Geol. Mag. **151** (*6*), *2014*, *pp. 1072–1094*. © *Cambridge University Press 2014*
doi:10.1017/S0016756813001131

Structural controls and origin of gold–silver mineralization in the Grampian Terrane of Scotland and Ireland

P. W. GEOFF TANNER*

School of Geographical and Earth Sciences, University of Glasgow, Gregory Building, Lilybank Gardens, Glasgow G12 8QQ, UK

(*Received* 20 April 2013; *accepted* 19 December 2013; *first published online* 25 February 2014)

Abstract – Gold-bearing mineral deposits occur over a strike distance of >300 km within the Grampian Terrane of Scotland and Ireland. This terrane consists of Neoproterozoic–Lower Ordovician rocks of the Dalradian Supergroup that were polyphase deformed and metamorphosed during the *c*. 470 Ma Grampian Orogeny. Sulphide-rich Au–Ag deposits occur in Scotland at Calliachar–Urlar Burn, Tombuie, Tyndrum and Cononish, and in Ireland at Curraghinalt (Omagh), Cavanacaw, Croagh Patrick, Cregganbaun and Bohaun. They are hosted by 0.1–6 m thick quartz veins and have a similar overall mineralogy, including native gold, As, Cu, Fe, Pb and Sn sulphides, with hessite, tetrahedrite and electrum present in the first six localities above. The mineralized quartz veins, which are characterized by open-space textures, crystallized at *c*. 3–5 km depth in the crust. All of the deposits were structurally controlled and, apart from Curraghinalt, occur within second-order Riedel R, R′ and T fractures resulting from a regional N–S-trending maximum principal stress. These deposits are of Upper Silurian to Lower Devonian (post-Scandian) age, and are inferred to have crystallized from hot, silica-rich metamorphic fluids derived from dehydration reactions at the greenschist/amphibolite-facies boundary. Curraghinalt is an older, Grampian, thrust-related deposit. Plutonic igneous rocks (mainly granitoid) contributed in part to the fluids, which were channelled into major orogen-parallel, strike-slip faults, to be injected by fault-valve pumping into the damage zones and fault breccias of newly formed Riedel fractures. Any residual fluid probably percolated to the ground surface to form Rhynie chert-type hot-springs.

Keywords: Dalradian, Riedel, fracture, strike-slip, quartz vein, fluid, deposit.

1. Introduction

The first gold mine in Scotland, at Cononish in the Grampian Highlands (Fig. 1) will possibly commence production soon and it is timely to review the nature of this and other Au–Ag deposits in the Caledonides of Scotland and Ireland. They have many features in common, and the aim of this paper is to propose a possible genetic model to explain their origin. The deposits occur in Dalradian rocks of Neoproterozoic–Lower Ordovician age that form the Grampian Terrane (Fig. 1), and in Ordovician and Silurian rocks that lie unconformably upon them, which were folded prior to the injection of the gold-bearing quartz veins. The Dalradian rocks were affected by polyphase deformation (D1–4) during the ~ 470 Ma Grampian Orogeny (Oliver, 2001; Cooper *et al*. 2011; Hollis *et al*. 2012; Tanner, 2012).

Gold-bearing deposits with economic potential were first discovered in the Caledonides of Scotland and Ireland during a burst of exploration activity in the bonanza years, 1983–1989. The finding of *in situ* gold mineralization at Curraghinalt in the Sperrin Mountains of Northern Ireland in 1983 was followed by similar finds at Lecanvey (Croagh Patrick) (1984); Cononish (1985); Cavanacaw (1985); Urlar Burn (1988); Cregganbaun (1988); and Tombuie and Bohaun in the late 1980s (for locations, see Fig. 1). These deposits, hereafter referred to as the 'Grampian Au–Ag deposits', were nearly all located by well-tried prospecting techniques such as field mapping combined with the panning of stream sediments, and tracing of mineralized, gold-bearing float back to its source. However, as is commonly the case, the next phase, that of finding new major deposits by geochemical analysis of stream sediments and soils; channel sampling; and diamond core drilling, has since 1990 been largely unsuccessful. An analogous situation occurred in the world-class Charters Towers goldfield in NE Australia where, in 1871, nearly all of the economic gold deposits were located within two weeks of the initial discovery, and no significant lode-gold deposits have since been found (Kreuzer *et al*. 2007).

Commercial exploitation of the Grampian Au–Ag deposits has proved difficult. The mineral exploration licence for Lecanvey, in the Irish Republic, was withdrawn in 1990, as it is located on Croagh Patrick Mountain, which is a religious pilgrimage site. In 2007, following a protracted public enquiry, an opencast mine was opened at Cavanacaw in Northern Ireland. In 2012, Scotgold Resources were granted permission to commence mining at Cononish in Perthshire, Scotland. However, the initial planning application was rejected, largely because the deposit lies within the Loch Lomond and the Trossachs National Park, and there

---

*E-mail: geoff.tanner@virgin.net

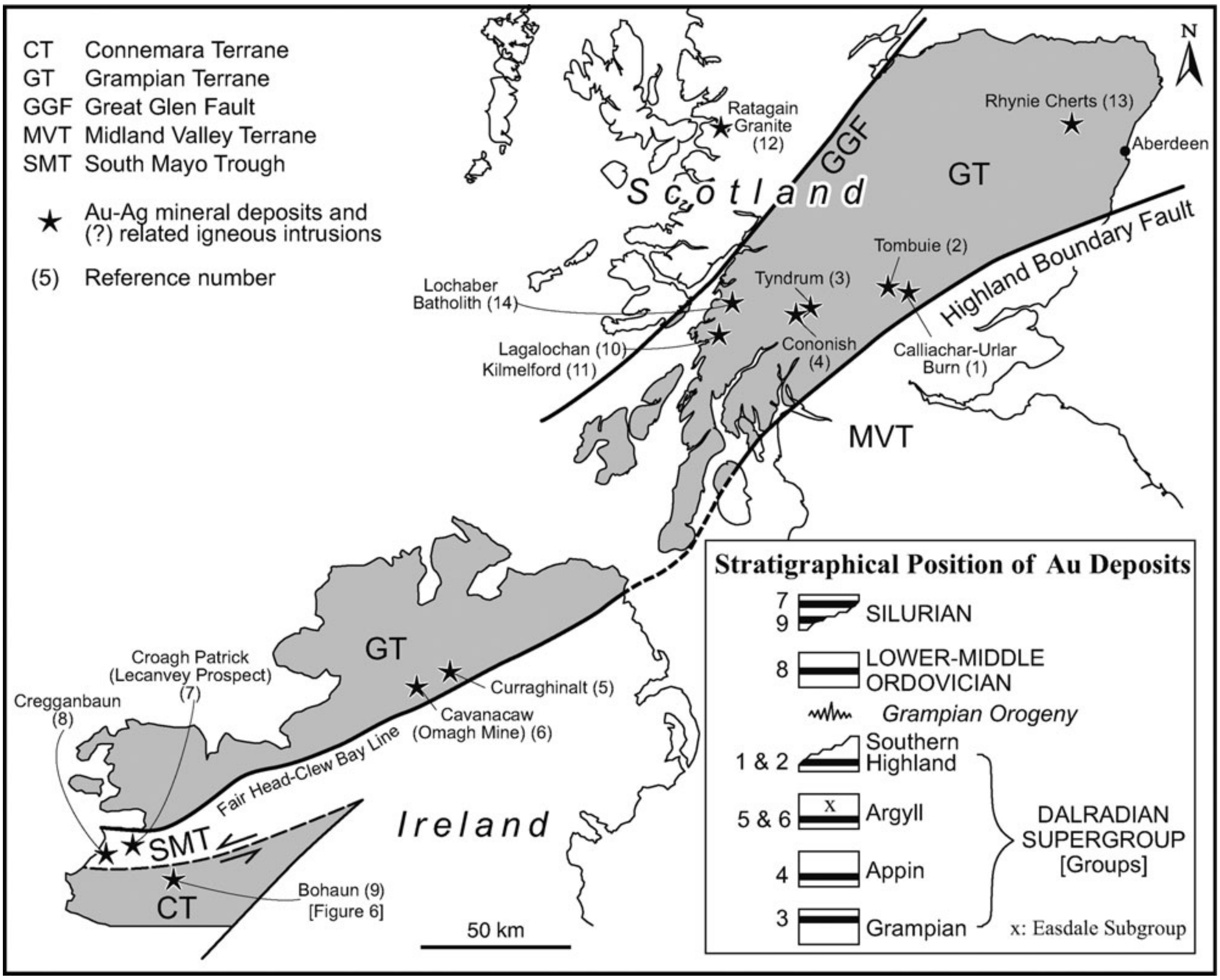

Figure 1. Outline map showing the names and locations of the gold-bearing mineral deposits (1–9), related igneous intrusions (10–12, 14) and the Rhynie cherts (13) in the Grampian Terrane (in grey) of Scotland and Ireland. The inset shows the approximate stratigraphic age of the host rock in each case (numbered as on the map).

were concerns about the environmental impact of mining in the area.

1.a. The stratigraphical setting

One specific feature of the stratigraphical succession merits special attention. The Dalradian Supergroup is divided into five groups (Fig. 1, inset), of which the Argyll Group records the first rifting event to presage the opening of the Iapetus Ocean. This event is recorded in the Easdale Subgroup by a sequence of sulphide-rich sediments, including two sedimentary exhalative sulphide (SedEx) deposits, and serpentine ostioliths and debris (Garson & Plant, 1973; Hall, 1993; Chew, 2001). Originally named the Pyrite Belt, this distinctive set of lithologies may be traced from NE Scotland to western Ireland. There are two main mineralized horizons, a lower Ba-rich horizon and an upper Pb–Zn–Cu–Ni-rich horizon (Fortey & Smith, 1986). The serpentine-bearing unit, characterized by the presence of fuchsite (chrome-rich muscovite), has been interpreted either as an ophiolite body (Garson & Plant, 1973), an intrusion (Hawson & Hall, 1987) or as a segment of serpentinized upper mantle or O–CT (ocean–continent transition) marking the floor of a transient rift basin (Chew, 2001).

The Ag–Au deposits occur in strata across the whole spectrum from Dalradian rocks of upper Proterozoic age, to Silurian rocks of Wenlock age, as shown on Figure 1 (inset). As the orebodies are structurally controlled, this is of lesser importance than the observation that most of them are linked in some way to one particular horizon, the Easdale Subgroup.

2. General features and mineralogy of the Ag–Au deposits

The Grampian Au–Ag mineralization is associated with quartz bodies that range in size from centimetre-thick veins, to quartz lodes up to 20 m thick, and are traceable for up to several kilometres. The thicker veins consist of massive quartz and/or quartz breccia with sulphide-rich, Au–Ag-bearing horizons. Open-space quartz textures have been reported from most of the deposits, and in the area around Tyndrum and Cononish (Tanner, 2012) (Fig. 1), the quartz breccia commonly consists of wallrock fragments encased in sheets of prismatic quartz crystals, forming a cockade texture (nomenclature after Vearncombe, 1993). Marginal alteration of the country rock varies from a slight 'bleaching', to metre-wide zones of chloritized, sericitized and silicified country rock. In several deposits, the introduction of K-feldspar has caused a pink-red colouration along each vein margin.

The mineralogy of the Grampian Au–Ag deposits in Scotland at Calliachar–Urlar Burn, Tombuie, Tyndrum and Cononish, and at Curraghinalt in Ireland (excluding quartz and gangue minerals), is as follows:

TYPE A: native Au + hessite (Ag_2Te) + electrum (Au, Ag) + tetrahedrite (Cu, Sb sulphosalt) + pyrite + chalcopyrite + arsenopyrite + galena + sphalerite.

(In addition, Bi minerals are present at Tombuie (Ixer, Pattrick & Stanley, 1997; Corkhill *et al.* 2010) and U minerals at Tyndrum (Pattrick, 1985).)

This is not a single, consanguineous mineral assemblage, as most of these deposits have had a long and complex history of mineralization. For example, two or three episodes of mineralization have been recognized in several of the deposits (Pattrick, 1985; Curtis *et al.* 1993; Wilkinson & Johnston, 1996), as well as up to four generations of quartz growth (Parnell *et al.* 2000).

The deposits in Scotland, at Calliachar–Urlar Burn, Tombuie, Tyndrum and Cononish, formed in Dalradian rocks at shallow levels in the Earth's crust (*c.* 3–5 km) and over a considerable temperature range (150–450 °C) (see Ixer, Pattrick & Stanley, 1997 and Treagus, Pattrick & Curtis, 1999 in addition to the references above). In Ireland, the mineralogy of the Curraghinalt veins is identical to that of the Scottish veins, but those from Croagh Patrick, Cregganbaun and Bohaun have a more restricted mineralogy, as follows:

TYPE B: native Au (with up to 41 wt % Ag) + pyrite + chalcopyrite ± other minor sulphides.

(In addition, the Bohaun deposit contains sericite, chlorite and haematite.)

The veins at Croagh Patrick, Cregganbaun and Bohaun are hosted by previously folded Ordovician or Silurian rocks. The latter lie unconformably upon Dalradian rocks, or in one instance (Bohaun) unconformably on previously deformed Ordovician rocks. They formed at a slightly higher level in the Earth's crust than the other veins, and at a lower mean temperature (175–320 °C).

The Curraghinalt structure in Northern Ireland differs from that of the other deposits, being probably controlled by structures related to late Grampian thrusting of the Dalradian rocks over Palaeozoic rocks to the SE (Parnell *et al.* 2000).

Despite the many fluid inclusion and stable isotope (H, O, S) studies that have been carried out on these deposits, there is a lack of agreement over the source of the fluids which gave rise to them, with Carboniferous basinal fluids (Lusty *et al.* 2011); plutons of 'Newer Granite' age (Curtis *et al.* 1993); the upper mantle (Ixer, Pattrick & Stanley, 1997); 'trapped' regional metamorphic fluids (Craw, 1990); and remobilized stratiform mineral deposits (Hall, 1985) having been invoked, with meteoric fluids also playing a crucial role (Craw & Chamberlain, 1996).

The aims of this study are to examine the possibility that the structural model proposed for the Cononish deposit (Tanner, 2012) can be applied to other Au–Ag deposits in the Scottish and Irish Caledonides, and, if possible, to determine whether or not these deposits had a common origin.

3. Transcurrent faulting: kinematics and nomenclature

The first step towards understanding the kinematics of faulting and fracturing in rocks was made by Coulomb in 1773, who concluded that when a rock is subjected to compressive stress, a conjugate pair of fractures develop that make an acute angle with the maximum principal stress, σ_1. The angle between the shear plane and σ_1 is given by $\theta = 45° \pm \phi/2$ (the Coulomb criterion), where ϕ is the internal angle of friction of the rock. In this paper, $\beta = \phi/2$, and is close to 30° for the average dry, intact crustal rock (Fig. 2a). Anderson's most important contribution lay in his recognition that the Earth's surface could not support a shear stress and is therefore a principal plane (Anderson, 1951). Faults and fractures that cut this 'free surface' are therefore restricted to three possible configurations, with each principal plane being in turn parallel to the Earth's surface.

Anderson (1951) used the Coulomb criterion to develop a pure shear (or Anderson–Coulomb) model for transcurrent or 'wrench faulting' (Fig. 2a), in which a conjugate pair of left- and right-lateral primary shear fractures (LS and RS, respectively), together with a set of extension fractures (XS), develop in response to a far-field stress, σ_{1R}. In explanatory Figure 2a, a hypothetical value for the strike of the left-lateral Y shear of 045° is used as an example, and illustrates that the fracture formed in response to σ_{1R} striking at 015°. Y is used to describe any plane parallel to the margin of the shear zone.

Moody & Hill (1956) extended this model to include second, third and higher order sets of fractures. They invoked several possible causes for the formation of these fractures, including 'stress reorientation in one fault block or a block between two parallel faults' (Moody & Hill, 1956, p. 1212), so anticipating the alternative model. During the same period, laboratory experiments by Riedel (1929), Cloos (1955) and later by Tchalenko (1970) provided the basis for a simple shear (or Riedel–Coulomb) model for transcurrent faulting (Fig. 2b, c), which differs from the pure shear model in that σ_{1R} gives rise to a secondary σ_{1S} at 45° to Y (the principal shear plane), which in turn is accompanied (potentially) by a further set of conjugate fractures. Other workers quantified different aspects of these two models: Hubbert & Rubey (1959) recognized the importance of pore

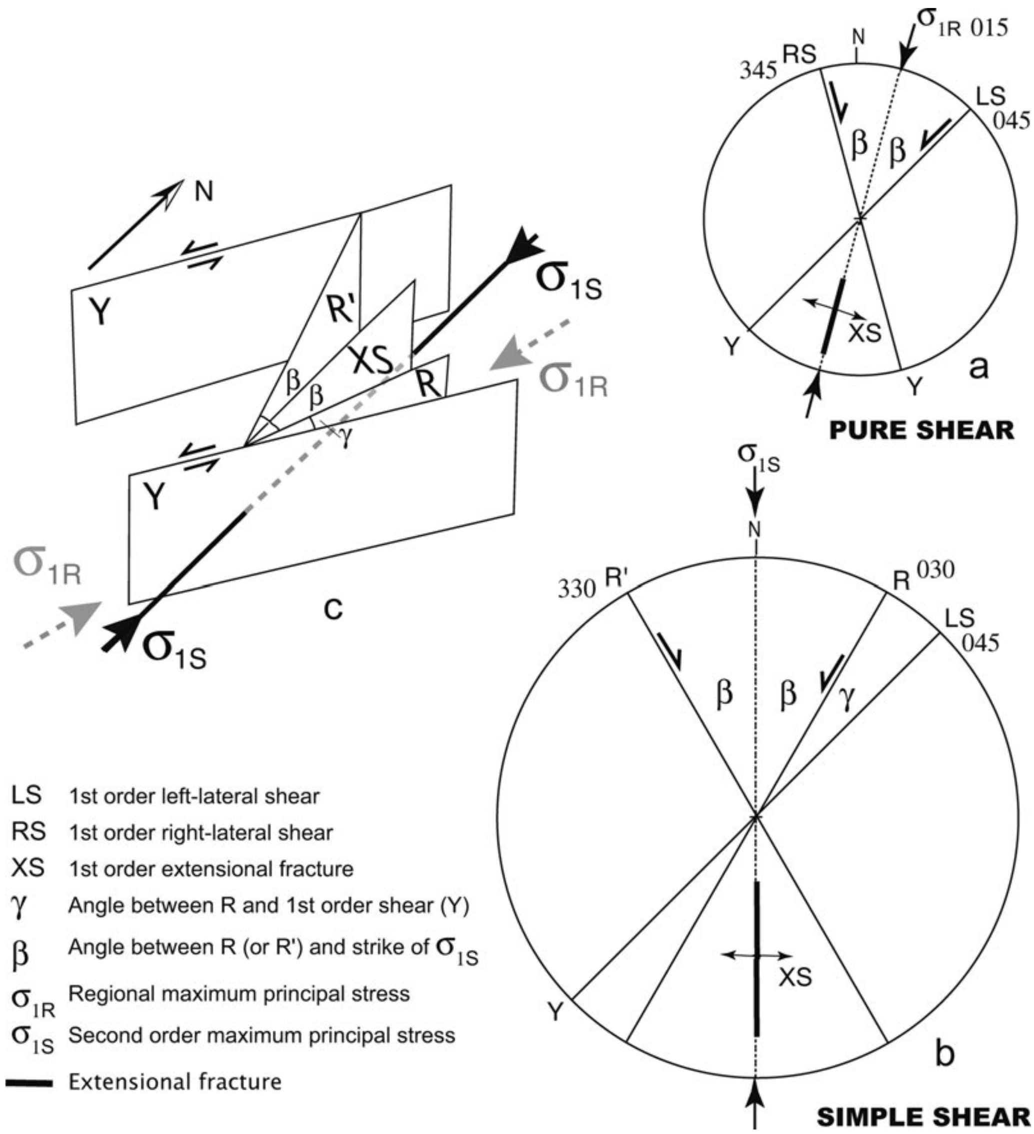

Figure 2. Pure shear (a) and simple shear (b) models for the development of major fractures in intact rock, according the Coulomb criterion. The two examples are based upon a notional left-lateral ‘Y’ shear (parallel to the margin of the shear zone) striking at 045°. Note that, on (b), the strike of the local secondary principal stress, σ_{1S}, lies 15° anticlockwise to the strike of the regional σ_{1R} (a). (c) A 3-D representation of (b), viewed from the SE.

fluids in reducing frictional resistance on a fracture surface; Griffith (1920) stressed the importance of microcracks in decreasing the strength of rock materials; and Secor (1965) demonstrated that overpressure in pore fluids could, in theory, permit extensional fractures to develop several kilometres below the Earth’s surface.

Sibson (2000) incorporated some of these concepts into the Sibson–Coulomb model (as named here), and demonstrated that β is reduced from 30° to 27° for fractures developed in the presence of a pore fluid. In this model, a pair of Riedel shear fractures, R (synthetic) & R′ (antithetic), form initially at $\beta = 27$–$30°$ to either side of σ_{1S}. They are accompanied, in some cases, by extensional fractures (T) parallel to σ_{1S} (Fig. 2b). β is used here for the angle seen in plan view, and β^* denotes the calculated maximum angle between the two structural elements. When applying one or other of these models to the Grampian Au–Ag deposits (see Section 7), it is important to appreciate that the regional or far-field stress, σ_{1R}, lies at an angle $\gamma = 15°$ anticlockwise to the secondary maximum principal stress, σ_{1S} (Fig. 2a, b). Because of a lack of published dip information at individual sites, strike-line diagrams are used in Figure 4 instead of stereograms. Faults and fractures are tacitly assumed, following Anderson (1951), to be vertical or nearly so. This is supported by the finding that 80 % of the faults in the Dalmally–Tyndrum area have a dip of $>65°$ (Tanner, 2012), and most of the large strike-slip faults are, on average, vertical, with the dip direction changing about the vertical along their length.

4. Geodynamic setting

The Grampian orogenic belt, which trends NE–SW across Scotland and the northern part of Ireland (Fig. 1), resulted, in Early Ordovician time, from either an arc–continent collision at the SE margin of Laurentia (Ryan & Dewey, 2011 and references therein), or from

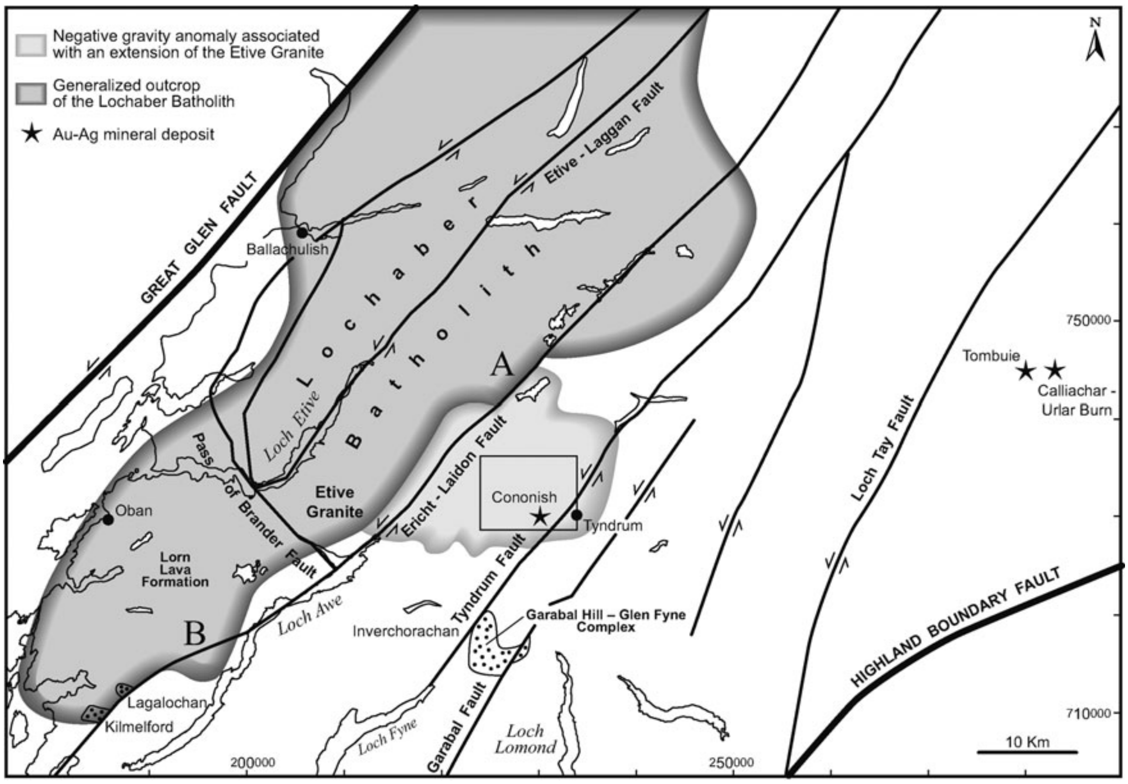

Figure 3. Map of part of the Central Highlands of Scotland showing the major, orogen-parallel, left-lateral faults of the ‘Great Glen’ set, and the negative gravity anomaly (palest grey), probably resulting from a buried extension of the Etive Granite at shallow depth beneath the Cononish area. An important feature of this map is that the long axis of the Lochaber Batholith lies parallel to the strike of the major transcurrent faults. A and B are localities mentioned in the text. The location of the Tyndrum–Dalmally area is shown boxed.

NW-directed subduction *beneath* this margin (Rose & Harris, 2000; Tanner, 2007, 2013). Details of the structural and regional metamorphic events that occurred in the short interval between 480 and 465 Ma ago (Oliver, 2001; Dewey, 2005) are not relevant here, but are to be found in Stephenson *et al*. (2013) and Tanner *et al*. (2013*a*,*b*).

Most of the previous models for the plate tectonic evolution of the Grampian Orogeny require that the leading edge of the Laurentian plate was being subducted beneath the Midland Valley Terrane to the SE during the Caradocian (~ 455 Ma), at which time subduction-flip took place (Atherton & Ghani, 2002 and references therein). Whichever model is favoured, it is generally agreed that once subduction-flip had occurred, NW-directed subduction continued until around 426 Ma (Atherton & Ghani, 2002; Neilson, Kokelaar & Crowley, 2009), whence it was halted by slab break-off and the emplacement of large volumes of intermediate and acid magmas, forming the ‘Newer Granites’.

This 426 Ma event is highly significant in the evolution of the Grampian Terrane as it was (1) the time at which large-scale fracturing of the Earth’s crust in the area being discussed changed from left-lateral transpression to orogen-parallel left-lateral transtension (Dewey & Strachan, 2003); (2) at this time that the Grampian Terrane in Scotland was divided into a series of compartments by NE-trending left-lateral transcurrent faults; (3) coeval with the post-Wenlock/pre-Early Devonian folding event, now recognized as being Scandian (Leake, in press).

The Garabal, Tyndrum, Ericht–Laidon and Etive–Laggan faults (Fig. 3) are broadly parallel to the Great Glen Fault and were probably contemporaneous with it for part of the period between 428 and 400 Ma (Neilson, Kokelaar & Crowley, 2009). Major faults that developed during the latter period, including the Great Glen Fault, had an extended and complex history, with some movement taking place prior to 426 Ma, followed by sticking of faults, stitching by plutons and subsequent rejuvenation (Treagus, 1991). A number of workers followed Watson (1984) in recognizing the causal relationship between these major faults and the emplacement of the Newer Granite suite (Hutton, 1987; Jacques & Reavy, 1994; Neilson, Kokelaar & Crowley, 2009).

New, high-precision radiometric dating, mainly by Re–Os on molybdenite (Neilson, Kokelaar & Crowley, 2009; Conliffe *et al*. 2010), has shown that the Lochaber Batholith (Neilson, Kokelaar & Crowley, 2009) (Fig. 3) was emplaced ~ 430–408 Ma ago. This coincided with the switch from transpression to transtension (Dewey & Strachan, 2003), when the compartments bounded by transcurrent faults would have been subjected to ‘pure’ simple shear and developed primary fractures with the angular relationships predicted by the Coulomb–Sibson model. Tanner (2012) concluded that the formation of the major sets of quartz veins described from the Tyndrum–Dalmally area took place at around 428–426 Ma, following the peak of the regional metamorphism in the Grampian Terrane at 470–465 Ma (Baxter, Ague & Depaolo, 2002), and the uplift and erosion of several tens of kilometres of Dalradian rocks. This estimate must now be upgraded to *c.* 410 Ma following recent radiometric dating (see Section 7.b), which shows that Si-rich fluids were being introduced into the Dalradian rocks at the same time as the youngest component of the Lochaber Batholith, the Starav dyke swarm, was being emplaced (Rice *et al.* 2013).

The Connemara Terrane represents part of the western continuation of the Grampian Terrane in western Ireland that has been moved southwards and translated to its present position by left-lateral transcurrent faulting late in the orogeny (Hutton & Dewey, 1986) (Fig. 1).

5. Salient features and structural controls of individual gold deposits

In the following accounts, the number in brackets is that assigned to each deposit on Figure 1.

5.a. Calliachar–Urlar Burn (1) and Tombuie (2)

These two small Type A Au–Ag deposits in Perthshire, Scotland, are considered together as they are only 4 km apart and both are hosted by psammites and semipelites of the Southern Highland Group (Dalradian) (Fig. 1. inset). They occur as mineralized quartz veins and fault breccias, with an almost identical mineralogy. The Loch Tay Fault is a major left-lateral transcurrent fault (Fig. 3) (Treagus, 1991), which passes 10 km west of the two deposits and trends at ~ 031° (Figs 3, 4).

The Calliachar–Urlar Burn mineral deposit occurs within the outcrop of the Southern Highland Group. Vertical cross-sections drawn close to the prospect (Treagus, 2000, figs 14, 18) show that the Easdale Subgroup is folded around a stack of recumbent D2 folds, the lowest of which, the Meall Tairneachan Fold, lies above the Boundary Slide. As a result of this folding, the Easdale Subgroup lies some 5 km below the surface in the Callichar Burn area, and a similar situation is found at Tombuie. The stratigraphical context is very similar to that at Cononish, where the Boundary Slide marking the structural top of the inverted Easdale Subgroup is 2–2.5 km below the surface.

The Calliachar–Urlar Burn deposit comprises 14 steeply dipping quartz veins up to 2 m thick with a mean trend of 152° (Ixer, Pattrick & Stanley, 1997, fig. 1). The veins are accompanied by extensive alteration of the country rock, seen in the field as sericitization, chloritization and ‘bleaching’. The Urlar Burn Fault trends at 016°, has a left-lateral displacement of 1.5 km and is occupied by a mineralized fault breccia up to 3 m thick. It postdates a felsite dyke and was later intruded by a microdiorite dyke (Ixer, Pattrick & Stanley, 1997).

The gold mineralization at Tombuie (Corkhill *et al.* 2010) is contained within quartz-carbonate veins that trend at 130–150°, and are associated with the NNE-trending Tombuie Fault, which shows both lateral and vertical displacements. Mineralization is of a type typically associated with a granitoid-derived hydrothermal fluid (Ixer, Pattrick & Stanley, 1997), and shows many geochemical features characteristic of the gold-bearing quartz vein system at Tyndrum.

Mineralization episodes. Only one episode of mineralization has been reported from each deposit.

Interpretation. Faults and fractures at Calliachar–Urlar Burn and Tombuie together form a conjugate pair (Ixer, Pattrick & Stanley, 1997) of Riedel shears with $\beta = 22$–$28°$, and R making an angle of 15° with the Loch Tay Fault (Fig. 4a), giving $\sigma_{1S} = 351°$. It is deduced that the mineralized veins at these two localities formed in a secondary stress field caused by left-lateral movement on the Loch Tay Fault (Fig. 4a).

5.b. Tyndrum Mine (3)

The Tyndrum base metal deposit lies on the Tyndrum Fault (Figs 3, 5) (Pattrick, 1985; Pattrick, Boyce & MacIntyre, 1988; Craw, 1990; Craw & Chamberlain, 1996; Treagus, Pattrick & Curtis, 1999; Tanner, 2012). It is marked by a shear zone 50–80 m thick of hydrothermally altered wallrock containing metre-scale mineralized quartz veins and the 1–5 m thick ‘Hard Vein’ of massive galena–sphalerite (Pattrick, 1985; Curtis *et al.* 1993; Treagus, Pattrick & Curtis, 1999), and is essentially a Pb–Zn deposit. The fault zone dips at 90 ± 15° SE, trends at 042° and has a left-lateral strike-slip displacement of > 4 km and a dip-slip displacement of 2 km down to the east (Treagus, 1991). Although it is structurally linked with the Cononish Au–Ag deposit (Treagus, Pattrick & Curtis, 1999; Tanner & Thomas, 2010; Tanner, 2012) (Fig. 4b), it generally yields low Au values.

The gold mineralization at Tyndrum is contained within Halliday’s Vein that consists of a mineralized quartz breccia that crops out in a stream a short distance NNE of the Tyndrum Pb–Zn mine. It is possibly related, both structurally and temporally, to the Cononish Vein, but no physical connection between them has been found.

Mineralization episodes. Three main episodes have been recognized, namely (1) quartz-bearing Au–Ag–Te mineralization (Pattrick, Boyce & MacIntyre 1988); (2) base metal Pb–Zn mineralization, which forms the major ore body in the Tyndrum Fault zone (Pattrick, 1985); and (3) rare U- and Ba-bearing veins (Pattrick, 1985).

Interpretation. The Tyndrum Pb–Zn deposit lies on a NE-trending primary strike-slip fault (Y) that forms the SE margin to the Tyndrum–Dalmally compartment (Fig. 5) (Tanner & Thomas, 2010) and is equated with the Lower Adit Vein at Cononish. Similarly, the Cononish Au-bearing vein is equated with Halliday’s Vein at Tyndrum.

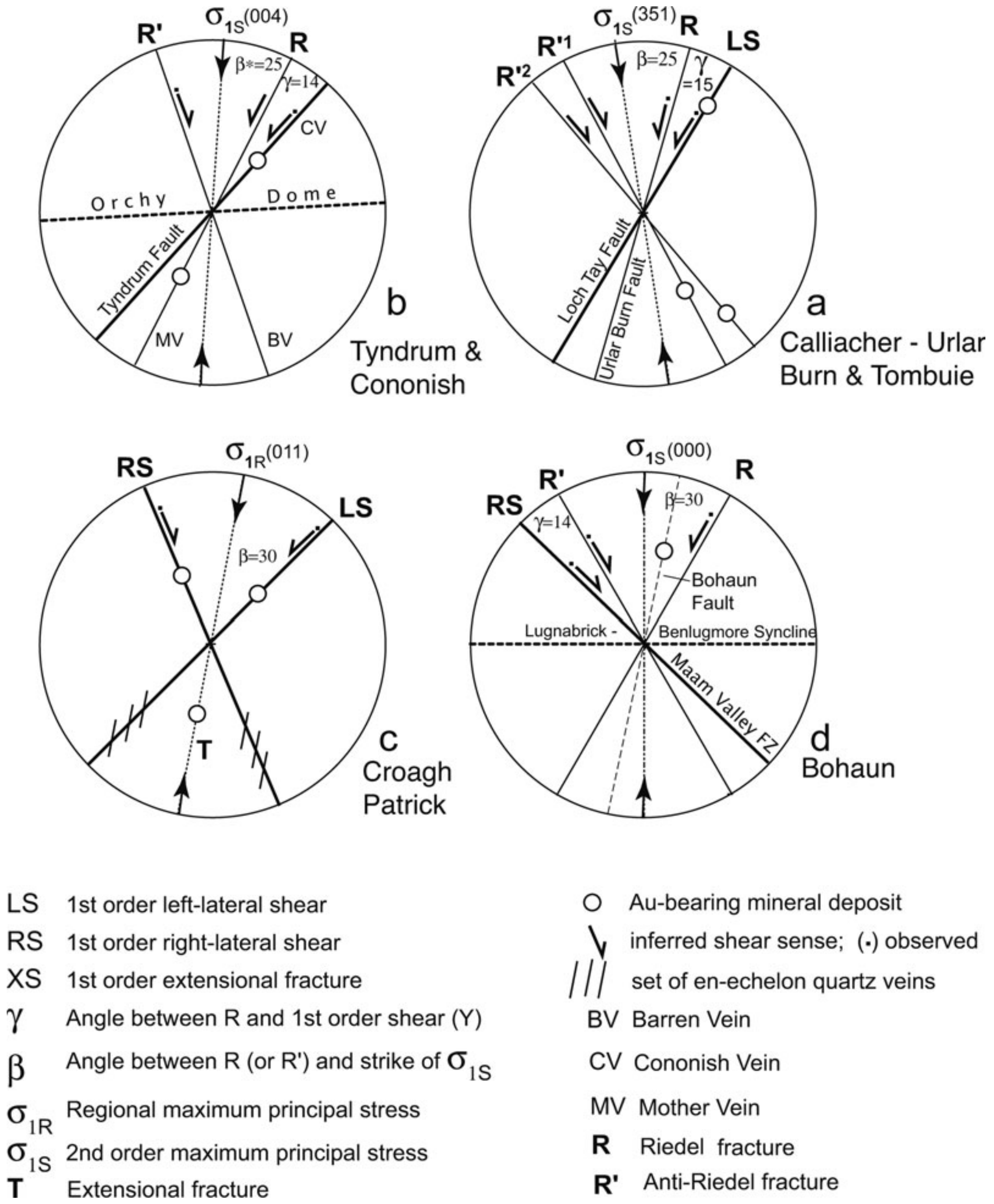

Figure 4. Strike-line diagrams showing the orientations of major structures at (a) Calliachar–Urlar Burn and Tombuie; (b) Tyndrum and Cononish; (c) Croagh Patrick; (d) Bohaun. The diagrams show how the mineralized veins (open circles) are located preferentially along secondary Riedel shears (R, R′) and some extensional fractures (T).

5.c. Cononish mineral deposit (4)

The Cononish deposit consists of a steeply dipping to vertical, mineralized quartz vein, up to 6 m thick (Parker, Clifford & Meldrum, 1989; Earls, Clifford & Meldrum, 1992; Curtis *et al*. 1993; Treagus, Pattrick & Curtis, 1999; Dominy *et al*. 2009; Hill *et al*. 2011; Tanner, 2012) that cuts the main foliation in the Dalradian rocks at a high angle, and can be traced for >1.5 km.

A late, regional-scale fold, the Orchy Dome (Bailey & Macgregor, 1912; Tanner & Thomas, 2010), which is probably of Scandian age (426 Ma, see below), dominates the structure of Dalradian rocks in this area (Fig. 5). This dome spatially controlled the emplacement of a suite of lamprophyre–appinite intrusions, which in the absence of the radiometric ages, were inferred to be 430–428 Ma old (Tanner, 2012). These intrusive bodies, which are associated with explosion breccia pipes, are cut by giant mineralized and non-mineralized quartz-breccia veins (Tanner, 2012) (Fig. 5).

The network of quartz-breccia veins in the Dalmally–Tyndrum area comprises a single, parallel set (Cononish set) and two separate conjugate sets (Figs 4b, 5a). The earlier of these conjugate sets, the proto-Mother Vein and River Vein pair, has $\beta = 30.5°$ ($\beta^* = 31°$), close to the value predicted by the Coulomb model for dry rock fractures, and $\gamma = 14°$, giving $\sigma_{1S} = 356°$. The later conjugate pair (Mother Vein – Barren Vein) has $\beta = 23°$ ($\beta^* = 25°$), close to the value predicted by the Coulomb–Sibson model for hydraulic fracturing, and $\gamma = 14°$, giving $\sigma_{1S} = 004°$ (Fig. 4b). Further details

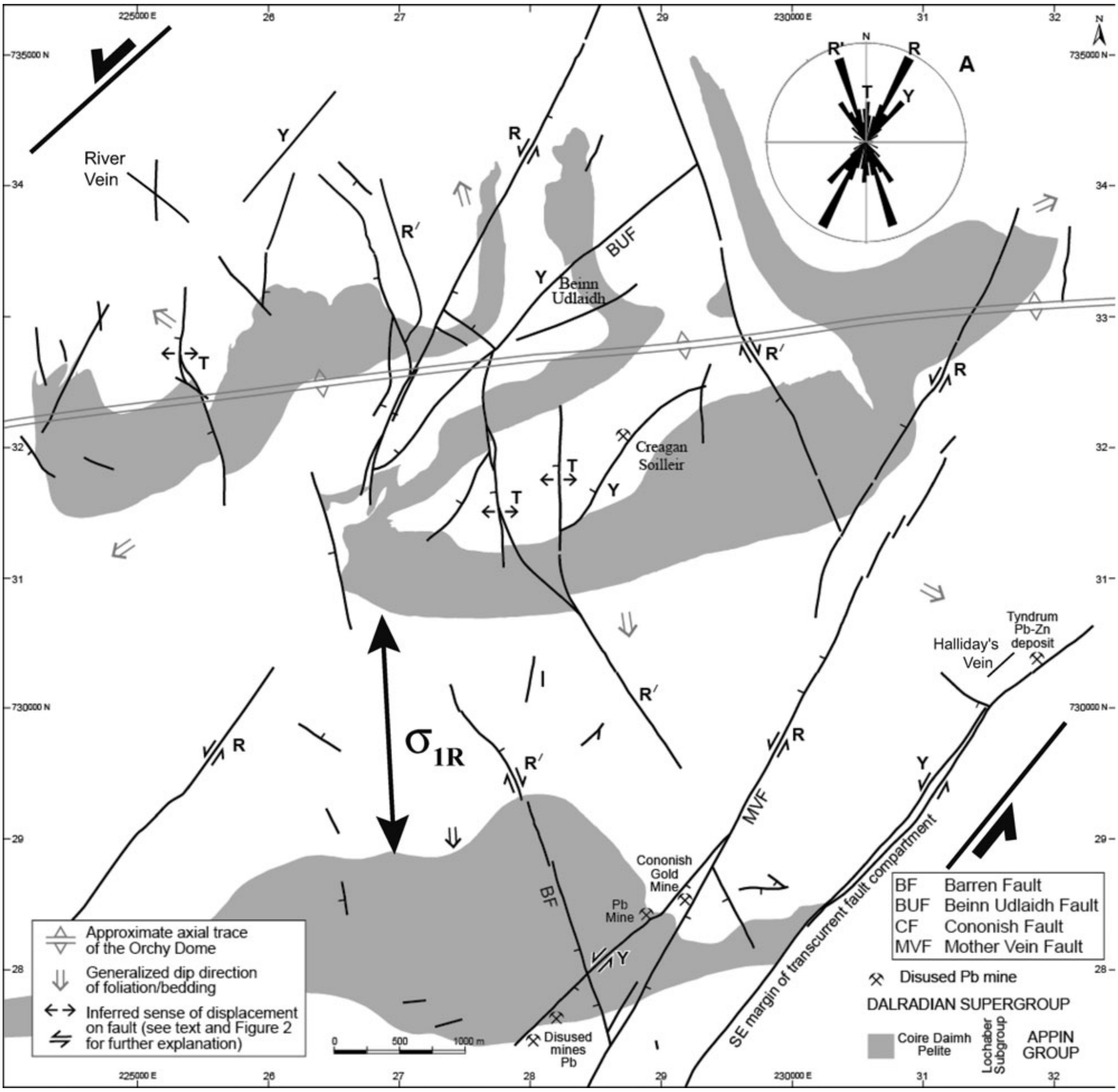

Figure 5. Geological map of the Tyndrum–Dalmally area, Scotland, showing the outcrop pattern of the Dalradian Coire Daimh Pelite (in grey), which is controlled by early major isoclinal folds, re-folded by the E–W-trending Orchy Dome, and cut by sets of major faults. The figure is based on figure 6 of Tanner (2012). The earliest faults and veins originated as 'Y' shears parallel to the Tyndrum Fault. They were followed by the development of secondary left-lateral Riedel and anti-Riedel shears, which form a conjugate set bisected by a N–S set of extensional fractures (T). The rose diagram (inset) shows the relationship between the total length of the mapped faults versus their strike direction, using a 2° interval. The bold half-arrows give the sense of displacement across the Dalmally–Tyndrum compartment. σ_{1R} is the calculated regional maximum principal stress.

of the structural geometry of the mineralized and non-mineralized veins from the Tyndrum–Dalmally area may be found in Tanner & Thomas (2010) and Tanner (2012).

The major Au–Ag deposit at Cononish is the mineralized portion of the Cononish Vein (Fig. 5), and is parallel to the Tyndrum Fault. Tanner (2012) concluded that the Cononish Vein set cuts the Orchy Dome, and that both the dome and the two sets of conjugate veins had formed in response to N–S shortening at around 428–426 Ma. The Easdale Subgroup is exposed in the south of the area; it is right-way-up, occupies the top limb of the southward-dipping Beinn Chuirn Anticline and rests upon the Boundary Slide. The now eroded continuation of the subgroup lies above the gold mine, but beneath the surface it passes around the hinge zones of three D2 folds to form a gently inclined, southward-dipping sheet, which lies *c.* 2.5 km vertically below the mine (Tanner, 2012, fig. 3f; Hill *et al.* 2013). As mentioned earlier, this structure is directly analogous in geometry and scale to that of the Calliachar–Urlar Burn deposit.

The giant quartz veins in the Cononish area preserve cockscomb, crustiform and vuggy textures that

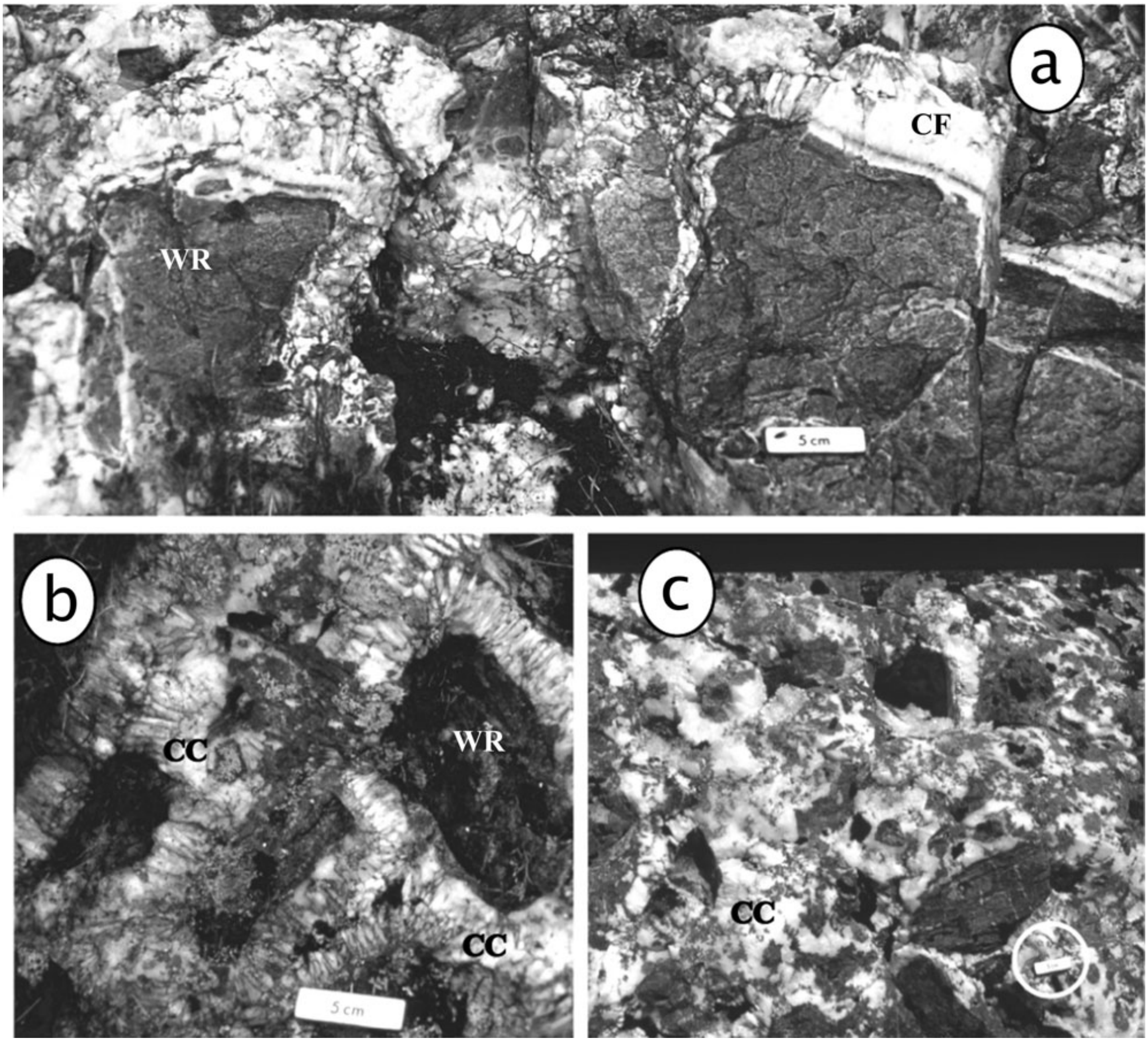

Figure 6. Open-space quartz fabrics in the giant Mother Vein from the Tyndrum–Dalmally area. They include: (a) breccia fragments (WR) encased within multiple generations of crack-fill (vuggy) veins, from the damage zone of the original fault, giving a crustiform texture (CF); (b) cockade texture (CC) from the interior part of the major vein; and (c) apparently massive quartz (with traces of cockades) containing angular fragments of the wallrock (WR). The scale bar is 5 cm long, ringed in (c).

are characteristic of open-space crystallization at a high level in the Earth's crust (Fig. 6). The minor quartz veins at Cononish are closely similar to those found in the external part of the Bohaun Vein (Lusty *et al*. 2011, fig. 4c, d). Cockade structures, in which country rock xenoliths are mantled by successive layers of quartz prisms orthogonal to the contact (Tanner, 2012, fig. 12) (Fig. 6b), are found in the interior of these veins, and resemble closely the texture found in the outer part of the quartz veins at Rhynie (Rice *et al.* 1995), with the difference that the layers there are composed of chert. The cores of these major veins commonly consist of a quartz-cemented breccia, as at Cononish (Fig. 6c), Bohaun (Lusty *et al*. 2011, fig. 4b) and Rhynie (Rice *et al.* 1995, fig. 12).

Mineralization episodes. There are two generally recognized mineralization episodes: (1) Au–Ag mineralization (the 'A-min') of Earls, Clifford & Meldrum (1992) at Cononish, which also occurs in the Beinn Udlaidh Vein; and (2) Pb–Zn mineralization ('B-min' or 'Lower Adit Vein'), which is generally associated with (1). The sequence of mineralizing events is undoubtedly more complex than this, but detailed petrographic, petrological or geochemical studies have yet to be carried out.

Interpretation. The quartz veins occupy fault planes that are identified as secondary R, R′ and T fractures, resulting from the shear stress imposed on a 15 km-wide crustal compartment by displacements on the Tyndrum and Ericht–Laidon major left-lateral transcurrent faults (Tanner, 2012) (Figs 3, 4b). The mineralized Cononish Vein probably formed first, as a Y-fracture parallel to the Tyndrum Fault (Figs 3, 4b), and was succeeded by the development of two sets of conjugate veins.

5.d. Curraghinalt (5)

Au–Ag mineral deposits hosted by quartz veins occur at Curraghinalt and Cavanacaw, in the Sperrin Mountains of County Tyrone, Northern Ireland (Fig. 1). They are occur 10 km apart in small, adjacent inliers of heavily faulted Dalradian rocks belonging to the Argyll Group (Fig. 1, inset), surrounded by strata of Lower Palaeozoic age. They are described separately as they differ in mineralogy, gold type and structure.

At Curraghinalt, the 'mineral deposit' occurs in Dalradian rocks correlated with the Easdale Subgroup and thrust SE onto Ordovician pillow lavas, and metasediments belonging to the Tyrone Igneous Complex (Alsop & Hutton, 1993). The 'deposit' comprises a number of parallel, steeply dipping to vertical, mineralized quartz veins that trend at 080°, are up to 2.7 m thick and may be traced for several kilometres (Earls, Clifford & Meldrum, 1992; Clifford, 1992; Parnell *et al.* 2000). They are parallel to near vertical E–W shear zones that are displaced by normal faults (Clifford, 1992; Parnell *et al.* 2000).

Mineralization episodes. Detailed studies of the Curraghinalt deposit by Wilkinson *et al.* (1999) and Parnell *et al.* (2000) showed that the vein complex developed in four stages, Q1–Q4. The earliest phase (equated with the Grampian event at 470 Ma) and Q3 and Q4 were thought to be caused by the circulation of brines associated with the inversion of the nearby Carboniferous Newtownstewart basin. The timing of the inferred '470 Ma event' has recently been modified by new ^{40}Ar–^{39}Ar ages of 461–449 Ma (Rice *et al.* 2013) from the Curraghinalt veins. They show that the veins formed after the peak of the regional metamorphism at 460 Ma, during the period when the orogen was beginning to collapse (Cooper *et al.* 2011).

At Curraghinalt, the major fractures appear to be controlled by a lateral ramp in the footwall to the E–W-trending Omagh Thrust, which underlies the area at a fairly shallow depth (Parnell *et al.* 2000) and is thought to have been active from around 460 Ma.

5.e. Cavanacaw (now Omagh Mine) (6)

The main feature of the Cavanacaw Au–Ag deposit in the Lack Inlier (Dalradian) is the N–S-trending quartz vein complex, the Kearney Structure (Cliff & Wolfenden, 1992). It is a steeply dipping 'structure' ~ 20 m across and 0.85 km long in which 16 named vein structures strike at 140° and dip steeply eastwards (Parker & Pearson, 2012). The veins locally reach 6.6 m in width and are accompanied by a selvedge several metres thick in which the wallrock has been sericitized and bleached. The Kearney vein structure may be interpreted as a T-fracture associated with the inferred N–S σ_{1R}. No mineralogical or geochemical studies have been carried out but the gold contains up to 2.5 parts of Ag to 1 part of Au and is associated with pyrite, chalcopyrite, arsenopyrite and galena (Parker & Pearson, 2012).

The Cavanacaw deposit is located in rocks originally thought to belong to the Southern Highland Group but have recently been correlated with the Easdale Subgroup (McFarlane, Cooper & Chew, 2009) that includes detrital serpentinite containing fuchsite, as in Scotland. The mineralogy of this deposit is not known in sufficient detail for it to be definitely assigned to Type A.

5.f. Croagh Patrick (7), South Mayo trough

This deposit, previously referred to as the Lecanvey Au–Ag prospect, is located 1–2 km west of Croagh Patrick (Fig. 1) (Aherne, Reynolds & Burke, 1992; Wilkinson & Johnston, 1996). Mineralized quartz veins cut the polyphase-deformed Silurian rocks that lie unconformably on the Ordovician Deer Park ophiolite in the footwall to the E–W-trending Omagh Thrust. In the Brocaigh zone (northern part of the prospect), gold mineralization is found in quartz veins that may be divided into three main sets: NNW–SSE- and NE–SW-trending veins that occupy shear zones, and E–W veins orientated parallel to S-directed thrusts.

The veins are generally 0.2–2.0 m thick (Johnston & McCaffrey, 1996) and where they occupy shear zones, they develop a set of en échelon 'feather veins' at ~ 30° to the strike of the zone (Fig. 4c) cut by a throughgoing thicker quartz vein (Fig. 4c). The large quartz veins have sigmoidal shapes, with the NE-trending set passing into the E–W-trending veins, suggesting contemporaneity. The quartz veins cut the Croagh Patrick Anticline, which is an isoclinal fold that verges and faces south, and is considered to have formed significantly earlier than the faulting and vein formation at this locality (Aherne, Reynolds & Burke, 1992).

Mineralization episodes. Multiple growth episodes were reported by Johnston & McCaffrey (1996), with five phases of quartz growth and fabric development being recognized.

Interpretation. The NNW- and NE-trending sets of quartz veins have an orientation, shear sense and $\beta = 30°$ (Fig. 4c), compatible with their being R and R′ shears (Aherne, Reynolds & Burke, 1992) that formed in response to σ_{1N} trending at 011°. Johnston (1992) attributed this system of shear fractures to late Caledonian left-lateral transpression across the Clew Bay – Fair Head Line (Fig. 1), but they could equally well be primary fractures, with the RS–LS fractures having formed synchronously with the E–W-trending, S-directed thrusts, as shown on Figure 4c.

5.g. Cregganbaun (8), South Mayo trough

This vein deposit is located in County Mayo (Fig. 1). It features a 10–14 m thick mineralized zone with quartz veins that trend E–W, but there is little published information available for this prospect. The Au-bearing quartz lode lies within the Cregganbaun Shear Zone that cuts tuffaceous Ordovician rocks belonging to the Sheeffry Formation. It can be traced along strike for 33 km and contains the assemblage quartz, gold,

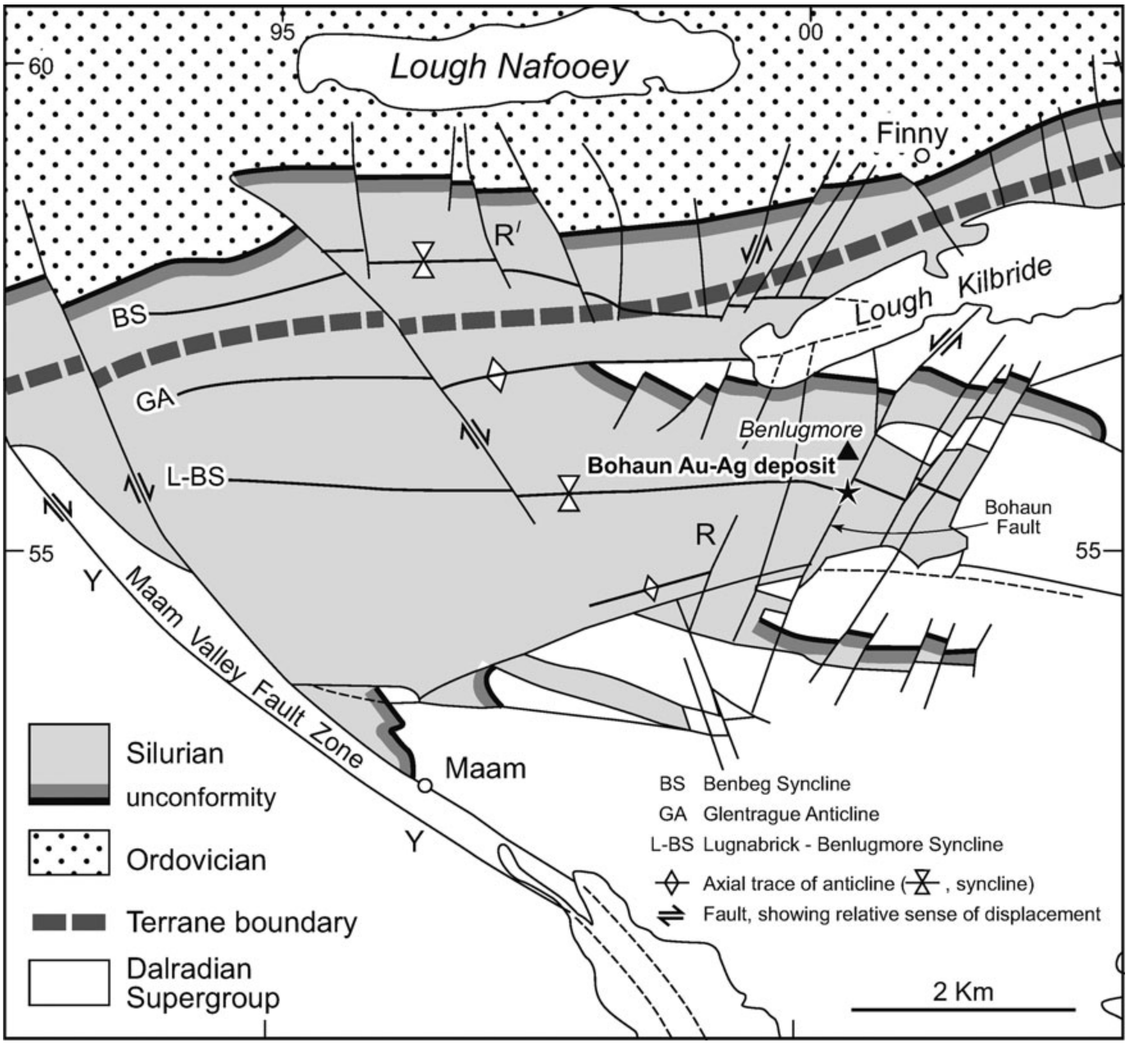

Figure 7. Geology of the Bohaun area, Connemara, showing sets of conjugate fractures (R and R′) formed as secondary structures related to left-lateral movement on the Maam Valley Fault Zone (Y). This figure is based on Leake & Tanner (1994, fig. 13).

pyrite, tetrahedrite, sphalerite and galena (Morris *et al.* 1995).

5.h. Bohaun (9), Connemara

This Au–Ag deposit occurs in NE Connemara and lies on the Bohaun Fault (Figs 1, 7), which cuts folded Silurian rocks (Leake & Tanner, 1994; Lusty *et al.* 2011). It belongs to a network of conjugate transcurrent faults that may be separated into two sets trending at approximately 030° and 330°. The Bohaun Fault displaces the Lugnabrick–Benlugmore Syncline, by a left-lateral displacement, accompanied by a small downthrow to the west (B. E. Leake, pers. comm).

The Silurian rocks lie unconformably across the faulted contact between deformed Ordovician rocks belonging to the South Mayo Trough and the Dalradian basement (Leake & Tanner, 1994, fig. 13). This contact is a continuation of the Doon Rock Fault (Ryan & Archer, 1980), and represents the terrane boundary along which the Connemara block had moved laterally to its present position south of the Grampian Terrane (Figs 1, 7). At Lough Nafooey, it has a downthrow to the north of ~15 km but is concealed beneath Silurian rocks in the study area. The Maam Valley Fault Zone is a major right-lateral transcurrent fault (Fig. 7) that may be traced for 40 km to the NW across part of the South Mayo Trough (Aherne, Reynolds & Burke, 1992, fig. 1).

The Bohaun mineralized zone is located just south of Benlugmore (Fig. 7), where it is marked by a unit of brecciated and silicified country rock up to 50 m wide that can be traced for 1.6 km. The fault zone trends at 015° and comprises a network of metre-scale veins and breccia units up to 50 m thick with a mean N–S orientation (Lusty *et al.* 2011, fig. 3). The range of quartz fabrics seen at outcrop, mainly open-space (Lusty *et al.* 2011, figs 4, 5), matches that in the Tyndrum–Dalmally area (Tanner, 2012, figs 6, 10, 12).

Mineralization episodes. The mineralization is rather sparse and quite different to that of the Scottish deposits. Quartz shows multiple growth stages, with evidence that two fluids of different salinity were involved.

Interpretation. The Bohaun deposit has many of the structural features seen in the Cononish area, and the structure may be interpreted as follows. The Maam

Valley Fault Zone is a primary right-lateral transcurrent fault (Y on Fig. 4d) (e.g. the mirror image of the Tyndrum Fault), with the conjugate faults being secondary Riedel shears (R, R′) that cut and displace E–W-trending folds. The Maam Valley Fault has a sinuous profile in plan view, and the orientation shown in Figure 4d is a mean value. The Bohaun Fault is interpreted as a pure tensional fracture (T) containing $\sigma_{1S} = 000°$; the upright folds in the Dalradian rocks could have formed first, locked up and been transected by the sets of transcurrent faults (?rejuvenated basement faults) that formed in the same stress field. The Bohaun deposit was considered ‘atypical’ when compared with other Grampian Au–Ag deposits (Lusty *et al.* 2011); however, it is seen here as the high-level equivalent to the Tyndrum and Cononish deposits, and is a member of the same continuum.

Conjugate sets of faults are developed throughout the Connemara Dalradian inlier (Leake & Tanner, 1994, pl. 1) and are related to a N–S σ_1 direction. Quartz breccias associated with these faults are almost unknown, but a striking exception is seen 25 km west of Bohaun where a 30 m thick fault breccia occupying the Bengower Fault (Leake & Tanner, 1994, pl. 1) forms a wall-like feature close to the summit of Bengower at [L 784 507]. The structural position of this open-space quartz breccia is significant as it occurs on a releasing-bend where the NW-trending, right-lateral transcurrent fault turns northwards to become N–S-trending. Minor quartz veins and contacts associated with the major breccia strike between 177 and 189° and dip 75–86° W. The breccia body has the geometry of a T-fracture, and is seen as an exploration target.

6. Related igneous features, including a putative hot-spring

6.a. Mineralized igneous intrusions

In the Grampian Terrane, there are two examples of a possible link between plutons emplaced at ~ 425 Ma and the mineralizing fluids:

(1) The Lagalochan ((10) on Fig. 1) and Kilmelford (11) granitoids acted as feeders for the Lorn Lavas and were subsequently truncated by the Ericht–Laidon Fault. The Kilmelford Igneous Complex gave a Re–Os (molybdenite) age of 425.8 ± 1.7 Ma (Conliffe *et al.* 2010), compared with a U–Pb (zircon) age of 425 ± 0.7 Ma for the Lorn Lavas (Neilson, Kokelaar & Crowley, 2009). The hydrothermally altered rocks in the sub-volcanic centre at Lagalochan contain pyrite, chalcopyrite, arsenopyrite, sphalerite, galena and molybdenite, and show high Au and Ag values (Zhou, 1988). The complex was affected by left-lateral transcurrent fault movement on the Ericht–Laidon Fault (Fig. 1), with some sulphide mineralization developed on subsidiary faults.

The porphyry-stock-related and plutonic-hosted mineralization associated with these two granitoids was studied by Lowry *et al.* (1995), who concluded that it took place at a depth of ~3 km, similar to that postulated for the Tyndrum and Cononish vein deposits (Curtis *et al.* 1993; Treagus, Pattrick & Curtis, 1999). Although the mineralizing fluid did not generally include Au or Ag, it is significant that it had a composition closely resembling that responsible for the formation of the vein systems in the Dalradian metasediments of the Tyndrum–Dalmally area (Curtis *et al.* 1993).

(2) The Ratagain Pluton ((12) on Fig. 1) cuts Moine rocks belonging to the Northern Highland Terrane (Fig. 1), but is included here as it has a petrological link with the Grampian deposits. It consists mainly of quartz-monzonites and diorites (see Alderton, 1988 and references therein). Prior to its complete crystallization it was deformed by left-lateral shear on the Strathconon Fault, a major NE-trending transcurrent fault belonging to the Great Glen set (Fig. 1) (Hutton & McErlean, 1991). The granite is of the same age (425 ± 3 Ma on baddeleyite (ZrO_2); Rogers & Dunning, 1991) as the Lagalochan & Kilmelford granitoids, and is cut by Au- and Ag-bearing quartz veins that have a full suite of minerals characteristic of the Au–Ag deposits, namely native gold, hessite, electrum, tetrahedrite, pyrite, chalcopyrite, arsenopyrite, galena, sphalerite and molybdenite (Alderton, 1988, fig. 2). These late veins at Ratagain have the same distinctive red (K-feldspar) selvedges as found associated with the Cononish and Island Vein sets in the Dalmally–Tyndrum area; they may be segregated from the granite magma or be infills of veins fed by the same fluids as are found in the Grampian Terrane.

(3) Gold mineralization also occurs within the shear zone marking the course of the Tyndrum Fault at Inverchorachan south of the mine (Fig. 3) (Scotgold, 2007), and may have been deposited from fluids generated by the emplacement of the Garabal Hill – Glen Fyne Complex (Rogers & Dunning, 1991), which is cut by the fault. This complex is the oldest member of the ‘Newer Granites’ and gave a (revised) U–Pb (zircon) age of 428 ± 9.8 Ma (Neilson, Kokelaar & Crowley, 2009).

These examples provide some evidence to suggest that igneous fluids were involved to a minor extent in the production of the mineralizing fluids, but they were probably more valuable for providing thermal energy to the system rather than for their gold content.

6.b. Relationship of the Rhynie cherts (13) to the Cononish Vein

The Rhynie cherts occur within a small outlier of Lower Devonian rocks in NE Scotland, west of Aberdeen (Fig. 1). They were laid down in a half-graben floored by Dalradian rocks belonging to the Southern Highland Group, together with igneous rocks (mainly norite) and are part of a sedimentary sequence that includes andesitic lavas and tuffs (Rice *et al.* 1995). The cherts are famous for their excellent preservation of the earliest land plants and arthropods, and were the product of the oldest known Au-bearing hot-springs (Rice *et al.*

Table 1. Radiometric ages of selected igneous intrusions, lavas and Au-bearing mineral deposits in the Grampian Terrane

Intrusion/lava/Au-bearing deposit	Radiometric ages
Rhynie hot-spring	407.6 ± 2.2 Ma (Mark, Rice & Trewin, 2013); 411.5 ± 1.3 Ma (Parry *et al.* 2011)
Cononish Au–Ag deposit	**408 ± 2 and 407 ± 1 Ma (Rice *et al.* 2013)**
Inner Starav Intrusion	408.0 ± 0.5 Ma (Neilson, Kokelaar & Crowley, 2009)
Etive Dyke swarm	417.8 ± 0.9 Ma (Neilson, Kokelaar & Crowley, 2009).
Silurian–Devonian boundary	418 Ma
SCANDIAN EVENT	
Lorn Lavas	425 ± 0.7 Ma (Neilson, Kokelaar & Crowley, 2009)
Lagalochan and Kilmelford Granitoids	425.8 ± 1.7 Ma (Conliffe *et al.* 2010)
Ratagain Granite	425 ± 3 Ma (Rogers & Dunning, 1991)
Rubha Mhor Appinite, Ballachulish	427 ± 3 Ma (Rogers & Dunning, 1991)
Garabal Hill & Glen Fyne Complex	428 ± 9.8 Ma (Neilson, Kokelaar & Crowley, 2009)
Curraghinalt Au–Ag deposit	**461–449 Ma (Rice *et al.* 2013)**
GRAMPIAN OROGENY	

1995). Together with the fault breccias, they are also of industrial interest, as they contain abnormally high concentrations of Au, As, Sb, W, Mo and Hg (Rice & Trewin, 1988; Rice *et al.* 1995). The mineralization is concentrated in fault breccias associated with steep to vertical N–NE-trending basin-bounding faults that delimit the west side of the basin. These breccias show open-space quartz textures and other features indicating that the growth of quartz took place at, or very close to, the surface of the Earth (Rice *et al.* 1995).

The most striking feature common to both the Cononish Vein and the Rhynie cherts is the presence of red, often vividly coloured, K-feldspar-rich selvedges to the Au-bearing chert veins. This form of hydrothermal wallrock alteration is also associated with a number of quartz veins, including the River Vein set 7 km NW of Cononish (Fig. 5) and the Au-bearing veins that cut the Ratagain Granite.

It was suggested by Rice, Trewin & Anderson (2002) that Rhynie-type cherts may have been deposited from the same fluids that, deeper in the crust, were responsible for the formation of mineral deposits similar to those at Cononish and Tyndrum. Initially, dating of the cherts by ^{40}Ar–^{39}Ar at 396 ± 12 Ma (Rice *et al.* 1995) and of K-feldspar from the metasomatized country rock adjacent to the Cononish Vein by K–Ar at 410 ± 14 Ma, made this unlikely (Tanner, 2012).

Further work led to an ongoing dispute over the timing of Rhynie hot-spring activity, which has arisen mainly from the use of different chronometers, between Mark, Rice & Trewin (2013), who favour 407.6 ± 2.2 Ma (^{40}Ar–^{39}Ar), and Parry *et al.* (2011), who determined an age of 411.5 ± 1.3 Ma (^{206}Pb–^{238}U, zircon). ^{40}Ar–^{39}Ar dating of hydrothermal K-feldspar from a feeder vein to the Rhynie system gave a (recalculated) age of 407.1 ± 2.1 Ma (Mark *et al.* 2011). This latest age determination is within error of new ^{40}Ar–^{39}Ar determinations (on metasomatic K-feldspar from the altered wallrock at Cononish) of 407 ± 1 and 408 ± 2 Ma (Rice *et al.* 2013) (Table 1).

These results show that at least some of the quartz veins in the Cononish–Tyndrum area were contemporaneous with the final magma pulse in the Lochaber Batholith (Table 1), and could have been linked to Rhynie-type hot-springs at the extant surface.

7. Structural synthesis

At six of the nine localities studied here (Fig. 4a, b, c, d), the attitudes of the mineralized veins and fractures, and in some cases their geometric relationship to folds and thrusts, can be provisionally interpreted in terms of a N–S secondary maximum principal palaeostress direction (σ_{1S}) that trends at 348–011°. The geometry of these features at one of the remaining localities, Curraghinalt, appears to have developed as a result of space problems caused by an oblique footwall ramp on the S-directed Omagh Thrust (Parnell *et al.* 2000), but there is insufficient published information with which to analyse the structures at Cavanacaw and Cregganbaun.

At most of the sites (Fig. 4a, b, d), the fractures are conjugate Riedel shears, having a conventional angular relationship to a master transcurrent fault (simple shear model). Of the remaining sites, only at Croagh Patrick (Fig. 4c) may the pattern be explained in terms of primary fractures (the pure shear model). In this model, the secondary σ_{1S} is 15° anticlockwise to σ_{1R}. When this correction is applied to the results in Figure 4a, b and d, the strike of σ_{1R} for Croagh Patrick at 011° compares well with the corrected values of 006° for Calliachar–Urlar Burn and Tombuie, 019° for Tyndrum and Cononish, and 015° for Bohaun, giving a mean value for these sites of $\sigma_{1R} = 013°$.

The preliminary conclusion drawn from this analysis is that the regional maximum principal stress (σ_{1N}) was consistently orientated approximately N–S in all of the locations described here in Scotland and Ireland for which adequate structural data are available. This stress pattern relates to the final collision of Avalonia with Laurentia.

7.a. Connectivity of the fault system

In models such as the one presented here, connectivity between the master fault (Y), which potentially scavenges fluids from mantle depths, and second-order faults (R, R′, T), in which they crystallized, is an essential requirement, as recognized by Neumayr, Hagemann & Couture (2000) and Groves *et al.* (2003). Indeed, the latter stated that 'Gold deposits are commonly, although not exclusively, in second- or third-order structures that were probably connected to the first-order structures at the time of gold mineralization' (Groves *et al.* 2003, p. 9). In the Cononish area, the main mineral deposit and its satellites lie on the LS set of Y shears (Cononish Vein) parallel to the Tyndrum Fault, which is host to the other economic Au–Ag deposit in the area (Figs 3, 4b). The conjugate sets of Riedel (R, R′) and extensional (T) faults are interconnected, but are not seen to be joined to the Y structures at the present level of erosion.

7.b. Dating of events

The previous estimate for the age of the quartz veins in the Dalmally–Tyndrum area (Tanner, 2012) was based on the field relationships between the Ericht–Laidon Fault and the lavas and plutons of the Lochaber Batholith, recently dated by Neilson, Kokelaar & Crowley (2009). If the thesis that the veins formed in Riedel shears in response to strike-slip movements on the Tyndrum and Ericht–Laidon fault-pair (Tanner, 2012) is correct, then the timing of the displacements on these faults will constrain the age of the fractures, and hence of the veins. As there is no indisputable field evidence that these fault movements continued after 426 Ma, the age of the veins was concluded to be between 428 Ma (the inferred age of the appinite–lamprophyre suite) and 426 Ma.

However, this suggestion has now to be reconsidered in the light of recent radiometric dating. The K–Ar age of 410 ± 14 Ma on K–feldspar from metasomatized country rock adjacent to the Cononish Vein (Treagus, Pattrick & Curtis, 1999) has recently been supported by Rice *et al.* (2013), who obtained an ^{40}Ar–^{39}Ar age of 407.1 ± 2.1 Ma by dating of similar material from Cononish. Whilst caution has to be taken in interpreting this result, as there are at least two major mineralizing events in the Cononish mineral deposit, the main vein-forming event in this area would therefore seem to be coincident with the final magmatic events in the Lochaber Batholith. This new age determination, together with the post-Early Devonian ($<$ 417 Ma) age of the fold structures cut by the veins at Croagh Patrick and Bohaun, suggests that the whole suite of Au–Ag deposits in the Grampian Terrane, apart from those at Curraghinalt and Cavanacaw, may be of Lower Devonian (*c.* 408 Ma) age.

8. Discussion

This section presents a critical assessment of progress to date in determining the sources of the fluids that gave rise to the Grampian Au–Ag deposits and a critique of the proposal that Riedel fractures (R, R′) are an important feature that controls the distribution and geometry of the mineralized quartz veins.

8.a. Origin of the fluids

The Grampian Au–Ag deposits form a coherent group, both in composition and in the local and regional structural controls on their emplacement, having a spatial distribution that is independent of stratigraphy (Fig. 1, inset). The deposits in Scotland, together with that at Curraghinalt in Northern Ireland, have overall an identical mineralogy (albeit the product of several mineralization episodes), including unusual minerals such as hessite, electrum and tetrahedrite. The mineralized quartz veins crystallized at moderate temperatures ($<$ 450 °C), and display open-space quartz textures betokening their shallow depth of formation (5–3 km). Microchemical characterization of detrital gold grains, sampled from small streams or burns in the vicinity of each deposit, supports the strong inter-relationship between the grains types from the Cregganbaun, Croagh Patrick, Cononish and Calliachar–Urlar Burn deposits (Chapman *et al.* 2000). Gold from the Grampian Terrane commonly contains $>$20 % Ag, in addition to inclusions of silver and bismuth tellurides that distinguish it from gold derived from deposits in neighbouring terranes. Despite their similarities in composition and field occurrence, no single model has been proposed that applies to all of the Grampian deposits, and many fundamental questions remain unanswered, such as:

(1) What was the nature of the source that: (a) supplied the extremely large volume of silica-rich fluid required to form the quartz veins, the largest of which are up to 7 km long and up to 20 m thick (Tanner, 2013)? Was this fluid injected into active fractures as countless pulses, or as mobile hydrofractures (Bons, 2001)? (b) generated sufficient fluid to scavenge, and transport, in solution, an estimated Joint Ore Reserves Committee (JORC) reserve of 169 200 oz Au, at a cut-off grade of 3.1 g/t and 631 300 oz Ag, to form the Cononish deposit? (c) provided fluid hot enough to dissolve pre-existing Au, Ag and metal sulphides and redeposit them at a shallower depth (3–5 km) in the Earth's crust, at temperatures of 300–400 °C? (d) supplied an additional aliquot of fluid rich in base metals, to form a separate Pb–Zn horizon spatially linked to the gold-bearing veins?

(2) How could regional metamorphic dehydration reactions provide the fluids necessary to create the Cononish orebody, as well as other gold-bearing veins, in the Grampian Terrane, when there is a mismatch between the time at which the fluid was produced (460–400 Ma ago) and the actual age of the quartz veins (467–408 Ma ago), a discrepancy of up to 60 Ma? i.e. how to reconcile the inferred sequence of events with the available radiometric ages.

Before addressing these questions, the various types of fluid that could be involved are listed, as follows:

(1) Sedimentary: pore fluid in chemical equilibrium with the host rock minerals, mobilized by the first deformation to affect the sediments. (In rocks subsequently affected by orogenesis, it is not possible at present to separate this fluid from that resulting from the early dehydration reactions, so it is not mentioned again in this account.)

(2) Basinal: brines arising from the development of an overlying or adjoining sedimentary basin.

(3) Metamorphic: fluids resulting from dehydration reactions that took place during regional metamorphism of the sedimentary prism, particularly at the greenschist to amphibolite-facies transition.

(4) Igneous: fluids arising from buried granitoid batholiths or plutons undergoing crystallization.

(5) Mantle: fluids from the upper mantle.

(6) Meteoric: surface waters driven by the hydrostatic head resulting from a juvenile topography developed during post-orogenic uplift of the orogen.

8.a.1. *Granitoid intrusions as a source of fluids*

A widely supported hypothesis for the origin of the Au–Ag mineral deposits in the Grampian Terrane is that the Si-rich mineralizing fluids originated from the crystallization of one or more igneous plutons at a shallow depth beneath the ground surface at that time (Curtis *et al*. 1993; Lowry *et al.* 1995; Tanner, 2013). The negative gravity anomaly in the Tyndrum–Dalmally area (Fig. 3) (Cononish deposit) might be taken to indicate the presence of a buried granitoid pluton 5–10 km below the contemporary ground surface. If confirmed, it would be a rare example of the preservation of the fractured and mineralized country rocks forming the roof of a pluton (Leake, 1990), a prospective but very rare situation. However, the Cononish–Tyndrum example may be a special case, as granitoid or similar plutons are not obviously associated with the other Au–Ag deposits in the Grampian Terrane, and some other fluid source must have been involved. More generally, it has been found that although circumstantial evidence supports the notion that buried igneous intrusions are responsible for supplying the mineralizing fluids in such cases, it is difficult to find incontrovertible evidence that this has occurred (Groves *et al.* 2003, p. 10).

8.a.2. *A mantle contribution?*

The inferred compositions of fluids responsible for forming the Tombuie, Tyndrum–Cononish and Curraghinalt deposits may indicate (Ixer, Pattrick & Stanley, 1997) that members of the lamprophyre–appinite suite made a minor contribution to the Au-bearing fluids in the Grampian Terrane. A minor intrusion belonging to this suite, in the Grampian Terrane of County Tyrone, has yielded a U–Pb (zircon) age of 426.7 ± 0.8 Ma (Cooper *et al.* 2013) (Table 1), with the magma being derived from the upper mantle. Other evidence for possible mantle involvement includes:

(1) The presence of Pt-bearing lamprophyres and picrites in the Tyndrum–Dalmally area that were derived from a depth of ~100 km (Atherton & Ghani, 2002); and the occurrence of picrite in the Appinite Complex in Glen Orchy (Kynaston & Hill, 1908; Atherton & Ghani, 2002), together with Pt-group minerals (D. Catterall, pers. comm., 2011);

(2) The occurrence of Pt-group minerals in the Sron Garbh Appinite Complex north of Tyndrum (Scotgold, 2012; Tanner, 2012).

8.a.3. *Basinal brines and the base metal mineralization*

There is evidence from fluid inclusion studies that basinal brines were responsible for introducing Pb–Zn mineralization into some of the deposits. For example, the latest generation of quartz-rich (Q4) fluids in the Curraghinalt deposit were thought to have been basinal brines possibly derived from the Carboniferous Newtownstewart basin (Wilkinson *et al.* 1999; Parnell *et al.* 2000). The isotopic signature of the Bohaun deposit was considered by Lusty *et al*. (2011) to reflect the importance at Bohaun of basinal fluid (Pb–Zn) of probable Carboniferous age.

8.a.4. *Significance of meteoric fluids*

These surface-derived fluids have an important role in the formation of Au–Ag deposits, not so much for their contribution to the metal content of the ore, but in reacting with warmer, mineralized and Si-rich fluids from below and establishing oxidizing conditions in which gold compounds are unstable, leading to precipitation of the gold. Evidence of this is seen in the presence of haematite in Au-bearing veins described by Craw & Chamberlain (1996), and in the Bohaun deposit by Lusty *et al*. (2011). It is significant that most of the Grampian Au–Ag deposits crystallized at depths of 3–5 km, equal to the maximum depth to which meteoric fluid can penetrate.

8.a.5. *A regional (Barrovian) metamorphic origin?*

Craw (1990) first recognized that leaching of certain elements had accompanied the formation of late (D3/D4) quartz veins in the rocks of the Southern Highland Group (Dalradian) exposed in road cuttings and natural exposures in an area 25–35 km south of Tyndrum and west of Loch Lomond (Fig. 3). The quartz veins crystallized at *c*. 350 °C at a depth of 8–10 km and contain the assemblage: chlorite + pyrite + pyrrhotite + chalcopyrite ± sphalerite ± galena ± cubanite ± native gold. The assemblage was thought to have formed at a late stage in the uplift of the Grampian Orogenic Belt. It closely resembles that of the Type B deposits described in this paper, but it seems unlikely that the same fluid that sourced these veins was responsible for the development of the major Tyndrum and Cononish veins, as the regional metamorphism reached a peak at 475–465 Ma and the veins formed between 430–407 Ma (see Tanner, 2013, p. 71).

At least some of the veins studied by Craw (1990) are more likely to be of D2 rather than D4 age (Tanner & Thomas, 2010), but this does not resolve the universal problem of how such fluids may be retained in the crust for tens of millions of years (for review, see Yardley & Cleverley, 2013). To the contrary, rapid uplift in the later stages of an orogenic event, as documented by Craw *et al.* (2010) from the Taiwan tectonic belt, favours the production of metal-bearing metamorphic fluids and the consequent formation of orebodies. Of relevance to the present problem, Yardley & Cleverley (2013) make the prescient statement that 'perhaps late orogenic metamorphism can be driven by fluids from late orogenic mineralization . . . '

8.a.6. A new approach: the Otago model

Pitcairn *et al.* (2006) tested the hypothesis that intergranular fluids resulting from metamorphic dehydration reactions could, while migrating upwards to the free surface, leach sufficient noble and other elements from the country rocks to form an economically viable ore deposit at a higher level in the crust. This study was based on the Otago and Alpine Schists on South Island, New Zealand, a group of monotonous metagreywackes and metabasalts of Mesozoic age that had been subjected to deformation and progressive regional metamorphism. The same group of schists was sampled (a) in their non-metamorphosed state; (b) where they had been affected by greenschist metamorphism; and (c) by amphibolite-facies metamorphism. From a statistical analysis of trace- and major-element analyses of these three groups of rocks, Pitcairn *et al.* (2006) demonstrated that certain elements were largely, if not wholly, removed from the greenschists during their conversion, by devolitization, to amphibolite-facies rocks. In order of decreasing depletion, they were: Au, Ag, As, Sb, Hg, Mo and W. By the time that the regional metamorphism had reached the garnet zone, pyrite, cobaltite, galena and sphalerite had also been removed from the system and, of the sulphur-bearing minerals, only pyrrhotite remained. Their most significant finding was that the minerals that constitute the Macraes orebody (the largest Au-bearing deposit in the Otago Schists) were identical to those that had been extracted from the greenschist-facies rocks and were present in the same relative proportions as in the host rocks. Peak metamorphic conditions in the amphibolite facies of the Otago Schists (Pitcairn *et al.* 2006) were $T = 650\,^{\circ}\mathrm{C}$ and $P = 10$ kb, identical to those in the Grampian Terrane (Vorhies & Ague, 2011).

Individual isotopic studies may be selected from work done on deposits in the Grampian gold province to show that crystallizing granitoid intrusions had probably contributed to the mineralizing fluids. However, the remarkable similarities in mineralogy and other features shown by the widely scattered Au–Ag Grampian deposits are an indication that the scale of the source region is greater than that of an individual hidden pluton.

Phillips & Powell (2010) presented a genetic model for the metamorphic devolatilization process that occurs at the greenschist to amphibolite-facies transition, referred to here as the 'dehydration front'. These reactions take place at 440–520 °C and yield 2–5 wt % aqueous fluid, and Phillips & Powell (2010) emphasized the importance of tectonic strain in liberating the intergranular fluid from the reaction site (Cox, 2005), enabling it to migrate towards the ground surface. Cu, Zn and Pb were not leached out during this process and remained *in situ*, available to be scavenged by a later hotter fluid from an (?)igneous source. This observation may explain the dichotomy between Au–Ag–Te deposits (which formed first) and Pb–Zn–Cu deposits, which generally accompany them and invariably developed at a later stage. Although there are problems with the Otago model, as recognized by Pitcairn *et al.* (2006, p. 1541) and later by Phillips & Powell (2010), it provides a quantitative testable framework for explaining the origin of the Grampian deposits.

Hill *et al.* (2013) made a comprehensive study of the S-isotopes in the Cononish Au–Ag deposit, to determine its origin. Like Gallacher (*in* Hall, 1993, p. 89), they speculated that the ore minerals in the Cononish deposit were probably derived by remobilization of elements from an underlying SedEx deposit in the Easdale Subgroup, which is associated with most of the deposits. Hill *et al.* (2013) found that much of the local Dalradian succession (Fortey & Smith, 1986) that lies structurally beneath the Cononish mineral deposit was deficient in sulphides and concluded that only the constituent Easdale Subgroup could have contributed sulphides in sufficient quantity to form the overlying Cononish deposit. They concluded that, on balance, the S-isotope data showed that the Cononish deposit was predominantly of sedimentary origin, but had a significant igneous-derived content. Although it does not affect their conclusion, it is worth noting that SedEx deposits can be derived from reduced seawater sulphates, rather than from magmatic or metamorphic S (Chang, Large & Maslennikov, 2008).

The paucity of Au, Ag and Te in the local Easdale Subgroup could be that, because they are at garnet grade (amphibolite facies), their content of Au and other metals will, according to the Otago model (Pitcairn *et al.* 2006), have already been depleted of ore minerals by devolatilization. This possibility carries the implication that the pyrite δ^{34}S values may have been modified during the scavenging process, before the second leaching by hotter igneous fluids. These provisos highlight the problem of determining the source of a sulphide deposit using a single isotope system (Phillips & Powell, 2010, p. 690), especially where there is a large variation in δ^{34}S values.

In an attempt to explain how Grampian deposits of differing ages, but with similar characteristics, formed, the early history of the terrane is now outlined, with two hypothetical examples to indicate briefly the different routes that could have been taken by the fluids depositing (a) the Curraghinalt orebody at 460 Ma, and (b) the Cononish orebody at 408 Ma.

8.a.7. *General model for the Grampian gold deposits*

During the early stages of the Grampian deformation, post-D1, pre-D2 planar, bedding-parallel quartz veins formed under greenschist-facies conditions, and the sedimentary fluids *sensu stricto* held in the pore space began to migrate towards the surface as the temperature of the fluid increased. The early veins were then folded and boudinaged, and a new generation of veins formed during D2 (Tanner & Thomas, 2010), accompanied by the widespread development of spaced pressure-solution cleavages. Much of the quartz was probably redistributed within local closed systems, but some may have been incorporated into the intergranular fluid and mixed with metamorphic fluids arising from the dehydration reactions. Noble metals, and elements such as As, were scavenged in increasing amounts as the temperature of the fluid increased. Some of the veins examined by Craw (1990) possibly formed at this time. Before the onset of D3, the D1/D2 fabric was flat-lying and the dehydration front probably had a similar orientation, with the greenschist-facies rocks overlying those of amphibolite facies (Tanner, 2013, fig. 5). Quartz veins of all sizes developed in the vanguard of the dehydration front.

8.a.7.a. *Formation of the Curraghinalt deposit*

At Curraghinalt, the Omagh Thrust carried Dalradian rocks SE over the Tyrone Igneous Complex (Alsop & Hutton, 1993); quartz veins developed in active fractures that developed to accommodate a ramp in the footwall of the major thrust. The regional metamorphic peak occurred at 475–465 Ma and the Curraghinalt veins formed at 467–461 Ma (Rice *et al.* 2013). The sulphides in this deposit are predicted to be largely of metamorphic origin, being supplied by fluids from the devolatilization process in rocks beneath the Tyrone Igneous Complex, but may have been contaminated with igneous and basinal fluids and reacted with meteoric fluid to form the deposit.

8.a.7.b. *Formation of the Cononish deposit*

The time line for this deposit is longer and more complex than that for Curraghinalt. A dehydration front would have been established 470–465 Ma ago, at a depth of some 30 km in the crust, and risen towards the Earth's surface as uplift and erosion took place. There are as yet no known gold-bearing deposits between 460–410 Ma in age in the Grampian Terrane in Scotland (Rice *et al.* 2013). The elements scoured from the country rocks by this fluid must either have been lost at the Earth's surface, as Rhynie-type hot springs, or crystallized as sub-economic quartz veins at a shallow depth, to be later recycled as erosion penetrated deeper into the greenschist-facies rocks. It is proposed that, during its waning stages, the Lochaber Batholith produced hot, reactive, Si-rich fluids, which scavenged the Dalradian rocks, and garnered the remaining noble metals to produce a mineral deposit (at 408 Ma) of mixed metamorphic–igneous parentage 'contaminated' (as in the case of Croagh Patrick) by additions of basinal, meteoric and mantle-derived fluids, to form the Cononish deposit.

These cameos may be discarded in the future as further radiometric age determinations and detailed stable isotope and geochemical studies reveal the true complexity of these processes. One aspect of the geology that has not been explained is why the widespread magmatic events at 426 Ma are not represented by, or did not give rise to, any mineral deposits between 430 and 408 Ma. If confirmed, the youngest gold deposits at 408 Ma can without doubt be related to the final magmatism in the batholith represented by the Inner Starav Granite at 408 Ma (Table 1) and probably occurred during a period of rapid uplift analogous to that reported from the Taiwan Orogen by Craw *et al.* (2010).

8.b. Structural controls on gold mineralization

The aim of this section is, in the light of the results presented in this paper, to review the hypothesis that Riedel fractures (R, R′) are an important factor in controlling the distribution and geometry of Au–Ag-bearing quartz lodes and veins in the upper crust.

Firstly, there are a number of well-documented, natural examples of simple shear fracture patterns that support the theoretical models of, for example, Coulomb (1773), Anderson (1951), Moody & Hill (1956) and Sibson (2000), and the experimental results of Riedel (1929), Cloos (1955) and Tchalenko (1970). The resulting Coulomb–Sibson model has been successfully applied to Au-bearing quartz lode and vein deposits (Mueller, Harris & Lungan, 1988; Vearncombe, 1998; Mares, 1998; Neumayr, Hagemann & Couture, 2000; Kolb & Hagemann, 2009; Dietrich *et al.* 2011), but is hampered in many cases by the lack of quantitative structural data, and the past tendency of mine geologists to record the strike but not the dip of planar surfaces. However, this is not such a serious omission when dealing with strike-slip faults, as they are usually steeply dipping to vertical.

Secondly, there are a number of case studies in which conjugate strike-slip faults, together with penecontemporaneous folds, and thrust, reverse and domino-style faults, form a two-fold symmetrical pattern about σ_1. Classical examples of this configuration have been described from the Devonian and Carboniferous rocks affected by the Variscan Orogeny in SW England and South Wales, UK. Anderson (1951; see also Hancock, 1965, fig. 1) described conjugate sets of mineralized and non-mineralized strike-slip faults from south Pembrokeshire, which were grouped as follows: dextral, trend 345°; sinistral, trend 055°; and associated fold traces, trend 280°; giving $\beta = 25°$ and $\sigma_1 = 020°$.

A similar pattern is seen farther west in Cornwall and South Devon where Dearman (1963) recognized that both mineralized and barren quartz veins occupy conjugate sets of strike-slip faults, but that, over much of the area, the major dextral faults are dominant, to the virtual exclusion of the sinistral set. The effects of this suppression of one of the two sets of faults forming the conjugate pattern was analysed in a detailed study of a small-scale strike-slip network by Nixon, Sanderson & Bull (2011) at Westward Ho!, North Devon. They examined how strain compatibility had been achieved within the network, between areas controlled by pure shear conjugate patterns and those dominated by rotational domino-style faults. A similar dichotomy, on a much larger scale, exists between the conjugate patterns of strike-slip faults with their small displacements, seen in the Dalmally–Tyndrum area (inset on Fig. 5), and the larger (by an order-of-magnitude), dominant Great Glen set of NE-trending, left-lateral strike-slip faults (Fig. 3) that caused their development.

On a smaller scale, Wright, Woodcock & Dixon (2009) described a strike-slip system from the Gower Peninsula, South Wales, where the morphology of individual fault-induced fissures and voids that had developed along a fault plane in the upper few kilometres of the Earth's crust could be examined in detail. The fissures are from 2–25 m wide and contain matrix-supported breccias and calcite veins with cockade textures. These primary (pure shear) fractures are seen as precursors to the type of vein found on Croagh Patrick, and the open fissures with a partial fill of different types of breccia are a proxy for the original nature of the quartz-breccia veins in the Cononish–Dalmally area (Tanner, 2012), before they were injected by silica-rich fluids. Thus, the geometrical relationships between faults and folds seen at a high crustal level in the frontal part of the Variscan orogen are replicated by some of the Grampian faults and quartz veins.

The importance of second- and third-order faults in localizing Au-deposits is becoming increasingly recognized, particularly in greenstone belts, such as the Yilgarn craton, Australia, and the Abitibi greenstone belt, Canada. Previous workers interpreted the major shear zones in these rocks as crustal-scale conduits for transporting mineralizing fluids to a higher level in the crust, *as well as* providing a host for the ore body. It is now recognized that whilst these shear zones enabled fluids to reach the upper crust, deposition of the mineral content took place largely in the network of smaller, second-order Riedel fractures that accompanied them (Mueller, Harris & Lungan, 1988; Vearncombe, 1998; Neumayr, Hagemann & Couture, 2000). The mineralized quartz veins that occupy these Riedel shears are disproportionately long compared to their width. Excellent examples of this style of deformation are provided by Katz, Weinberger & Aydin (2004) and in particular, by Davis *et al.* (1999) (compare their small-scale map of the Sheets Gulch area (fig. 16) with Fig. 4 of this paper). Complications in interpretation arise when vein formation is initiated before polyphase deformation affecting the host rocks has ceased (Mares, 1998), or there is a change in shear direction (Kolb & Hagemann, 2009).

The clearest demonstration that mineralization took place on second-order Riedel fractures is given by the analysis of the 2 km long Huevos Verdes vein system in the Deseado massif, Argentina, by Dietrich *et al.* (2011). In the San José district of the massif, a pair of sinistral strike-slip faults trending 018–028° bracket a compartment in which R (350°) and R′ (280°) faults and veins are developed. The main mineralized (extensional) fractures (T) trend at around 315° and $\beta = 35°$, identical to that predicted for Coulomb fractures in wet rock.

9. Conclusions

Most of the Au–Ag mineral deposits described here from the Grampian Terrane of Scotland and Ireland are hosted by primary and secondary faults that cut and displace folded and metamorphosed rocks belonging to the Neoproterozoic–Lower Ordovician Dalradian Supergroup (Tanner & Sutherland, 2007 and references therein). There is neither stratigraphical nor local lithological control on the development of these deposits and they are confined spatially to a 50 × 350 km area (Fig. 1) designated the Grampian orogenic gold province. In addition, several deposits (Bohaun, Cregganbaun & Croagh Patrick) occur in younger, folded Ordovician and Silurian rocks. This folding was previously thought to be an end-Silurian event, but has now been shown, through a combination of stratigraphical and radiometric dating in the west of Ireland, to be of Scandian (426 Ma) age (Table 1) (Leake, in press).

The Dalradian rocks were strongly deformed in the *c.* 470 Ma Grampian Orogeny that resulted from NW-directed subduction of part of the floor and of the contents of the Dalradian basin, beneath the SE margin of Laurentia (Tanner, 2013). This process operated throughout the duration of the orogeny, and supplied heat and fluids to the orogen until slab break-off occurred at 426 Ma (Atherton & Ghani, 2002). It resulted in the emplacement of magma and hot fluids into the metasediments, and culminated in the formation of the Lochaber Batholith. The 'Great Glen' set of NE-trending strike-slip faults in Scotland is thought to have been intimately involved in the emplacement of the sub-crustal and crustal melts that formed the 'Newer Granite' suite, and either triggered this process (Watson, 1984) or arose from it (Neilson, Kokelaar & Crowley, 2009). This involvement forged links between the strike-slip faults, the Newer Granites (Lochaber Batholith) and the gold-bearing deposits.

Au–Ag deposits are found at Calliachar–Urlar Burn, Tombuie, Tyndrum and Cononish in Scotland and Curraghinalt, Cavanacaw (Omagh mine), Croagh Patrick, Cregganbaun and Bohaun in Ireland. An important feature of these deposits is that most of them share the same overall mineralogy, although they are dispersed over a distance of >300 km, parallel to the strike of the Caledonide belt (Fig. 1). The general assemblage is: native gold, electrum (Au, Ag), hessite (Ag_2Te), tetrahedrite, pyrite, chalcopyrite, arsenopyrite, galena and sphalerite ± bornite. Published isotopic and fluid inclusion data (Curtis *et al.* 1993; Wilkinson & Johnston, 1996; Ixer, Pattrick & Stanley, 1997; Treagus, Pattrick & Curtis, 1999; Wilkinson *et al.* 1999; Parnell *et al.* 2000; Lusty *et al.* 2011) showed that the veins, both regionally and in individual deposits, crystallized under broadly similar *P*–*T* conditions with minimum temperatures of 140–290 °C and maximum temperatures of 240–350 °C at a burial depth of *c.* 3–5 km.

The Au–Ag vein complexes in Ireland, at Cregganbaun and Bohaun, occur in deformed Lower Palaeozoic rocks within the confines of the Grampian Terrane. These deposits show a more restricted mineralogy than the group described above, and only occur in western Ireland. The quartz veins at Curraghinalt and Cavanacaw occur in Dalradian host rocks and have an almost identical mineralogy to those in Scotland.

Repetition of the same structural style is a significant, unifying aspect of the Au–Ag deposits in the Grampian Terrane. All of these deposits, for which some structural data are available, have their development controlled by conjugate pairs of Andersonian faults. The mineralization occurred in second-order Riedel fractures or in the primary left-lateral transcurrent faults that gave rise to them (Fig. 4a, b, c, d). The calculated regional maximum principle stress (σ_{1R}) direction is surprisingly constant across the Grampian Terrane at 348–011°, and β (the angle between σ_{1R} and the Riedel fracture, R) varies from 25–30°, compared with the theoretical value of 27° for fractures developed in the presence of a pore fluid (Sibson, 2000). At Cononish and Bohaun the primary faults (Y) are accompanied by folds, the Orchy Dome at Cononish and the Lugnabrick–Benlugmore Syncline at Bohaun, and by major thrusts, such as the Omagh Thrust at Curraghinalt, that appear to have formed under the same kinematic regime. It is concluded that, during Late Silurian to Early Devonian times, the Au-bearing quartz vein systems described here from the Grampian Terrane developed in response to a N–S-trending σ_{1R} of Scandian age, linked to the final closure of the Iapetus Ocean to the south.

Research into the origin of the fluids that gave rise to the Au-bearing deposits has so far proven inconclusive. The Grampian Au–Ag deposits have many features in common, such as a highly specific mineralogy and a similar gold microchemical fingerprint, that can only be explained in the context of a province-wide mechanism or process. A large volume of hot Si-rich fluid is necessary to produce a mineral deposit, but as there was a dearth of igneous intrusions of an appropriate age and volume to supply this, the sole remaining option would appear to be the metamorphic fluid. The basic tenet of the Otago model (Pitcairn *et al.* 2006) adopted here is that this fluid was released *in situ* by regional metamorphic dehydration reactions. This 'devolatization' process (Phillips & Powell, 2010) was most active at the greenschist/amphibolite-facies boundary where, for example, hydrous minerals like chlorite were converted to biotite with the consequent liberation of a few per cent water. Owing to the large surface area presented by porous clastic rocks in particular, this fluid was able to scavenge Au and other noble metals, together with some base element sulphides, from the metasediments and transport them towards the Earth's surface. A 'dehydration front' developed that separated amphibolite-facies rocks at depth, which had been depleted of much of their metal content, from the overlying greenschist-facies rocks. Thus, early in the development of the orogenic belt, rocks metamorphosed at a higher grade than greenschist facies will have had most of their ore minerals removed by leaching. It is inferred that the overlying greenschist rocks were traversed by small bodies of silica-rich fluid that crystallized as metalliferous quartz veins. Alternatively, these narrow passageways could have developed into conduits capable of draining a large volume of fluid with the potential of developing economically viable Au-bearing quartz veins in these upper crustal greenschists.

It is thought that major transcurrent faults developed in the upper crust, propagated downwards and connected with conduits fed from below to supply overpressured fluids to the breccia-filled cores and damage zones of a network of second-order R, R′ and T fractures (Tanner, 2012). These once-open voids were now seen as crystalline open-space quartz veins and quartz breccias. Hot fluids from crystallizing acid igneous magmas possibly provided the driving force for this process, and as any residual fluids approached the contemporary ground surface, boiling took place, and the remaining gold was precipitated during hot-spring activity (Rice *et al.* 1995).

The application of the Otago model (Pitcairn *et al.* 2006) to the problems posed by the Grampian deposits, primarily that of finding a source for the mineralizing fluids, has introduced a new layer of complexity to the search but does offer the possibility of constructing a quantitative framework that can be tested using a number of different techniques.

Acknowledgements. I am indebted to Judith Tanner for her probing questions and painstaking attention to detail whilst helping to prepare this manuscript, and to Mike Shand (University of Glasgow) for invaluable assistance with the draughting. I am grateful to Chris Sangster and Jeff Smith (both of Scotgold Resources); David Catterall (Farscape Exploration); Nyree Hill and Gawen Jenkin (both of Leicester University); and Clive Rice (University of Aberdeen) for many useful discussions on the geology of the Cononish gold–silver deposit and its surroundings; also to Mark Cooper (Geological Survey of Northern Ireland) for a constructive critique of an early draft of the manuscript; to two anonymous referees for their advice, and for alerting me to some key references; and to Dave Craw (University of Otago) for taking a critical look at the final manuscript.

References

Aherne, S., Reynolds, N. A. & Burke, D. J. 1992. Gold mineralization in the Silurian and Ordovician of south Mayo. In *The Irish Minerals Industry 1980–1990* (eds

A. A. Bowden, G. Earls, P. G. O'Connor and J. F. Pyne), pp. 39–49. Irish Association for Economic Geology.

Alderton, D. H. M. 1988. Ag–Au–Te mineralization in the Ratagain complex, northwest Scotland. *Transactions of the Institution of Mining and Metallurgy (Section B: Applied Earth Sciences)* **97**, 171–80.

Alsop, G. I. & Hutton, D. H. W. 1993. Major south-east directed Caledonian thrusting and folding in the Dalradian rocks of mid-Ulster: implications for Caledonian tectonics and mid-crustal shear zones. *Geological Magazine* **130**, 233–44.

Anderson, E. M. 1951. *The Dynamics of Faulting and Dyke Formation with Applications to Britain*, 2nd ed. Edinburgh: Oliver & Boyd, 206 pp.

Atherton, M. P. & Ghani, A. A. 2002. Slab breakoff: a model for Caledonian, Late Granite syn-collisional magmatism in the orthotectonic (metamorphic) zone of Scotland and Donegal, Ireland. *Lithos* **62**, 65–85.

Bailey, E. B. & MacGregor, M. 1912. The Glen Orchy Anticline (Argyllshire). *Quarterly Journal of the Geological Society, London* **68**, 164–79.

Baxter, E. F., Ague, J. J. & Depaolo, D. J. 2002. Prograde temperature-time evolution in the Barrovian type-locality constrained by Sm/Nd garnet ages from Glen Clova, Scotland. *Journal of the Geological Society, London* **159**, 71–82.

Bons, P. D. 2001. The formation of large quartz veins by rapid ascent of fluids in mobile hydrofractures. *Tectonophysics* **336**(1–4), 1–17.

Chang, Z., Large, R. R. & Maslennikov, V. 2008. Sulfur isotopes in sediment-hosted orogenic gold deposits: evidence for an early timing and a seawater sulfur source. *Geology* **36**, 971–74.

Chapman, R. J., Leake, R. C., Moles, N. R., Earls, G., Cooper, C., Harrington, K. & Berzin, R. 2000. The application of microchemical analysis of alluvial gold grains to the understanding of complex local and regional gold mineralization: A case study in the Irish and Scottish Caledonides. *Economic Geology* **95**, 1753–73.

Chew, D. M. 2001. Basement protrusion origin of serpentinite in the Dalradian. *Irish Journal of Earth Sciences* **19**, 23–35.

Cliff, D. C. & Wolfenden, M. 1992. The Lack gold deposit, Northern Ireland. In *The Irish Minerals Industry 1980–1990* (eds A. A. Bowden, G. Earls, P. G. O'Connor & J. F. Pyne), pp. 65–75. Irish Association for Economic Geology.

Clifford, J. A. 1992. A note on gold mineralization in County Tyrone. In *The Irish Minerals Industry* 1980–1990 (eds A. A. Bowden, G. Earls, P. G. O'Connor and J. F. Pyne), pp. 45–7. Irish Association for Economic Geology.

Cloos, E. 1955. Experimental analysis of fracture patterns. *Geological Society of America Bulletin* **66**, 241–56.

Conliffe, J., Selby, D., Porter, S. J. & Feely, M. 2010. Re–Os molybdenite dates from the Ballachulish and Kilmelford igneous complexes (Scottish Highlands): age constraints for late Caledonian magmatism. *Journal of the Geological Society, London* **167**, 297–302.

Cooper, M. R., Crowley, Q. G., Hollis, S. P., Noble, S. R. & Henney, P. J. 2013. A U–Pb age for the Late Caledonian Sperrin Mountains minor intrusions suite in the north of Ireland: timing of slab break-off in the Grampian terrane and the significance of deep-seated, crustal lineaments. *Journal of the Geological Society, London* **170**, 603–14.

Cooper, M. R., Crowley, Q. G., Hollis, S. P., Noble, S. R., Roberts, S., Chew, D., Earls, G., Herrington, R. & Merriman, R. J. 2011. Age constraints and geochemistry of the Ordovician Tyrone Igneous Complex, Northern Ireland: implications for the Grampian orogeny. *Journal of the Geological Society, London* **168**, 837–50.

Corkhill, C., Ixer, R. A. F., Mason, J. S., Irving, D. & Pattrick, R. A. D. 2010. Polymetallic auriferous vein mineralization near Loch Tay, Perthshire, Scotland. *Scottish Journal of Geology* **46**, 23–30.

Coulomb, C. A. 1773. Essai sur une application des regles des maximis et minimis a quelques problemes de statique relatifs a l'architecture. *Mémoires présentés par divers savants à l'Académie des Sciences, Paris* **7**, 343–82.

Cox, S. F. 2005. Coupling between deformation, fluid pressures, and fluid flow in ore-producing hydrothermal systems at depth in the crust. *Economic Geology* **100**, 39–75.

Craw, D. 1990. Regional fluid and metal mobility in the Dalradian metamorphic belt, Southern Grampian Highlands, Scotland. *Mineralium Deposita* **25**, 281–8.

Craw, D. & Chamberlain, C. P. 1996. Meteoric incursion and oxygen fronts in the Dalradian metamorphic belt, southwest Scotland: a new hypothesis for regional gold mobility. *Mineralium Deposita* **31**, 365–73.

Craw, D., Upton, P., Yu, B.-S., Horton, T. & Chen, Y.-G. 2010. Young orogenic gold mineralisation in active collisional mountains, Taiwan. *Mineralium Deposita* **45**, 631–46.

Curtis, S. F., Pattrick, R. A. D., Jenkin, G. R. T., Fallick, A. E., Boyce, A. J. & Treagus, J. E. 1993. Fluid inclusion and stable isotope study of fault-related mineralization in Tyndrum area, Scotland. *Transactions of the Institute of Mining and Metallurgy (Section B: Applied Earth Sciences)* **102**, 39–47.

Davis, G. H., Bump, A. P., Garcia, P. E. & Ahlgren, S. G. 1999. Conjugate Riedel deformation band shear zones. *Journal of Structural Geology* **22**, 169–90.

Dearman, W. R. 1963. Wrench-faulting in Cornwall and South Devon. *Proceedings of the Geologists' Association* **74**, 265–87.

Dewey, J. F. 2005. Orogeny can be very short. *Proceedings of the National Academy of Sciences, USA* **102**, 15286–93.

Dewey, J. F. & Strachan, R. A. 2003. Changing Silurian–Devonian relative plate motion in the Caledonides: sinistral transpression to sinistral transtension. *Journal of the Geological Society, London* **160**, 219–29.

Dietrich, A., Gutierrez, R., Nelson, E. P. & Layer, P. W. 2011. Geology of the epithermal Ag–Au Huevos Verdes vein system and San Jose district, Deseado massif, Patagonia, Argentina. *Mineralium Deposita* **47**, 233–49.

Dominy, S. C., Platten, I. M., Xie, Y. & Sangster, C. J. S. 2009. Analysis of geological mapping data at the Cononish Gold-Silver Mine, Perthshire, Scotland. In *Proceedings of the Seventh International Mining Geology Conference, Perth, WA*, pp. 187–96. Melbourne: The Australasian Institute of Mining and Metallurgy.

Earls, G., Clifford, J. A. & Meldrum, A. H. 1992. Curraghinalt gold deposit, County Tyrone, Northern Ireland. In *The Irish Minerals Industry 1980–1990* (eds A. A. Bowden, G. Earls, P. G. O'Connor & J. F. Pyne), pp. 50–51. Irish Association for Economic Geology.

Fortey, N. J. & Smith, C. G. 1986. Stratabound mineralisation in the Dalradian rocks near Tyndrum, Perthshire. *Scottish Journal of Geology* **22**, 377–93.

Garson, M. S. & Plant, J. A. 1973. Alpine type ultramafic rocks and episodic mountain building in the Scottish Highlands. *Nature* **242**(116), 34–8.

GRIFFITH, A. A. 1920. The phenomena of rupture and flow in solids. *Philosophical Transactions of the Royal Society A* **221**, 163–98.

GROVES, D. I., GOLDFARB, R. J., ROBERT, F. & HART, C. J. R. 2003. Gold deposits in metamorphic belts: overview of current understanding, outstanding problems, future research and exploration significance. *Economic Geology* **98**, 1–29.

HALL, J. 1985. Geophysical constraints on crustal structure in the Dalradian region of Scotland. *Journal of the Geological Society, London* **142**, 149–55.

HALL, A. J. 1993. Stratiform mineralisation in the Dalradian of Scotland. In *Mineralisation in the British Isles* (eds R. A. D. Pattrick and D. A. Polya), pp 38–101. London: Chapman and Hall.

HANCOCK, P. L. 1965. Axial-trace-fractures and deformed concretionary rods in south Pembrokeshire. *Geological Magazine* **102**, 143–63.

HAWSON, C. A. & HALL, A. J. 1987. Middle Dalradian Corrycharmaig serpentinite, Perthshire, Scotland: an ultramafic intrusion. *Transactions of the Institute of Mining and Metallurgy (Section B: Applied Earth Sciences)* **96**, B173–7.

HILL, N. J., JENKIN, G. R. T., BOYCE, A. J., SANGSTER, C. J. S., CATTERALL, D. J., HOLWELL, D. A., NADEN, J., GUNN, G. & RICE, C. M. 2011. New gold occurrences in the Scottish Dalradian, UK – nature and constraints on genesis. In *Fermor 2011 – Ore Deposits in an Evolving Earth, Abstract Book*, p. 25. London: The Geological Society.

HILL, N. J., JENKIN, G. R. T., HOLWELL, D. A., CATTERALL, D., BOYCE, A. J., MARK, D., NADEN, J. & RICE, C. M. 2013. How the Neoproterozoic S-isotope record illuminates the genesis of vein gold systems: an example from the Dalradian Supergroup in Scotland. In *Ore Deposits in an Evolving Earth* (eds G. R. T. Jenkin, P. A. J. Lusty, I. McDonald, M. P. Smith, A. J. Boyce & J. J. Wilkinson). Geological Society of London, Special Publication no. 393. Published online 22 November 2013. doi: 10.1144/SP393.9.

HOLLIS, S. P., ROBERTS, S., COOPER, M. R., EARLS, G., HERRINGTON, R., CONDON, D. J., COOPER, M. J., ARCHIBALD, S. M. & PIERCEY, S. J. 2012. Episodic arc-ophiolite emplacement and the growth of continental margins: late accretion in the Northern Irish sector of the Grampian–Taconic orogeny. *Geological Society of America Bulletin* **124**, 1702–23.

HUBBERT, M. K. & RUBEY, W. W. 1959. Role of fluid pressure in the mechanisms of overthrust faulting. *Geological Society of America Bulletin* **70**, 115–205.

HUTTON, D. H. W. 1987. Strike-slip terranes and a model for the evolution of the British and Irish Caledonides. *Geological Magazine* **124**, 405–25.

HUTTON, D. H. W. & DEWEY, J. F. 1986. Palaeozoic terrane accretion in the western Irish Caledonides. *Tectonics* **5**, 1115–24.

HUTTON, D. H. W. & MCERLEAN, M. 1991. Silurian and Early Devonian sinistral deformation of the Ratagain granite, Scotland: constraints on the age of the Caledonian movement on the Great Glen fault system. *Journal of the Geological Society, London* **148**, 1–4.

IXER, R. A. F., PATTRICK, R. A. D. & STANLEY, C. J. 1997. Geology, mineralogy and genesis of gold mineralization at Calliachar-Urlar Burn, Scotland. *Transactions of the Institute of Mining and Metallurgy (Section B: Applied Earth Sciences)* **106**, B99–108.

JACQUES, J. M. & REAVY, R. J. 1994. Caledonian plutonism and major lineaments in the SW Scottish Highlands. *Journal of the Geological Society, London* **151**, 955–69.

JOHNSTON, J. D. 1992. The fractal geometry of vein systems: the potential for ore reserve calculation. In *The Irish Minerals Industry 1980–1990* (eds A. A. Bowden, G. Earls, P. G. O'Connor & J. F. Pyne), pp. 105–17. Irish Association for Economic Geology.

JOHNSTON, J. D. & MCCAFFREY, K. J. W. 1996. Fractal geometries of vein systems and the variation of scaling relationships with mechanism. *Journal of Structural Geology* **18**, 349–58.

KATZ, Y., WEINBERGER, R. & AYDIN, A. 2004. Geometry and kinematic evolution of Riedel shear structures, Capitol Reef National Park, Utah. *Journal of Structural Geology* **26**, 491–501.

KOLB, J. & HAGEMANN, S. 2009. Structural control of low-sulfidation epithermal gold mineralization in the Rosario-Bunawan district, East Mindanao Ridge, Philippines. *Mineralium Deposita* **44**, 795–815.

KREUZER, O. P., BLENKINSOP, T. G., MORRISON, R. J. & PETERS, S. G. 2007. Ore controls in the Charter Towers goldfield, N.E. Australia: constraints from geological, geophysical and numerical analyses. *Ore Geology Reviews* **32**, 37–80.

KYNASTON, H. & HILL, J. B. 1908. *The Geology of the Country near Oban and Dalmally (Sheet 45)*. Memoir of the Geological Survey, Scotland.

LEAKE, B. E. 1990. Granite magmas: their sources, initiation and consequences of emplacement. *Journal of the Geological Society, London* **147**, 579–89.

LEAKE, B. E. In press. A new map and interpretation of the geology of part of Joyces Country, Counties Galway and Mayo. *Irish Journal of Earth Sciences*.

LEAKE, B. E. & TANNER, P. W. G. 1994. *The Geology of the Dalradian and Associated Rocks of Connemara, Western Ireland*. Dublin: Royal Irish Academy, 96 pp.

LOWRY, D., BOYCE, A. J., FALLICK, A. E. & STEPHENS, W. E. 1995. Genesis of porphyry and plutonic mineralisation systems in metaluminous granitoids of the Grampian Terrane, Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **85**, 221–37.

LUSTY, P. A., NADEN, J., BOUCH, J. J., MCKERVEY, J. A. & MCFARLANE, J. A. 2011. Atypical gold mineralization in an orogenic setting–the Bohaun deposit, western Irish Caledonides. *Economic Geology* **106**, 359–80.

MARES, V. M. 1998. Structural development of the Soldiers Cap Group in the eastern fold belt of the Mt Isa Inlier: a succession of horizontal and vertical deformation events and large-scale shearing. *Australian Journal of Earth Sciences* **45**, 373–87.

MARK, D., RICE, C. M., FALLICK, A. E., TREWIN, N. H., LEE, M. R., BOYCE, A. & LEE, J. K. W. 2011. ^{40}Ar/^{39}Ar dating of hydrothermal activity, biota and gold mineralization in the Rhynie hot-spring system, Aberdeenshire, Scotland. *Geochimica et Cosmochimica Acta* **75**, 555–69.

MARK, D., RICE, C. M. & TREWIN, N. H. 2013. Discussion on 'A high-precision U–Pb age constraint on the Rhynie Chert Konservat-Lagerstätte: time scale and other implications'. *Journal of the Geological Society, London* **168**, 863–72.

MCFARLANE, J. A. S., COOPER, M. R. & CHEW, D. M. 2009. New geological and geophysical insights into the Dalradian Lack Inlier, Northern Ireland: implications for lithostratigraphy and gold mineralisation. In *2009 Irish Association for Economic Geology Annual Review*, pp. 57–8.

MOODY, J. D. & HILL, M. J. 1956. Wrench-fault tectonics. *Bulletin of the Geological Society of America* **67**, 1207–46.

MORRIS, J. H., LONG, C. B., MCCONNELL, B. & ARCHER, J. B. 1995. *Geology of Connemara. An Introduction to the Physical Structure, Ancient Environments and Modern Landscapes of Parts of Northwest Galway and Southwest Mayo, to Accompany the Bedrock Geology 1:100,000 Scale Map Series. Sheet 10, Connemara*. Dublin: Geological Survey of Ireland.

MUELLER, A. G., HARRIS, L. B. & LUNGAN, A. 1988. Structural control of greenstone-hosted gold mineralization by transcurrent shearing: a new interpretation of the Kalgoorie mining district, western Australia. *Ore Geology Reviews* **3**, 359–87.

NEILSON, J. C., KOKELAAR, B. P. & CROWLEY, Q. C. 2009. Timing, relations and cause of plutonic and volcanic activity of the Siluro-Devonian post-collision magmatic episode in the Grampian Terrane, Scotland. *Journal of the Geological Society, London* **166**, 545–61.

NEUMAYR, P., HAGEMANN, S. G. & COUTURE, J.-F. 2000. Structural setting, textures, and timing of hydrothermal vein systems in the Val d'Or camp, Abitibi, Canada: implications for the evolution of transcrustal, second- and third-order fault zones and gold mineralization. *Canadian Journal of Earth Sciences* **37**, 95–114.

NIXON, C. W., SANDERSON, D. J. & BULL, J. M. 2011. Deformation within a strike-slip fault network at Westward Ho!, Devon U.K.: domino vs conjugate faulting. *Journal of Structural Geology* **33**, 833–43.

OLIVER, G. J. H. 2001. Reconstruction of the Grampian episode in Scotland: its place in the Caledonian Orogeny. *Tectonophysics* **332**, 23–49.

PARKER, R. T. G., CLIFFORD, J. A. & MELDRUM, A. H. 1989. The Cononish gold–silver deposit, Perthshire, Scotland. *Transactions of the Institute of Mining and Mineralogy (Section B, Applied Earth Science)* **98**, B51–2.

PARKER, R. & PEARSON, N. 2012. Technical report on the Omagh gold project. Counties Tyrone and Fermanagh, Northern Ireland. ACA Howie International Limited, pp. 4–33.

PARNELL, J., EARLS, G., WILKINSON, J. J., HUTTON, D. H. W., BOYCE, A. J., FALLICK, A. E., ELLAM, R. M., GLEESON, S. A., MOLES, N. R., CAREY, P. F. & LEGG, I. 2000. Regional fluid flow and gold mineralization in the Dalradian of the Sperrin Mountains, Northern Ireland. *Economic Geology* **95**, 1389–416.

PARRY, S. F., NOBLE, S. R., CROWLEY, Q. G. & WELLMAN, C. H. 2011. A high-precision U-Pb age constraint on the Rhynie Chert Konservat-Lagerstätte: time scale and other implications. *Journal of the Geological Society, London* **168**, 863–72.

PATTRICK, R. A. D. 1985. Pb-Zn and minor U mineralization at Tyndrum, Scotland. *Mineralogical Magazine* **49**, 671–81.

PATTRICK, R. A. D., BOYCE, A. & MACINTYRE, R. M. 1988. Gold-silver vein mineralization at Tyndrum, Scotland. *Mineralogy and Petrology* **38**, 61–76.

PHILLIPS, G. N. & POWELL, R. 2010. Formation of gold deposits: a metamorphic devolatilization model. *Journal of Metamorphic Geology* **28**, 689–718.

PITCAIRN, I. K., TEAGLE, D. A. H., CRAW, D., OLIVO, G. R., KERRICH, R. & BREWER, T. S. 2006. Sources of metals and fluids in orogenic gold deposits: insights from the Otago and Alpine Schists, New Zealand. *Economic Geology* **101**, 1525–46.

RICE, C. M., ASHCROFT, W. A., BATTEN, D. J., BOYCE, A. J., CAULFIELD, J. B. D., FALLICK, A. E., HOLE, M. J., JONES, E., PEARSON, M. J., ROGERS, G., SAXTON, J. M., STUART, F. M., TREWIN, N. H. & TURNER, G. 1995. A Devonian auriferous hot spring system. Rhynie, Scotland. *Journal of the Geological Society, London* **152**, 229–50.

RICE, C. M., MARK, D. F., SELBY, D. & HILL, N. J. 2013. Dating vein-hosted gold deposits in the Caledonides of N. Britain. In *Mineral Deposits Studies Group, 36th Annual Winter Meeting, 2–4 January, 2013, Programme and Abstract Volume*, p. 88.

RICE, C. M. & TREWIN, N. H. 1988. A Lower Devonian gold-bearing hot spring system. Rhynie, Scotland. *Transactions of the Institution of Mining and Metallurgy* **97**, B141–4.

RICE, C. M., TREWIN, N. H. & ANDERSON, L. I. 2002. Geological setting of the Early Devonian Rhynie cherts, Aberdeenshire, Scotland: an early terrestrial hot spring system. *Journal of the Geological Society, London* **159**, 203–14.

RIEDEL, W. 1929. Zur Mechanik geologischer Brucherscheinungen. *Zentral blatt für Mineralogie Abteilung* **B**, 354–68.

ROGERS, G. & DUNNING, G. R. 1991. Geochronology of appinitic and related granitic magmatism in the W Highlands of Scotland: constraints on the timing of transcurrent fault movement. *Journal of the Geological Society, London* **148**, 17–27.

ROSE, P. T. S. & HARRIS, A. L. 2000. Evidence for the Lower Palaeozoic age of the Tay Nappe: the timing and nature of Grampian events in the Scottish Highland sector of the Laurentian Margin. *Journal of the Geological Society, London* **157**, 381–91.

RYAN, P. D. & ARCHER, J. B. 1980. The stratigraphy and petrochemistry of the Lough Nafooey Group (Tremadocian), western Ireland. *Journal of the Geological Society, London* **137**, 443–58.

RYAN, P. D. & DEWEY, J. F. 2011. Arc-continent collisions in the Ordovician of western Ireland: stratigraphic, structural and metamorphic evolution. In *Arc-Continent Collision* (eds D. Brown & P. D. Ryan), pp. 373–401. Berlin, Heidelberg: Springer-Verlag.

SCOTGOLD. 2007. *Prospectus for Initial Public Offering on the Australian Stock Exchange*. Scotgold Resources Limited, 97 pp.

SCOTGOLD. 2012. *ASX Announcement, March, 2012*. Scotgold Resources Limited.

SECOR, D. T. 1965. Role of fluid pressure in jointing. *American Journal of Science* **263**, 633–46.

SIBSON, R. H. 2000. A brittle failure mode plot defining conditions for high-flux flow. *Economic Geology* **95**, 41–8.

STEPHENSON, D., MENDUM, J. R., FETTES, D. J. & LESLIE, A. G. 2013. The Dalradian rocks of Scotland: an introduction. *Proceedings of the Geologists' Association*, **124**, 3–82.

TANNER, P. W. G. 2007. Origin of the Tay Nappe, Scotland (abstract). In *The Peach and Horne Meeting. Symposium on Continental Tectonics and Mountain Building, Ullapool, 2007.*

TANNER, P. W. G. 2012. The giant quartz veins in the Tyndrum-Dalmally area, Grampian Highlands, Scotland: their geometry, origin, and relationship to the Cononish gold-silver deposit. *Earth and Environmental Transactions of the Royal Society of Edinburgh* **103**, 51–76.

TANNER, P. W. G. 2013. A kinematic model for the Grampian Orogeny, Scotland. In *New Perspectives on the Caledonides of Scandinavia and Related Areas* (eds F. Corfu,

D. Gasser & D. M. Chew). Geological Society of London, Special Publication no. 390. Published online 26 November 2013. doi: 10.1144/SP390.23.

Tanner, P. W. G., Bendall, C. A., Pickett, E. A., Roberts, J. L., Treagus, J. E. & Stephenson, D. 2013*a*. The Dalradian rocks of the South-west Grampian Highlands of Scotland. *Proceedings of the Geologists' Association* **124**, 83–147.

Tanner, P. W. G. & Sutherland, S. 2007. The Highland Border Complex, Scotland: a paradox resolved. *Journal of the Geological Society, London* **164**, 111–16.

Tanner, P. W. G. & Thomas, P. R. 2010. Major nappe-like D2 folds in the Dalradian rocks of the Beinn Udlaidh area, Central Highlands, Scotland. *Earth and Environmental Transactions of the Royal Society of Edinburgh* **100**, 371–89.

Tanner, P. W. G., Thomas, C. W., Harris, A. L., Gould, D., Harte, B., Treagus, J. E. & Stephenson, D. 2013*b*. The Dalradian rocks of the Highland Border region of Scotland. *Proceedings of the Geologists' Association* **124**, 215–62.

Tchalenko, J. 1970. Similarities between shear zones of different magnitudes. *Geological Society of America Bulletin* **81**, 1625–39.

Treagus, J. E. 1991. Fault displacements in the Dalradian of the Central Highlands. *Scottish Journal of Geology* **27**, 135–45.

Treagus, J. E. 2000. *Solid Geology of the Schiehallion District: Memoir for 1:50 000 Geological Sheet 55W (Scotland)*. British Geological Survey.

Treagus, J. E., Pattrick, R. A. D. & Curtis, S. F. 1999. Movement and mineralization in the Tyndrum Fault Zone, Scotland and its regional significance. *Journal of the Geological Society, London* **156**, 591–604.

Vearncombe, J. R. 1993. Quartz vein morphology and implications for formation depth and classification of Achaean gold-vein deposits. *Ore Geology Reviews* **8**, 407–24.

Vearncombe, J. R. 1998. Shear zones, fault networks, and Archean gold. *Geology* **26**, 855–8.

Vorhies, S. H. & Ague, J. J. 2011. Pressure–temperature evolution and thermal regimes in the Barrovian zones, Scotland. *Journal of the Geological Society, London* **168**, 1147–66.

Watson, J. 1984. The ending of the Caledonian orogeny in Scotland. *Journal of the Geological Society, London* **141**, 193–214.

Wilkinson, J. J., Boyce, A. J., Earls, G. & Fallick, A. E. 1999. Gold remobilization by low-temperature brines: evidence from the Curraghinalt gold deposit, Northern Ireland. *Economic Geology* **94**, 289–96.

Wilkinson, J. J. & Johnston, J. D. 1996. Pressure fluctuations, phase separation, and gold precipitation during seismic fracture propagation. *Geology* **24**, 395–8.

Wright, V., Woodcock, N. H. & Dickson, J. A. D. 2009. Fissure fills along faults: Variscan examples from Gower, South Wales. *Geological Magazine* **146**, 890–902.

Yardley, B. W. D. & Cleverley, J. S. 2013. The role of metamorphic fluids in the formation of ore deposits. In *Ore deposits in an Evolving Earth* (eds G. R. T. Jenkin, P. A. J. Lusty, I. McDonald, M. P. Smith, A. J. Boyce & J. J. Wilkinson). Geological Society of London, Special Publication no. 393. Published online 7 October 2013. doi: 10.1144/SP393.5.

Zhou, J.–X. 1988. A gold and silver-bearing subvolcanic centre in the Scottish Caledonides near Lagalochan, Argyllshire. *Journal of the Geological Society, London* **145**, 225–34.