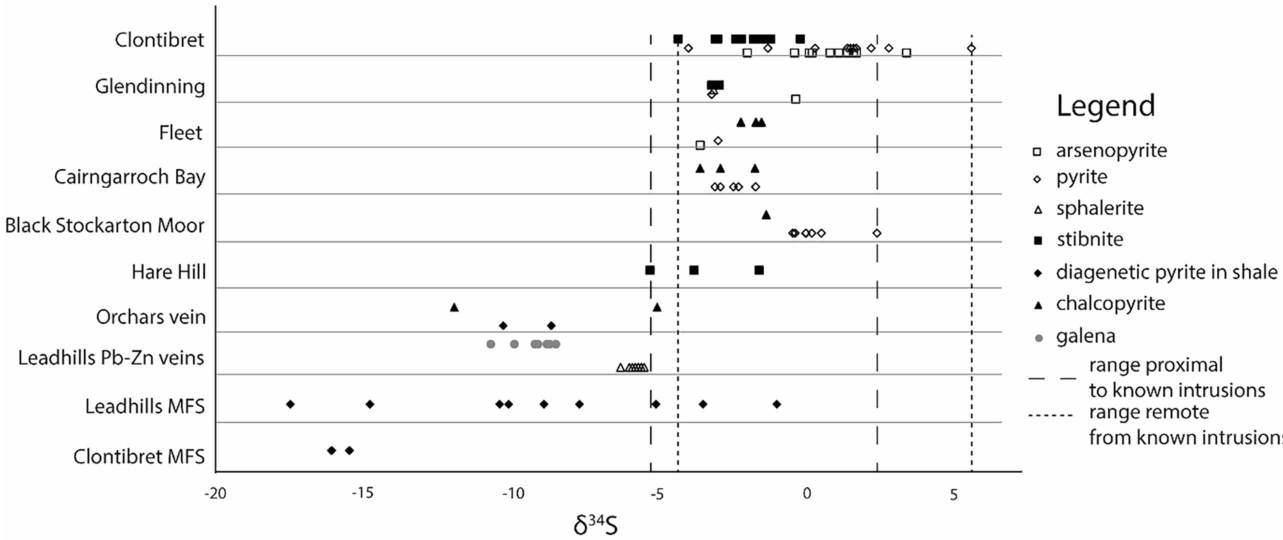


Fig. 14. Comparison of $\delta^{34}S$ for sulphides for Caledonian gold-bearing mineralised localities in the SUDLT, Leadhills Pb-Zn veins and diagenetic pyrite from shale (Moffat Shale; MFS) at Leadhills and Clontibret. Data from Lowry (1991), Steed and Morris (1997), Naden and Caulfield (1989), Duller et al. (1997), Anderson et al. (1989).

Grampian Highlands indicating comparable gold mineralising processes there (Graham et al., 2017; Hill et al., 2013).

7.8. Oxygen and hydrogen isotopes

Silicate minerals in the hydrothermally altered and mineralised zones exhibit higher $\delta^{18}O$ values than the unmineralised rocks (Naden and Caulfield, 1989). Measured δD and $\delta^{18}O$ values for minerals and fluid inclusions in early (Caledonian gold phase) and late (Pb-Zn-Cu) veins are shown in Fig. 15, together with calculated $\delta^{18}O$ values for the mineralising fluids. $\delta^{18}O$ was not reported for the early quartz veins at Leadhills.

The $\delta^{18}O$ and δD values for quartz veins at Cairngarroch Bay and Fleet fall clearly within the range for magmatic fluids and overlap with the field for metamorphic fluids (Lowry et al., 1997). The values from Clontibret correspond well with those for Fleet and Cairngarroch Bay, but here the calculated isotopic composition of the fluid falls outside the range for magmatic water. Fluid isotope values should not be considered to directly reflect the isotopic composition of the primary source fluid because fluid rock interaction greatly influences fluid isotopic compositions (Boehlke and Kistler, 1986). The narrow range of $\delta^{18}O$ values for Clontibret, Fleet and Cairngarroch Bay indicates that the Caledonian mineralising fluid is unlikely to have been an evolved meteoric fluid because fluid-rock interaction is not likely to produce such a narrow isotopic range (Steed and Morris, 1997).

Late base metal veins in the Southern Uplands have δD values between -40 and -70‰ and $\delta^{18}O$ values that range from -7.5 to $+6.5$‰ (Fig. 15) (Samson and Banks, 1988). The $\delta^{18}O$ value of one of

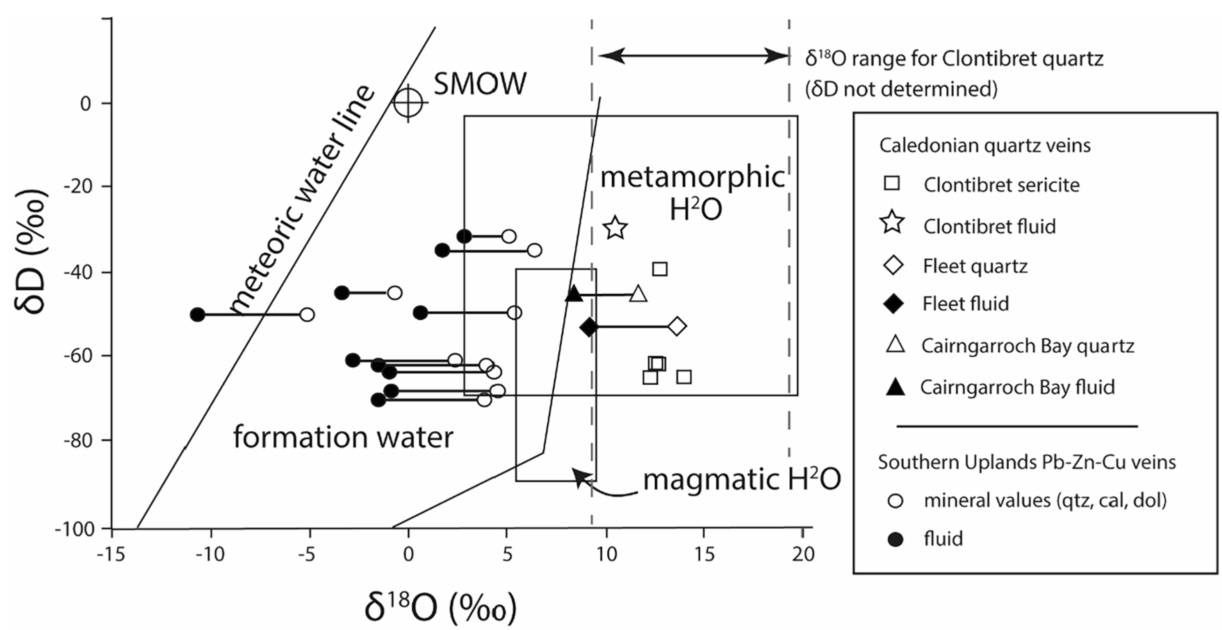


Fig. 15. Oxygen-hydrogen isotope relationships for mineralising fluids for Clontibret lode gold (after Steed and Morris, 1997), Fleet and Cairngarroch Bay (after Lowry et al., 1997) and Pb-Zn carbonate veins at Leadhills (after Samson and Banks, 1988). δD values for Leadhills from fluid inclusions. $\delta^{18}O$ values calculated from mineral values using fractionation factors and temperatures of 80–120 °C. Magmatic and meteoric water compositions from Taylor (1979). Meteoric water line from Craig (1961).

these samples is so low that it indicates a fluid $\delta^{18}O$ below the lower limit for meteoric water and is therefore unreliable. The measured δD constrains the minimum possible $\delta^{18}O$ value for the fluid to $-7.5‰$. These data indicate a minimum precipitation temperature of ~110 °C, which is consistent with the measured fluid inclusion homogenisation temperatures (Samson and Banks, 1988). On a regional scale, the range of δD and $\delta^{18}O$ values for the Southern Uplands Pb-Zn veins predominantly lie between the compositions of meteoric water and magmatic and metamorphic fluids (Samson and Banks, 1988). The very low calculated fluid δD for some of the Pb-Zn veins suggests that metamorphic fluids were not involved in the Pb-Zn mineralisation (Samson and Banks, 1988). This is consistent with the marked differences between the Pb-Zn veins and the Caledonian (Au) quartz veins in terms of fluid inclusion compositions and homogenisation temperatures. Mineral parageneses and vein cross-cutting relationships indicate that the Pb-Zn-Cu veins significantly post-date Caledonian mineralisation. Low fluid temperatures and a lack of consistent spatial correlation with igneous intrusions indicates that the late-stage fluid was of purely meteoric origin, isotopically modified by interaction with igneous and metamorphic rocks (Samson and Banks, 1988).

8. Discussion

This review of legacy data provides several new constraints on the nature and genesis of gold mineralisation in the SUDLT at the terrane-scale, including: (1) the lithological and structural relationships of gold mineralisation; (2) the mineralogical and geochemical characteristics and relationships of hydrothermal Au mineralisation; (3) the conditions of mineralisation and the origin of fluids and sulphur; (4) the timing of gold mineralisation relative to regional hydrothermal, magmatic and tectonic deformational events. From this, we set out below a genetic model for gold mineralisation in the SUDLT and assess the wider implications for gold mineralisation in the Caledonides of the British Isles and comparable tectonic settings worldwide.

8.1. Lithological controls

It has been suggested that host-rock lithology is an important control of gold mineralisation in the SUDLT (Lusty et al., 2012). The gold occurrences are concentrated in the Northern Belt (Fig. 2) and, therefore, exhibit a general spatial correlation with more metalliferous metasedimentary units (Lusty et al., 2012). This could reflect either local derivation of metals or chemical reactivity of the host rock. However, gold anomalies occur within a range of lithologies and with the exception of the Moffat Shale, which forms the locus of major shear-zones such as the Leadhills Fault, the gold occurrences do not exhibit any strong association with a particular staratigraphic unit (Lusty et al., 2012).

Gold occurs in proximity to outcrops of the Moffat Shale (and equivalent units in Ireland) in several areas e.g. Leadhills, Moorbrock Hilll, Clay Lake and Slieve Glah. Sheared black carbonaceous shales commonly host auriferous lodes within Phanerozoic and some Proterozoic orogenic gold deposits globally, e.g. the Ashanti Belt in the Birimian Shield of West Africa (Goldfarb et al., 2005, 2001; Groves et al., 2003; Oberthuer et al., 1996). The Moffat Shale represents a source of sulphur and metals as well as carbon, promoting gold mobility in aqueous fluid (Williams-Jones et al., 2009). Furthermore, due to its mechanical properties, the Moffat Shale has preferentially accommodated tectonic strain by acting as the principal decollement (Anderson, 2001; Leggett et al., 1982) and later, subvertical strike-slip shear-zones (Phillips et al., 1995) that provided a structural fluid conduit from depth and a likely favourable pathway for magma and/or gold-bearing hydrothermal fluids.

Gold mineralisation commonly exhibits a spatial association or structural relationship with late Caledonian TSS igneous rocks (Lowry et al., 1997). However, the relationship is not ubiquitous (Lusty et al., 2012). At some localities, e.g. Glendinning and Clay Lake, associated intrusions have not been identified. Minor intrusions have been identified in the vicinity of Leadhills and Clontibret (Boast and Harris, 1984; Morris et al., 1986; BGS 1: 10 000 scale geological mapping; authors unpublished data) and at some localities, e.g. Black Stockarton Moor and Glenhead, a genetic relationship between magmatism and hydrothermal gold mineralisation has been demonstrated (Brown et al., 1979; Leake et al., 1981). In detail, the relationships between the polyphase magmatism and gold mineralisation appear to be complex. Gold occurrences remote from significant igneous bodies exhibit remarkably similar mineralogy and geochemistry indicating that they share a common magmatic-hydrothermal origin (Duller et al., 1997). It is possible that intrusions occur in these areas but are buried or unexposed.

8.2. Structural controls

At the regional scale, gold occurrences are generally spatially associated with major D_1 shear zones e.g. the Southern Uplands Fault, the Leadhills Fault and the Orlock Bridge Fault and/or Moniaive Shear Zone (Fig. 2), especially where these structures intersect major steeply-dipping transverse D_3 faults. The second order ~N-S and ~NW-SE trending transverse faults control the mineralisation and orientation of the lodes at the prospect scale (Fig. 7). This is confirmed at several localities in the patterns of soil geochemical anomalies and drill-core (Beale, 1984; Boast et al., 1990; Charley et al., 1989; Conroy Gold and Natural Resources, 2014c; Duller et al., 1997; Morris et al., 1986). Comparison with regional structural data confirm that these correspond to ~N-S-striking sinistral strike-slip faults and ~NW-SE-striking dextral strike-slip faults (Fig. 6). Relationships between hydrothermal mineraliation and tectonic brecciation indicate that mineralisation occurred during initiation of these structures (Duller et al., 1997). The age of these structures and of gold mineralisation is constrained by cross-cutting relationships with dated rocks and is discussed below (8.5).

8.3. Conditions of mineralisation and multiple sources of hydrothermal fluids

Gold identified in bedrock in the SUDLT is associated with the earlier of two separate metallogenic hydrothermal events that are recognised throughout much of Scotland and Ireland including at mineralised localities in the Dalradian rocks of the Grampian Highlands Terrane e.g. Cononish (Fig. 1) (Baron and Parnell, 2005; Craw and Chamberlain, 1996; Curtis et al., 1993; Rice et al., 2016; Wilkinson et al., 1999). The later phase carries Pb-Zn-Ag mineralisation. Both phases are evidenced within individual lodes, demonstrating a common history of structural reactivation accompanied by fluid flow (Baron and Parnell, 2005).

Fluid inclusions in the relatively early, auriferous veins have moderate to high homogenisation temperatures (158–386 °C) and low salinities compatible with a magmatic-hydrothermal origin (Duller et al., 1997; Lowry et al., 1997; Naden and Caulfield, 1989; Steed and Morris, 1997). The homogenisation temperatures are also consistent with the low grade prehnite-pumpellyite metamorphic mineral assemblage in the metasedimentary rocks (Oliver, 1978), suggesting a Caledonian origin at depths of $<\sim 10$ km (Merriman and Roberts, 2000).

The low to moderate salinity and high CO_2 contents of fluid inclusions in the early auriferous veins indicate a partially magmatic source of fluid is highly likely (Duller et al., 1997; Lowry et al., 1997; Naden and Caulfield, 1989; Stone et al., 1995). This is consistent with the S-isotope data that indicate either mixing between magmatic-hydrothermal and metamorphic-derived fluids, or isotopic re-equilibration due to fluid-rock interaction. Some of the higher boiling temperatures of fluid inclusions from veins in the Southern Uplands within igneous host rocks are comparable to those for porphyry gold systems (Lowry et al., 1997; Naden and Caulfield, 1989). However, $\delta^{18}O$ values calculated for the primary ore fluid (e.g. +10.7‰ at Clontibret) are slightly above the range for magmatic waters +5.5 to +10.0‰ (Taylor, 1979). Although the fluid inclusion data alone do not preclude a metamorphic origin for the early fluid, most of the veins could have formed from a mixture of magmatic and formation waters. These results are comparable to S-isotope data that indicate a mixed metasedimentary and magmatic source of sulphide sulphur for gold mineralisation in the Tyndrum area of the Grampian Terrane (e.g. Cononish) (Hill et al., 2013).

Lowry et al. (1997) proposed that the secondary fluid inclusions are Caledonian in age and represent meteoric water that was heated by the intrusions and mixed with magmatic fluids; sulphide precipitation was caused by mixing between the two fluids. However, this is difficult to reconcile with the evidence for two consistently distinct fluid phases found in the veins regionally. The later fluid was a low temperature (< ~228 °C; Baron and Parnell, 2000; < ~150 °C; Samson and Banks, 1988), higher salinity (1.4–29 wt% NaCl), aqueous fluid, most likely to be of meteoric origin. The late stage fluid is interpreted as a basinal brine and represents markedly different physical conditions from the earlier gold-bearing fluid and is, therefore, interpreted as significantly younger (Figs. 12 and 13). The later, low temperature fluid could have occurred at any time after the Caledonian Orogeny. However, although data are lacking, it is considered likely that the late Pb-Zn mineralising event recognised throughout much of the British and Irish Caledonides is equivalent in age to the major, well-constrained, Carboniferous Pb-Zn mineralisation in Central Ireland (e.g. Silvermines) (Baron and Parnell, 2005, 2000; Ineson and Mitchell, 1974; Lowry et al., 1997; Moles and Nawaz, 1996; Samson and Banks, 1988; Temple, 1956; Wilkinson, 2003) which sourced sulphur and metals in the underlying Lower Palaeozoic metasediments of the SUDLT (Banks et al., 2002).

8.4. Role of magmatism in gold mineralisation in the SUDLT

Magmatic-derived mineralising hydrothermal fluids have been suggested in previous studies for several individual gold occurrences in the SUDLT: Glendinning (Duller et al., 1997), Black Stockarton Moor (Brown et al., 1979), Clontibret (Steed and Morris, 1997), Fore Burn (Charley et al., 1989), Hare Hill (Boast et al., 1990). Furthermore, magmatic-derived hydrothermal mineralising fluids have been implicated in late Caledonian (early Devonian) gold-mineralisation in the Grampian Terrane in Scotland (Graham et al., 2017; Hill et al., 2013) and for numerous deposits within orogenic gold belts globally, e.g. Mother Lode deposit, USA (Bierlein and Crowe, 2000; Steed and Morris, 1997), Wasamac and other deposits in the Abitibi Greenstone Belt, Canada (Meriaud and Jebrak, 2017), Otago, New Zealand (de Ronde et al., 2000).

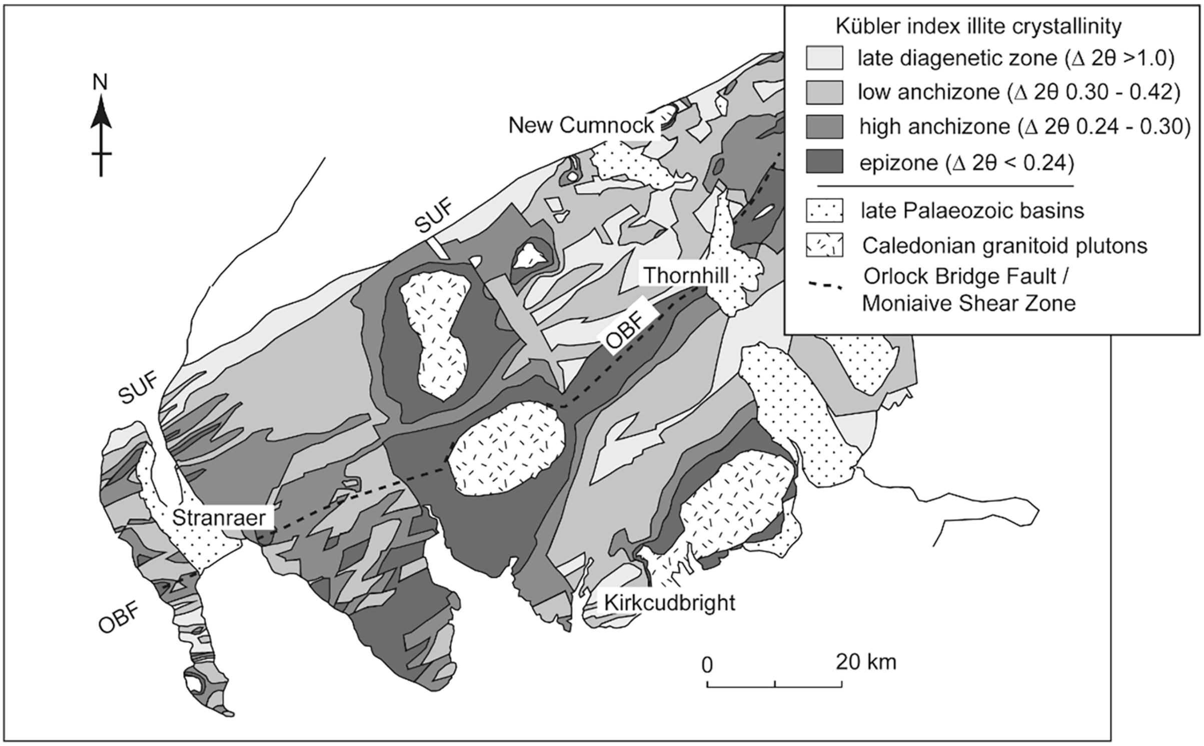
In the SUDLT, the apparent, although not ubiquitous, spatial association between mineralisation and large intrusive complexes may simply reflect the shared geodynamic setting and structural controls, rather than any direct genetic association (Goldfarb et al., 2005; Tomkins, 2013). Steed and Morris (1997) suggested that the spatial association could be explained by the enhanced capacity for brittle fracturing and vein development resulting from contact metamorphism. In contrast, Lowry et al. (1997), on the basis of isotope, fluid inclusion and mineralogical evidence, consider that the plutons were the source of heat but that fluids, sulphur and metals were mobilised from both the intrusions and the metasedimentary country rocks. Lowry et al. (1997) suggest that that the very low metamorphic grade of the metasedimentary rocks at the time of late Caledonian magmatism was an important factor controlling the ‘fertility’ of the terrane with respect to mineralising fluids.

Zonation of the alteration assemblages, comparable to porphyry-type deposits is recorded at some localities, but noted to be lacking at others (Allen et al., 1982; Boast et al., 1990; Brown et al., 1979; Duller et al., 1997; Morris et al., 1986; Steed and Morris, 1997), possibly due to subsequent deformation. Nevertheless, the geochemical enrichment and depletion accompanying peak phyllic-propylitic hydrothermal alteration associated with gold mineralised structures in the SUDLT is consistent with the potassic metasomatism expected from the interaction of a fluid derived from a potassic calc-alkaline magma (Allen et al., 1982; Boast et al., 1990; Brown et al., 1979; Duller et al., 1997; Leake et al., 1981; Shaw et al., 1995; Stanley et al., 1987; Steed and Morris, 1997). Furthermore, hydrofracturing, alteration and mineralization of country rocks immediately overlying minor intrusions at Glenhead Burn and Black Stockarton Moor (Fig. 9) clearly demonstrate that mineralisation here was directly related to shallow-level emplacement of granodiorites and monzonites. It is reasonable to conclude that gold lodes with the same paragenesis, alteration mineralogy and geochemistry remote from any significant exposed intrusion, e.g. Central Ireland, Glendinning and Leadhills (Fig. 2) (Boast and Harris, 1984; Duller et al., 1997; Morris et al., 1986) formed from the same magmatic-derived hydrothermal fluid.

Sulphur isotope values provide further support for a fundamental link between gold deposition and magmatism (Fig. 14) (Duller et al., 1997; Lowry et al., 1997). Subcrustal I-type magmatic sulphur, with $\delta^{34}S$ values −1 to +3‰, was the predominant source at Black Stockarton Moor, Cairngarroch Bay and Fleet, with a greater contribution of sedimentary sulphur (< 50%) evident in greywacke-hosted veins compared to intrusion-hosted veins (Lowry et al., 1997). A minor component of sedimentary sulphur is possible for the granitoid-hosted hydrothermal mineralisation, for which $\delta^{34}S$ values are mostly in the range −3 to 0‰ (Lowry et al., 1997).

The wide range of $\delta^{34}S$ values from hydrothermal gold mineralisation in the SUDLT is incompatible with a single source and supports a contribution of magmatic-derived fluid. The $\delta^{34}S$ values range between those for subcrustal magmatic sulphur and the strongly depleted sulphur of the SUDLT metasedimentary rocks (Moffat Shale). This could reflect either hydrothermal equilibration between fluids and host rocks and/or mixing between magmatic and metamorphic fluids. In the context of the SUDLT, the metamorphic fluids would most likely have been derived from contact metamorphic dewatering (Lowry, 1991; Lowry et al., 2005, 1997). A contribution of S from metasedimentary host rock sulphides during early Devonian vein gold mineralisation is also evident in the Grampian Terrane, evidenced by S-isotope data from the Tyndrum area (Graham et al., 2017; Hill et al., 2013). Here also, the S-isotope evidence suggests probable mixing between magmatic and metasedimentary host rock-derived S during early Devonian (~410 Ma) hydrothermal gold mineralisation (Graham et al., 2017; Hill et al., 2013; Rice et al., 2012; Treagus et al., 1999). In both areas, dissolution of sulphide in the fluid may have contributed to the capacity for the hydrothermal fluid to carry and transport gold-sulphide complexes in greater concentrations and over greater distances, enhancing the capacity for economic gold concentrations regionally.

There is no evidence for deep burial or melting or assimilation of SUDLT metasedimentary rocks to generate the TSS magma. In contrast, zircon Hf, O and Pb isotopes provide convincing evidence for a magmatic source in underplated Avalonian crustal rocks comparable to the Skiddaw Slate of the Lakesman Terrane, with no involvement of Southern Uplands material (Miles et al., 2014, 2016; Thirlwall, 1989). The apparent spatial and temporal association of gold mineralisation with the relatively early phase of more mafic, oxidised, I-type magmatism with a subcrustal S isotope signature may reflect the ability of oxidised magmas to supress early sulphide saturation and, therefore, have a greater potential to transport gold-sulphide complexes over greater vertical distances (Ishihara, 1981; Robb, 2005). Progressive melting and assimilation of sulphide-rich crustal metasedimentary rocks, e.g. Skiddaw Group, would be expected to lead to more reducing magma compositions and possibly eventual over-saturation with respect to sulphide, thus removing gold-sulphide complexes as a dense immiscible melt. This could account for the lack of gold associated with the relatively late, more silicic, S-type granitoid inner zones of the TSS plutons compared to the more reduced I-type rims.



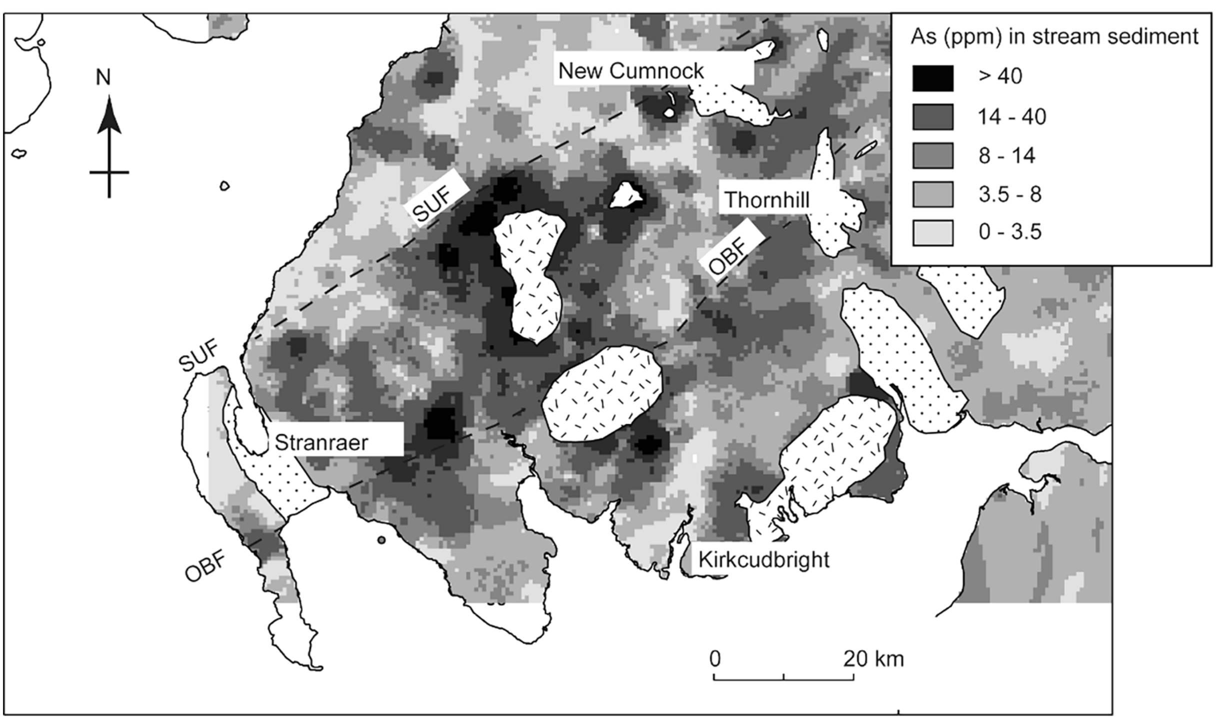


Fig. 16. (a) Contoured map of metamorphic grade in the central and western Southern Uplands, south-west Scotland after Merriman and Roberts (2000). (b) map of arsenic abundances in stream sediments (BGS G-base geochemical survey data ©NERC) interpolated using Kriging. SUF: Southern Uplands Fault. OBF: Orlock Bridge Fault. Basins and plutons shown as for (a).

There is no evidence that hydrothermal gold mineralisation is spatially associated with the Caledonian lamprophyres. However, a general spatial and temporal association between the lamprophyres, TSS intrusions and hydrothermal mineralisation is indicative that they were generated during the same tectonic event.

8.4.1. The significance of orthomagmatic mineralisation in the SUDLT

The Au-PGE-enriched orthomagmatic sulphide deposit within an appinite-diorite intrusion at Talnotry is a clear example of a magmatic source of gold, demonstrating that late Caledonian magmas were capable of transporting and concentrating precious metals (Power et al., 2004). The appinite is the coarser-grained (plutonic) equivalent of the calc-alkaline K-lamprophyres (vogesites and spessartites) which occur regionally. As such, in terms of its genesis, the PGE-enriched intrusion at Talnotry is comparable to other magmatic PGE-Au sulphide occurrences in Britain, most notably at Srón Garbh in the Grampian

Highlands, located close to the economically significant vein gold deposit at Cononish (Graham et al., 2017). For Srón Garbh, it has been demonstrated on the basis of petrographic, whole-rock and mineral geochemical data that metal enrichment of the magma resulted from low-degree partial melting of a metasomatically hydrated and fertilised mantle source. However, sulphide saturation resulted from assimilation of Dalradian metasedimentary country rocks (Graham et al., 2017). A tectonic model involving late Caledonian slab break-off has been proposed to account for the petrogenesis and mineralisation at Srón Garbh (Graham et al., 2017). The petrogenesis of the appinite-diorite at Talnotry is likely to be similar to that for Srón Garbh and a similar process is likely to account for the metal enrichment (Lowry et al., 1997; Power et al., 2004). However, appinites in the highlands have zircon U-Pb ages of 426–428 Ma (Neilson et al., 2009; Rogers and Dunning, 1991) and, therefore, slightly pre-date lamprophyric magmatism in the SUDLT which occurred between 418 and 400 Ma (Anderson, 1987; Rock et al., 1986). This is consistent with southwards propagating delamination of the sub-continental lithospheric mantle of the subducted Avalonian margin (Miles et al., 2016).

8.5. Age of gold mineralisation

As noted above, most of the gold localities in the SUDLT exhibit remarkably similar ore mineralogy, alteration assemblages, geochemistry and structural control. This suggests that they share a common origin and represent a single hydrothermal event. Furthermore, it this implies that observations that constrain the timing of mineralisation at one locality can be considered applicable other localities. At Glendinning there is structural evidence that hydrothermal alteration and auriferous sulphide deposition occurred during initial brecciation associated with the onset of D_3 deformation (Duller et al., 1997). The age of mineralisation is therefore constrained by the maximum age of the D_3 transverse faults. The age of transverse D_3 strike-slip faults is constrained by broadly contemporaneous lamprophyric dykes, dated between ~400 and ~418 Ma (MacDonald et al., 1985; Rock et al., 1986). Minor intrusions and hydrothermally altered rocks are hornfelsed in the contact metamorphic aureoles of the Criffel and Loch Doon plutons and are truncated by, and found as xenoliths within, the plutonic complexes, indicating that dyke emplacement and hydrothermal mineralisation preceded emplacement of the large plutons (Brown et al., 1979). However, auriferous ~N-S veins occur within the relatively early dioritic rocks in the rim of the Loch Doon Plutonic Complex (Fig. 10) (Leake et al., 1981). These relationships indicate that gold mineralisation was polyphased and overlapped with the progressive emplacement of the Loch Doon Plutonic Complex at 408 ± 2 Ma (Rb-Sr mineral and whole-rock ages) (Halliday et al., 1980). Locally preserved brecciation, hydraulic fracturing and alteration of metasedimentary rocks immediately above granodiorite sheets at Black Stockarton indicates that hydrothermal alteration and mineralisation were syn-magmatic (e.g. Black Stockarton Moor; Brown et al., 1979). The granodiorite sheets at Black Stockarton are cut by the 410 ± 6 Ma Criffel Pluton (zircon U-Pb age; Miles et al., 2014). Taken together, these observations indicate that gold mineralisation occurred between ~418 and ~410 Ma.

8.6. Tectonic-magmatic controls of metamorphism and hydrothermal mineralisation in the SUDLT

The very low metamorphic grade metasedimentary rocks of the SUDLT range from late diagenetic to epizone facies, indicating maximum temperatures of around 300 °C (Merriman and Roberts, 2000). The metasedimentary rocks exhibit an S_1 cleavage defined by phyllosilicates resulting from thrust-imbrication and tectonic burial within the subduction-accretion complex. The pattern of very low grade metamorphism in SW Scotland is shown in Fig. 16 and has been interpreted as the result of burial metamorphism during subduction-accretion (Merriman and Roberts, 2000). However, no consistent relationship is seen between metamorphic grade and the age or structural position of the rock units, as would be expected for burial metamorphism. The spatial pattern appears to reflect two controls; (1) contact metamorphism around plutons and; (2) major strike-slip shear zones, for example the Moniaive Shear Zone. The metamorphic map indicates that low grade metamorphism in the SUDLT was focussed by D_3 Caledonian shear zones and TSS intrusions. Porphyroblast textural relationships within the shear zone indicate that D_3 strike-slip movement overlapped with TSS magma emplacement (Miles et al., 2014, 2016; Phillips et al., 1995). The pattern of low-grade metamorphism, therefore, clearly postdates any very low-grade burial metamorphism associated with S_1 cleavage.

Several exploration geochemical studies in the SUDLT have established that arsenic is the strongest pathfinder element for gold (Boast et al., 1990; Boast and Harris, 1984; Charley et al., 1989; Duller et al., 1997; Steed and Morris, 1997). BGS stream sediment geochemical survey data (G-Base) for arsenic were plotted in a GIS and compared with the map of variations in very low-grade metamorphism (Fig. 16). The spatial distribution of arsenic anomalies in stream sediments and variations in metamorphic grade show a remarkable degree of similarity, suggesting a fundamental link between metamorphism and hydrothermal gold mineralisation. Auriferous hydrothermal mineralisation is, therefore, likely to have been coeval with very low-grade metamorphism and, therefore, also controlled by coeval magmatism and strike-slip deformation. The pattern exhibited by metamorphic grade and arsenic indicates that metamorphism and hydrothermal gold mineralisation post-date thrust imbrication of the subduction-accretion complex. The metamorphic map, therefore, supports syn-kinematic (D_3) hydrothermal metamorphism related to magmatism consistent with post-subduction recovery of a perturbed geothermal gradient and/or asthenospheric upwelling as documented in relation to post-subduction porphyry mineralisation in South Tibet (Section 8.7) (Hou et al., 2017, 2015).

The pattern of metamorphism in the SUDLT (Fig. 16) most probably reflects the activity of magmatic-hydrothermal fluids in both transferring heat to shallow levels and lowering the temperatures of metamorphic reactions by increasing the aH_2O (Jamtveit and Austrheim, 2010). In this way, at shallow crustal levels, hydrothermal fluids can localise low grade metamorphism around structural fluid pathways (Jamtveit and Austrheim, 2010; Robb, 2005). Metamorphic grade contrasts across Caledonoid structures could, therefore, be explained by fault reactivation or permeability contrasts. Hydrothermally promoted prograde metamorphic reactions could, in turn, have produced additional fluids and released S and metals from the country rock. The temperature range, relative timing and structural controls of metamorphism are compatible with an epizonal orogenic-type gold mineralising system (Groves et al., 1998).

8.7. Gold mineralisation related to post-subduction magmatism

Groves et al. (1998) suggested that orogenic gold deposits cannot form at less than ~2.5 km depth due to gold solubility relationships below ~200 °C. However, the recognition of post-subduction porphyry Cu (Au) and epithermal vein gold deposits in orogenic settings (Hou et al., 2017, 2015; Richards, 2009) indicates that post-subduction magmatism may play an important role in extending the range of ore-forming environments in orogenic settings. Furthermore, post-subduction (or non-arc) porphyry deposits indicate the potential for overlapping conditions of ore-formation between orogenic, IRGS, porphyry, skarn and epithermal vein deposit types. This explains the overlap between deposit characteristics and the long-standing problem of their classification (Groves et al., 1998; McCuaig and Hronsky, 2014; Richards, 2009).

Gold mineralisation in the SUDLT, together with the Grampian Highlands (Graham et al., 2017), appears to provide a relatively underexplored example of mineralisation related to post-subduction magmatism. However, this hypothesis needs to be fully tested with new field and analytical data. In an alternative approach to exploring for a wide range of mineral deposit types at the regional scale, (McCuaig and Hronsky, 2014) advocate four critical elements of the general 'mineral system': (1) favourable lithospheric architecture; (2) transient geodynamics; (3) a fertile source and; (4) preservation potential. Irrespective of the fit to any particular deposit model, data from the SUDLT indicate a good match with these criteria.

There is growing recognition of the role of transient geodynamic scenarios in mineralising systems. For example, where changing plate-boundary kinematics during post-subduction slab break-off and sub-continental lithospheric mantle delamination cause pulses of anomalous heat, magmatism and hydrothermal activity. In soft collisional settings, where crustal thickening is insufficient to cause regional metamorphism to greenschist-amphibolite facies, such processes may be particularly important to facilitate the necessary mass and energy flux for gold mineralisation (McCuaig and Hronsky, 2014; Richards, 2009).

8.8. A geodynamic model for late Caledonian gold mineralisation in the SUDLT

In summary, this review demonstrates that gold mineralisation and phyllic-propylitic hydrothermal alteration in the SUDLT was broadly spatially and temporally associated with the pattern of peak low-grade metamorphism, major and minor intrusions and controlled, at the deposit scale, by discordant, steeply-dipping transverse D_3 strike-slip faults and fractures. Mineralisation occurred in sub-greenschist facies conditions in the upper crust probably at < 10 km depth and at temperatures between 300 and 400 °C (Merriman and Roberts, 2000), consistent with conditions in the upper crust during late Caledonian soft continental collision. The evidence for the timing of gold mineralisation in the SUDLT (see Section 8.5), taken together with the relatively well-constrained tectonic evolution of the British and Irish Caledonides, limits the range of possible geodynamic models.

Cross-cutting relationships between mineralised structures and dated igneous intrusions indicate that gold mineralisation occurred between ~418 and ~410 Ma and, therefore, closely followed final closure of Iapetus along the Solway Line (Dewey and Strachan, 2003; Miles et al., 2016). The area-weighted age spectra of the TSS granites show that their emplacement was modulated by alternating phases of transtension and transpression between ~426 and ~387 Ma (Miles et al., 2016; Rock et al., 1986). The TSS granites have a remarkably similar age distribution to the high Ba-Sr post-collisional granites in the Grampian Highlands to the NW (Miles et al., 2016; Neilson et al., 2009). There appears to be no significant difference in the timing of magmatism and hydrothermal gold mineralisation between the SUDLT and the Grampian Highlands in Scotland. In contrast, evidence from Curraghinalt in the Midland Valley Terrane in Northern Ireland indicates a Grampian age (~462–452 Ma) for hydrothermal gold mineralisation there (Rice et al., 2016).

Northward subduction of Iapetus beneath Laurentia, as recorded by the progressive sedimentation and deformation in the SUDLT between ~455 and ~420 Ma, immediately followed the Grampian deformation of terranes to the northwest (Oliver et al., 2003; Rushton et al., 1996; Stone, 2014). The calc-alkaline geochemistry of the TSS and Grampian granites indicates a subduction-influenced mantle source. However, their age clearly post-dates the termination of subduction of Iapetus oceanic lithosphere (Fig. 3). This, together with the high Ba-Sr geochemical signature of Grampian granites is compatible with slab break-off as the cause of melting (Fig. 17a) (Atherton and Ghani, 2002; Graham et al., 2017). However, Miles et al. (2016) point out that slab drop-off is difficult to reconcile with the observation that the TSS suite straddles the Iapetus Suture Zone. It is, therefore, most likely that mantle melting was promoted by delamination of the Avalonian lithospheric mantle following the arrival of the Avalonian margin at the subduction zone, as suggested by Atherton and Ghani (2002), Freeman et al. (1988), Graham et al. (2017) and Miles et al. (2016) (Fig. 17).

The Miles et al. (2016) model (Fig. 17c) suggests that the Avalonian sub-continental lithospheric mantle may have broken off completely from the Avalonian plate, exploiting a pre-existing south-dipping subduction zone. This would have allowed the asthenosphere to flow from south to north through the slab-window, comparable to the model of Graham et al. (2017) (Fig. 17a). However, the subduction-influenced character of the TSS and the isotopic evidence for an Avalonian crustal source (Miles et al., 2014, 2016) are also compatible with migration of asthenosphere from the north. This is also consistent with the slightly older ages obtained for appinites in the Scottish Grampian Highlands (Graham et al., 2017; Miles et al., 2016).

Geophysical evidence of post-subduction lithospheric mantle delamination elsewhere (Ikeda, 2000; van Hinsbergen et al., 2010) indicates that slab-pull force causes the lithospheric mantle of the down-going plate to delaminate as it sinks and retreats following collision, creating a space problem between it and the partially subducted continental crust. It, therefore, seems likely that lithospheric mantle delamination is inherent during soft continental collision, where the rate of overall plate convergence is less than the rate of slab retreat. In models of post-subduction magmatism and related magmatic-hydrothermal mineralisation lithospheric mantle delamination or slab drop-off causes asthenospheric upwelling and, in turn, partial melting of the overlying lithospheric mantle that has been metasomatically fertilised by the history of subduction (Atherton and Ghani, 2002; Graham et al., 2017; Hou et al., 2017, 2015). Following this model, the widely accepted north-dipping polarity of the Iapetus subduction zone means that melting of metasomatised Laurentian lithospheric mantle would more likely have been triggered by asthenosphere upwelling from the northwest. Migration of magmatism from north to south fits with the very slightly older magmatism in the Grampian Highlands (Miles et al., 2016) and is, therefore, the preferred model here (Fig. 18).

Fig. 18 illustrates our preferred model for the geodynamic context of hydrothermal gold mineralisation in the SUDLT. The Ordovician-Silurian history of northwest-dipping subduction of Iapetus Oceanic lithosphere beneath the Laurentian margin metasomatically enriched and fertilised the mantle wedge (Fig. 18a). Delamination of the Avalonian sub-continental lithospheric mantle began when the Avalonian margin began to underthrust Laurentia (Fig. 3). Progressive delamination caused asthenospheric mantle to flow and upwell from the northwest (Fig. 18b, c). The upwelling, hot asthenosphere, heated the Laurentian lithospheric mantle, causing low-degree partial melting to generate potassic calc-alkali lamprophyric magma. At roughly the same time, the transition from orthogonal subduction to transcurrent motion on the plate boundary initiated deeply-penetrating subvertical and intermittently dilatant structures along which the hot lamprophyric melts could rise rapidly (Fig. 18b, c). During their ascent, the hot lamprophyric melt transferred significant heat to the partially subducted Avalonian crust, causing it to partially melt to generate the calc-alkaline magma of the TSS granite suite (Fig. 18b, c). The rising magma exsolved a potassic magmatic-hydrothermal fluid that flowed along the active subvertical D_3 strike-slip faults and carried S, Au, As, Fe, Cu, Sb and other metals (Fig. 18c).

Our model explains how slab delamination of the Avalonian plate at ~420–405 Ma (Miles et al., 2016), together with regional transtension and, most probably, post-subduction thermal relaxation provided a favourable transient geodynamic scenario for gold mineralisation. The low amount of crustal thickening meant that the SUDLT was 'fertile' with respect to H_2O and resulted in low amounts of post-collisional exhumation, increasing the preservation potential of the shallow-level hydrothermal gold system.

9. Conclusions

This synthesis represents the first regional-scale review of gold

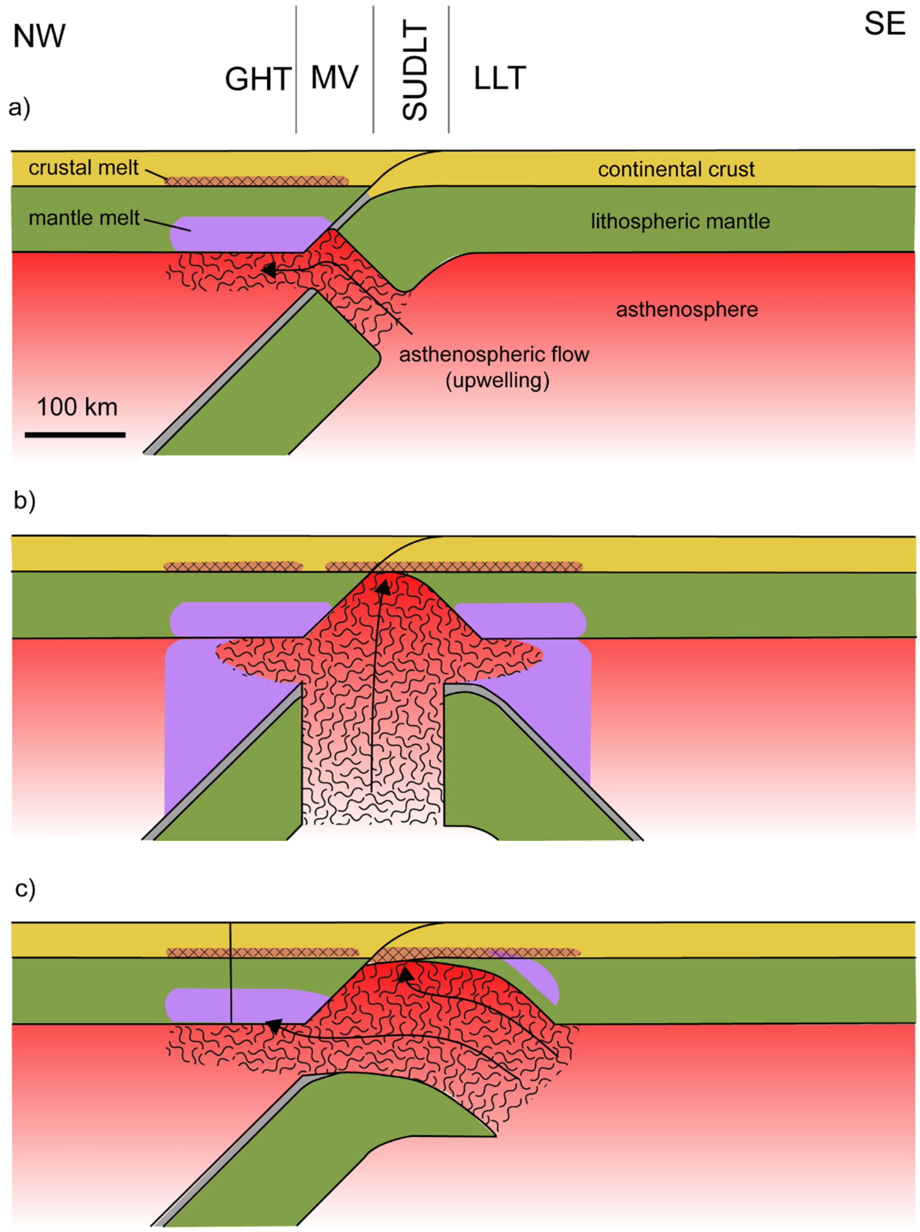


Fig. 17. Summary of tectonic geodynamic models proposed for late Caledonian magmatism: (a) Atherton and Ghani (2002), Graham et al. (2017), Neilson et al. (2009); (b) Oliver et al. (2008); (c) Miles et al. (2016).

mineralisation in the SUDLT. The individual occurrences, previously interpreted in terms of orogenic, porphyry and epithermal deposit types, exhibit a range of remarkably similar characteristics, indicating a common origin. Structural, mineralogical and rock relations, together with the correlation between the spatial distribution of As and very low metamorphic grade indicate gold mineralisation was spatially and temporally associated with the pattern of peak low-grade metamorphism, phyllic-propylitic hydrothermal alteration, major and minor TSS intrusions and is controlled, at the deposit scale by discordant, steeply-dipping transverse D_3 structures. Mineralisation occurred in sub-greenschist facies conditions in the upper crust probably at $<\sim 10$ km depth and at temperatures between ~150 and ~350 °C, consistent with conditions in the upper crust during Caledonian soft continental collision. Sulphur isotope values indicate that magmatic-hydrothermal fluid exsolved and mixed with hydrothermal fluids derived from contact metamorphic dewatering of the country rocks.

An Early Devonian age (~418 and ~410 Ma) is indicated for gold mineralisation; coeval with soft collision, regional transtension and lithospheric delamination (Dewey and Strachan, 2003; Miles et al., 2016). This scenario is supported by tectonic discrimination of lamprophyric minor intrusions in the SUDLT that indicate a post-subduction geodynamic setting.

Magma is considered to have an important role in hydrothermal mineralisation in soft collision zones, transferring energy (heat) and mass (fluids and metals) to shallow crustal levels, beyond the range traditionally indicated for orogenic gold deposits. Zones of soft continental collision, such as the Caledonides in the British Isles, where lithospheric mantle delamination and post-subduction magmatism are likely to occur are, therefore, considered to be inherently prospective for hydrothermal gold mineralisation for five reasons:

(1) Delamination of the lithospheric mantle from the crust of the down-going plate is considered likely to occur during soft continental collision due to the relatively slow rate of advance of the down-going plate relative to the rate of descent due to the negative buoyancy of the slab.

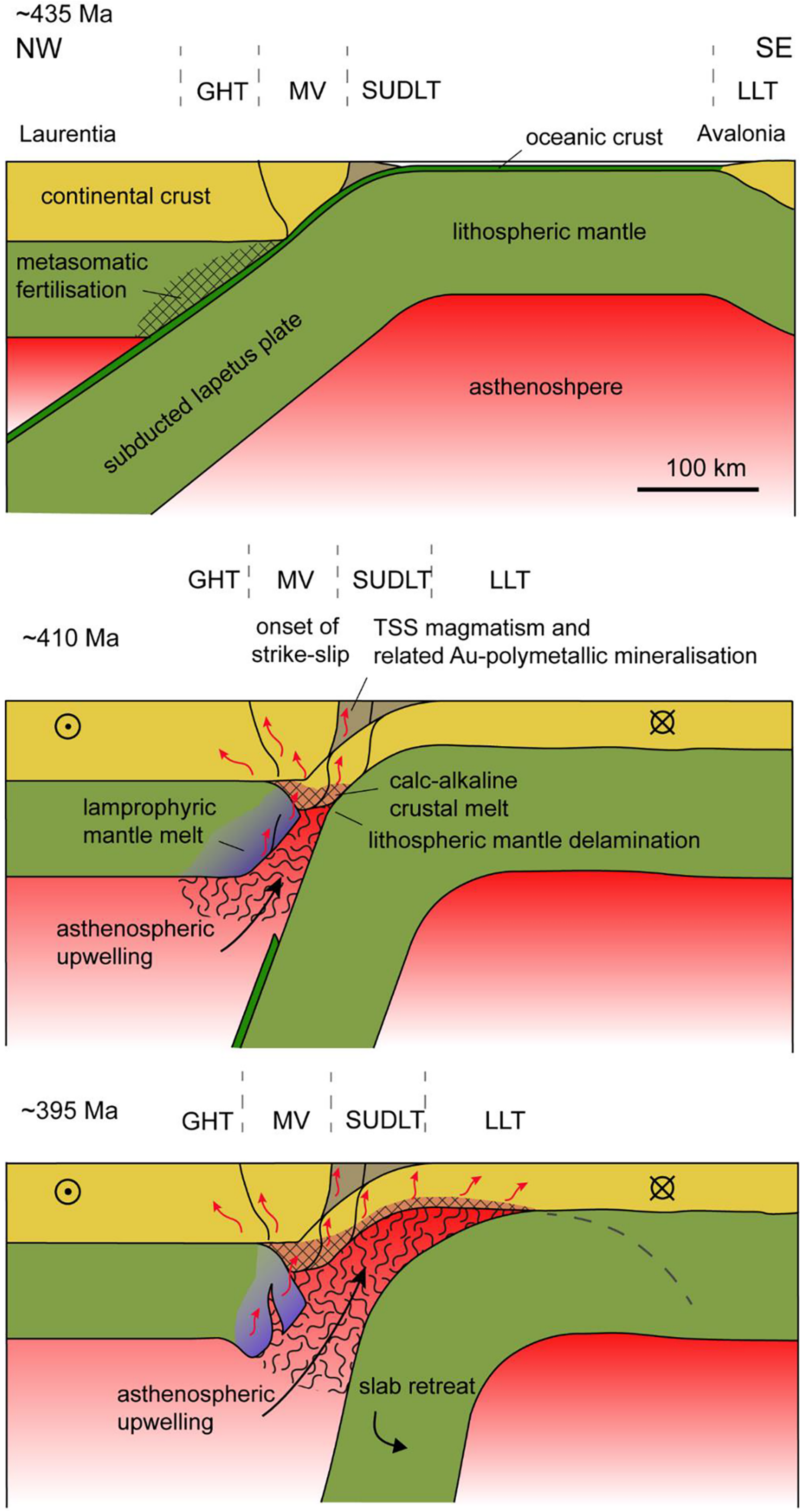


Fig. 18. Preferred model for the geodynamic setting and regional scale controls of late Caledonian gold mineralisation in the SUDLT and neighbouring areas (modified after Miles et al., 2016).

(2) The pre-collisional history of subduction metasomatically hydrates and fertilises the lithospheric mantle to provide a fertile source region; a critical element of a mineralising system that is inherent in collisional orogenic belts.
(3) Transient geodynamics, for example the change in deformation regime from orthogonal to strike-slip, are common during soft continental collision and are recognised as a critical element of mineralising systems.
(4) The switch to transpression and transtension provides a favourable lithospheric architecture for the effective and rapid flux of mass and energy from deep to shallow environments.
(5) Continental crust is unlikely to be subjected to significant tectonic thickening during soft collision, resulting in low degrees of subsequent exhumation and an increased preservation potential for high-level mineral deposits.

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