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# A progressive model for the development of the Cavanacaw Au–Ag–Pb vein deposit, Northern Ireland, and implications for the evolution and metallogeny of the Grampian Terrane

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ABSTRACT

Deformed vein systems may exhibit complex geometries with kinematics that are not always easily reconciled within the overall tectonic framework and interpreted palaeostress fields. In ore exploration and mining, the misinterpretation of complex vein geometries as polyphase deformation, as opposed to progressive deformation, may be detrimental to developing effective exploration strategies or geometric models for ore bodies. An example of this is the Cavanacaw Au–Ag–Pb vein deposit in Northern Ireland which has previously been interpreted to have had a polyphase deformation history linking economic mineralisation to span both the Caledonian and Variscan orogenies. Here, we present structural analysis to demonstrate that the geometries and kinematics of the broadly N to WNW-striking vein system is more easily explained with a single progressive kinematic model incorporating overall sinistral shearing along Silurian ENE–WSW-striking transcurrent faults during the Scandian event of the Caledonian orogeny. This progressive deformation further accounts for a regional, abrupt 'knee bend' strike swing in Dalradian Supergroup rocks that is probably related to the wider mineralisation and penetrative mid-Silurian deformation in the area. Our analysis additionally implies that Cavanacaw is younger than the nearby Late Ordovician Curraghinalt deposit which is related to the Grampian event, but is also slightly older than the Early Devonian Cononish deposit in Scotland that similarly links to the Scandian event. This study ultimately demonstrates how an understanding of progressive deformation can have key scientific and economic implications by informing regional and tectonic deformation models and exploration strategies, respectively.

## 1. Introduction

The vortical flow associated with progressive deformation within shear zones and between shear zone pairs can significantly affect the geometries of pre-existing and contemporaneous fabrics and structures (e.g., veins, faults, and dykes; Beach, 1975; Platt, 1983; Ramsay et al., 1983a; Lister and Snoke, 1984; Passchier, 1986; Olson and Pollard, 1991; Alsop et al., 2021). This occurs at a variety of scales, and correctly interpreting these geometries with an appreciation for rotational dynamics can greatly enhance both local and regional structural and tectonic models (e.g., Fossen et al., 2019). These interpretations not only have fundamental scientific implications, but can also have key practical applications where ore bodies in the form of e.g., vein systems, intrusions, and stratiform layers are progressively deformed (Hodgson, 1989; Windh, 1995; Laing, 2004; Perret et al., 2020). Despite the concept of vorticity being widely recognised in structural geology (e.g., Xypolias, 2010), its application including an appreciation of the implications for ore deposit evolution has been much more uncommon (e.g., Blenkinsop et al., 2020). Instead, ore deposit models typically treat metalliferous vein systems as planar fractures that propagate with predictable opening modes and orientations relative to an overarching stress field, without considering contemporaneous and progressive rotation or folding (e.g., Sibson, 1996; Robert and Poulsen, 2001). In such models, discrepancies in vein geometry and evidence of successive deformation is typically assigned to separate and polyphase deformation events. In those ore deposit vein models which do document progressive deformation, the vein systems are typically treated as *en-echelon* tension vein arrays with a principal focus on how the geometry of the forming

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ore body evolves with increasing strain (Fig. 1A) (e.g., Laing, 2004). However, the next step into an understanding of more complex vein geometries should involve an appreciation of the complexity of shear zones and how geometric and kinematic reversals can occur along veins during rotation within evolving shear zones and between shear zone pairs (e.g., Fig. 1B and 1C) (Ghosh, 1966; Ramsay et al., 1983b; Hudleston, 1989; Harris, 2003). Lack of this appreciation could lead to metalliferous vein deposits being misinterpreted to have polyphase deformation histories to account for opposing geometric and kinematic indicators that can instead be explained by a single and coherent progressive model (e.g., Fig. 1B and 1C) (after Fossen et al., 2019). A consequence of such misinterpretations might be how metallogenic events relate to the regional structural and tectonic evolution of a province which can subsequently impair exploration models and strategies.

In this contribution, we investigate whether the formation of an economic vein deposit that has previously been interpreted to have formed during successive phases of polyphase deformation can instead be better explained by a progressive formation model. We do this by examining the Cavanacaw (formerly known as the Omagh or Lack) vein-hosted Au–Ag–Pb deposit (>0.5 Moz Au) in Northern Ireland (Fig. 2) (Galantas Gold Corporation, 2014). The hosting Dalradian Supergroup rocks of the Grampian Terrane are part of the Irish-Scottish sector of the Laurentian Caledonian belt which formed during the prolonged Caledonian Orogeny (Ordovician–Devonian), but was locally affected by the later Variscan Orogeny (Carboniferous). The Laurentian Caledonides hosts several auriferous and polymetallic vein deposits and non-economic occurrences that are interpreted to relate to either or both orogenic cycles (Fig. 2) (Pattrick, 1985; Pattrick et al., 1988; Samson and Banks, 1988; Pattrick and Russell, 1989; Earls et al., 1992; Cliff and Wolfenden et al., 1992; Curtis et al., 1993; Earls et al., 1996; Ixer et al., 1997; Wilkinson et al., 1999; Treagus et al., 1999; Parnell et al., 2000; Lusty et al., 2011; Mark et al., 2013; Rice et al., 2016; Tanner, 2014; Rice et al., 2018). For Cavanacaw, previous studies used cathodoluminescence, fluid inclusion, and stable isotope analyses to interpret the deposit to have had a long-lived and polyphase deformation history that was directly associated with the economic mineralisation: the broadly N–S-striking, complexly deformed vein system is inferred to have been initiated during the Ordovician Grampian event of the Caledonian orogeny (*c.* 470 Ma) and to have been mineralised through the reactivation and injection of two distinct regional fluid flow pulses during the Caledonian (470–400 Ma) and Variscan (*c.* 327 ± 13 Ma) orogenies (Earls et al., 1996; Parnell et al., 2000). Earlier studies have further documented broad similarities in ore mineral assemblages, associated gangue phases, and fluid chemistry to interpret the world-class Curraghinalt orogenic gold deposit (>6 Moz Au), located *c.* 27 km to the northeast of Cavanacaw, to be genetically related (Fig. 3) (Earls et al., 1996; Wilkinson et al., 1999; Parnell et al., 2000; Dalradian Resources Inc, 2018). These interpretations above are problematic, however, as: (1) the vein systems at both localities have significantly different strike orientations and kinematics that are not easily reconciled by a common and contemporaneous event; (2) the ore mineralogy and paragenesis between the two deposits actually differs significantly, with arsenopyrite abundant in the primary stage and galena dominating in the secondary stage following intense brecciation at Cavanacaw, whereas these phases are largely absent at Curraghinalt (Earls et al., 1996; Parnell et al., 2000); and (3) gold in the form of electrum differs in alloy composition and is most abundant in the primary sulphide stage at Curraghinalt but is associated with the secondary stage at Cavanacaw (Earls et al., 1996; Chapman et al., 2000; Parnell et al., 2000). The Curraghinalt deposit has recently been dated through $^{40}Ar/^{39}Ar$ (sericite) and Re–Os (molybdenite) to have formed during a *c.* 10 Ma

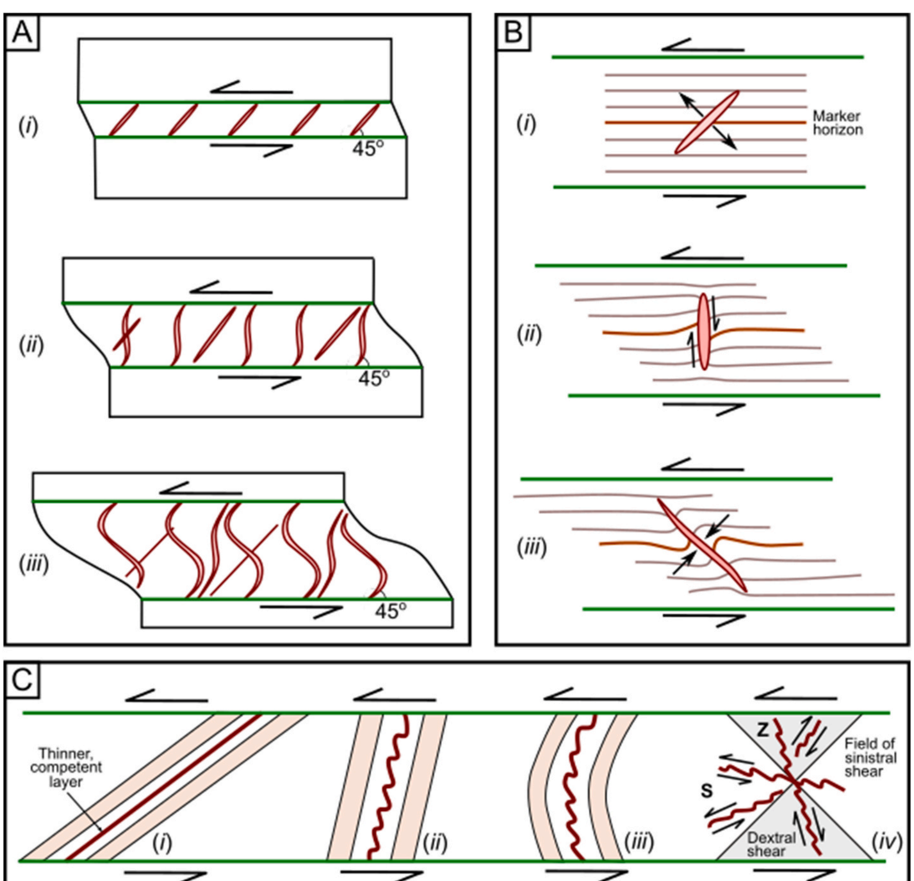


**Fig. 1.** Schematic diagrams displaying how veins can geometrically and kinematically evolve in different ways during progressive deformation within a sinistral shear zone. **(A)** The continuous geometric evolution of sigmoidal *en-echelon* veins with increasing strain (*i* to *iii*) within a progressive shear zone (Ramsay et al., 1983a); **(B)** The evolution of a vein that formed instantaneously during the early shear increments of simple shear (*i*) and was subsequently rotated passively (*ii* to *iii*). Note the development of flanking folds and how their sole interpretation could lead to the wrong sense of displacement along the vein being deduced without the presence of offset horizons (after Hudleston, 1989); and **(C)** The geometric evolution of an inclined vein (*i*) during progressive deformation showing how buckles can preferentially form with an opposite sense of vergence to the overall shear direction within thinner, competent layers (*ii* and *iii*). Diagram (*iv*) shows the fields in which both sinistral and dextral asymmetries (s and z buckles, respectively) can form (after Ghosh, 1966 and Harris, 2003).

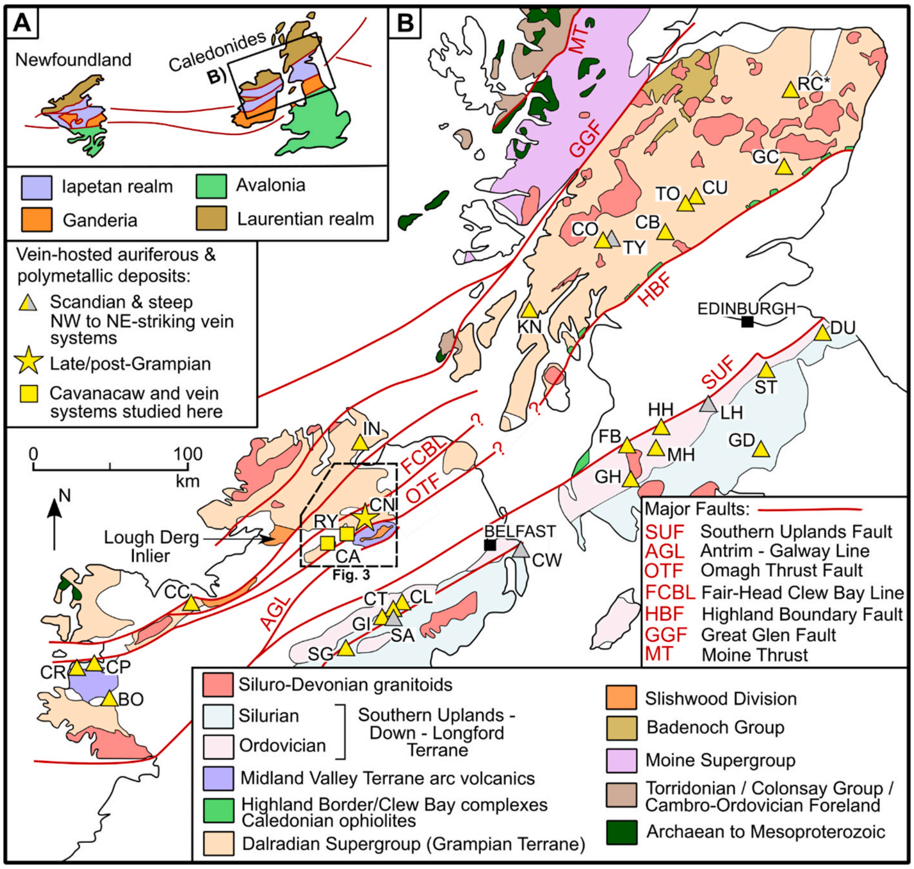


**Fig. 2. (A)** Early Mesozoic restoration of the North Atlantic and the British-Irish and Newfoundland sectors of the Appalachian-Caledonian orogen (modified after Williams, 1984; Hibbard et al., 2007). **(B)** Setting of Cavanacaw and other auriferous and polymetallic vein deposits and occurrences north of the Iapetus Suture in Ireland and Scotland. Deposit/locality abbreviations from SW to NE: **CR**: Creganbaun; **CP**: Croagh Patrick; **BO**: Bohaun; **CC**: Cloonacool; **SG**: Slieve Glah; **GI**: Glenish; **SA**: South Armagh; **CT**: Clontibret; **CL**: Clay Lake; **CA**: Cavanacaw; **RY**: Rylagh; **CN**: Curraghinalt; **IN**: Inishowen; **CW**: Clonlig – Whitespots; **KN**: Knapdale; **FB**: Fore Burn; **GH**: Glenhead; **CO**: Cononish; **TY**: Tyndrum; **HH**: Hare Hill; **MH**: Moorbrock Hill; **LH**: Leadhills; **CB**: Coire Buidhe; **TO**: Tombuie; **CU**: Calliachar-Urlar; **GD**: Glendinning; **ST**: Stobshiel; **GC**: Glen Clova; **RC**: Rhynie Chert*; **DU**: Duns. Curraghinalt is the only known gold deposit to be late to post-Grampian (Ordovician) in age (Rice et al., 2016). Where age data are available (CO and RC) they show Scandian (Early Devonian) ages (Treagus et al., 1999; Mark et al., 2011; Parry et al., 2011; Rice et al., 2012). A Late Caledonian origin is also proposed for CB (by Pattrick, 1984; Smith et al., 2003; Corkhill et al., 2010) and GC (by Coats, 1993) but radiometric age data are still lacking from these. CC is hosted by broadly N–S-striking steep veins (Playfair Mining, 2016); IN is associated with the transcurrent NNW–SSE-striking Glentogher Fault (Arkle Resources, 2019); KN hosts NNE–SSW-striking steep veins at Stronchullin that are comparable to other Scandian auriferous orogenic veins in Scotland (Gunn et al., 1996; Western Gold Exploration, 2020); *RC are not strictly vein-hosted, however, the high-sulphidation epithermal site is auriferous and is dated to be Scandian (Early Devonian) in age. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

window in the Late Ordovician (462.7–452.8 Ma), i.e., during the late/post-Grampian, post-orogenic 'collapse' event (Rice et al., 2016). Few age data from the other known polymetallic systems in the UK and Irish Caledonides exist but the available data from Cononish and Rhynie in Scotland show considerably younger Early Devonian U–Pb (zircon) and $^{40}Ar/^{39}Ar$ (K-feldspar) ages between 412–407 Ma (Fig. 2; Treagus et al., 1999; Mark et al., 2011; Parry et al., 2011; Rice et al., 2012). The implications of the geochronological data in respect to Cavanacaw and other vein occurrences in the Caledonides is yet to be considered despite Curraghinalt being the largest known gold deposit in the UK and Ireland by a considerable margin (>5 Moz Au).

In this study, we demonstrate through the examination and interpretation of largely unpublished archival historic trench and underground maps, as well as through our own structural measurements and observations, that although the wider Cavanacaw area records a polyphase deformation history, the formation of the economic, metalliferous vein system can be explained by a single progressive deformational model. The progressive deformation model accounts for the varying vein orientations and textures, swings in host rock foliation orientations from the regional trend, and opposing vein geometries/kinematics in respect to the overall shear direction. The model produced has significant implications for interpretations regarding the timing and geodynamic setting in which the vein system formed (e.g., Cliff and Wolfenden et al., 1992; Earls et al., 1996; Parnell et al., 2000). We also present analysis from other nearby gold vein occurrences in the western Sperrin Mountains to assess how these may link to Cavanacaw and, in turn, develop a regional structural and tectonic model to account for the large-scale structures that appear to be significant for the economic mineralisation. Finally, we use our analysis to assess how Cavanacaw may relate to both the nearby, and better understood, Late Ordovician and Grampian event related Curraghinalt deposit and to the broader gold and polymetallic vein metallogeny hosted by the Laurentian Caledonian belt of Ireland and Scotland.

## 2. Geological setting and context of metallic mineralisation in the Laurentian Caledonides

The Dalradian Supergroup rocks of the Grampian Terrane that host the Cavanacaw deposit represent a succession of late Neoproterozoic to Cambrian metasedimentary and metaigneous rocks (Figs. 2 and 3). These were deposited onto the southeastern passive margin of the Laurentian continent during the opening of the Iapetus Ocean (*c.* 800–510 Ma) (Cooper and Johnston, 2004). The subsequent convergence of Laurentia with Baltica and Avalonia lead to the closure of Iapetus during the prolonged Caledonian-Appalachian Orogeny, which in the UK and Ireland is subdivided into the Grampian event (Early–Middle Ordovician) and the Scandian event (Silurian–Early Devonian) (McKerrow et al., 2000; Leslie et al., 2008; Stephenson et al., 2013; Chew and Strachan, 2014).

The Grampian event in Northern Ireland initiated with an island arc-ophiolite complex from the Midland Valley Terrane (the Tyrone Igneous Complex) accreting onto an outboard microcontinent block of Laurentia (the Tyrone Central Inlier) (*c.* 475 Ma) (Figs. 2 and 3) (Chew et al., 2008; Cooper et al., 2011; Hollis et al., 2012, 2013). The continuing NW–SE convergence and the closure of the palaeo-ocean between the composite Tyrone Igneous Complex and Laurentia subsequently folded the

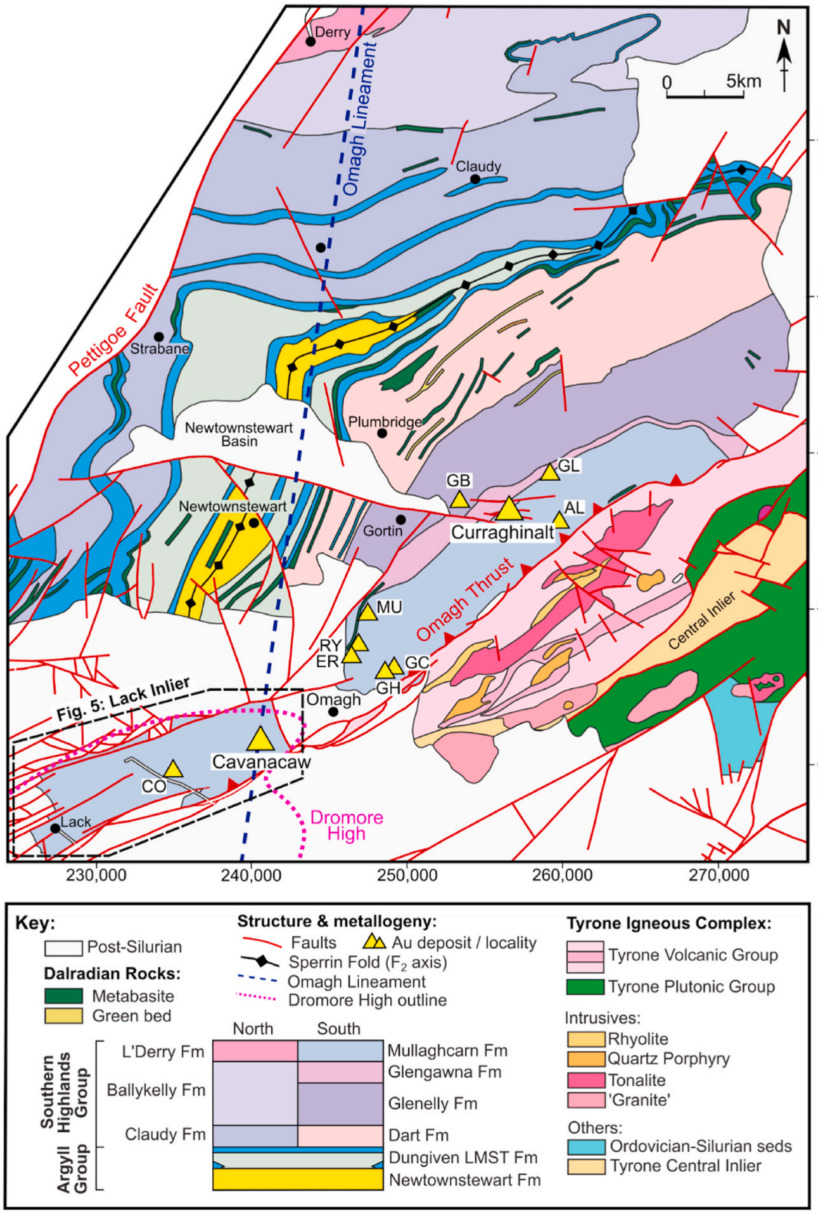


**Fig. 3.** Geological map of the Dalradian Supergroup rocks of the Sperrin Mountains with gold deposits and localities marked (after the geological map of Northern Ireland, 1: 250,000; GSNI, 1997). The Tyrone Igneous Complex is also shown. The current Geological Survey of Northern Ireland interpretation regarding how the Dalradian Supergroup rocks in Northern Ireland correlate is provided in the key. Gold locality abbreviations from SW to NE: **CO**: Cornavarrow; **ER**: Erganagh; **RY**: Rylagh; **GH**: Glenhordial; **GC**: Glencurry; **MU**: Mullaghcarn; **GB**: Golan Burn; **AL**: Alwories; **GL**: Glenlark. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Dalradian Supergroup rocks into recumbent SE-to SSE-verging isoclinal nappes to produce regional stratigraphic repetitions; this closure culminated in ESE-directed oblique-dextral thrusting of the Dalradian nappes over the Tyrone Igneous Complex and Central Inlier along the Omagh Thrust (*c.* 475–465 Ma) (Figs. 3 and 4) (Alsop and Hutton, 1993a). Cavanacaw, as well as the Curraghinalt deposit, are hosted on one of the SSE-verging, overturned limbs of these major isoclinal nappes; the Sperrin Nappe (Fig. 3). At the current exposure level, upper greenschist to lower amphibolite grade metamorphic conditions were reached during nappe formation (Alsop and Hutton, 1993a). The ESE-directed motion of the nappe was principally accommodated by the regional Omagh Thrust Fault, which broadly dips moderately (40°) towards the NW to NNW (Figs. 3 and 5) (Alsop and Hutton, 1993a). The Omagh Thrust Fault is interpreted to be a footwall splay of the steeper, concealed Fair Head–Clew Bay line which is thought to be the continuation of the Highland Boundary Fault in Scotland (Fig. 2) (Max and Riddihough, 1975; Hutton, 1987). The recent geochronological data from the Curraghinalt deposit (*c.* 463–453 Ma) suggests that the vein propagation and mineralisation occurred immediately after the main thrusting and crustal thickening of the Grampian event (Rice et al., 2016). The exact structural setting of the Curraghinalt deposit and its relationship to the overall Grampian orogenic evolution is still unclear as no detailed, deposit-specific structural data and model have yet been published; however, the WNW–ESE-striking vein array appears to be spatially associated with E–W-striking shear zones (Fig. 3). The Curraghinalt mineralisation age is only slightly younger than a suite of *c.* 470–464 Ma calc-alkaline 'stitching' intrusions in the Tyrone Igneous Complex that were interpreted to be associated with subduction polarity reversal (Fig. 3) (Cooper et al., 2011).

The subsequent Scandian event involved a sinistrally transpressive closure of the Iapetus Ocean as Laurentia and its accreted island arc and ophiolite complexes collided with Baltica and Avalonia (Soper et al., 1992). In the UK and Ireland, the regional crustal thickening and metamorphism associated with the 'head-on' Laurentia and Baltica collision (*c.* 440–429 Ma) appears to be largely restricted to the Northern Highland Terrane of Scotland (resulting in the deformation within the Moine Supergroup; Fig. 2), while the Grampian Terrane was either: (1) located several hundred kilometres south of the collision zone (Dewey and Strachan, 2003); or (2) a rigid block within the contractional deformation zone at the leading edges of the colliding plates

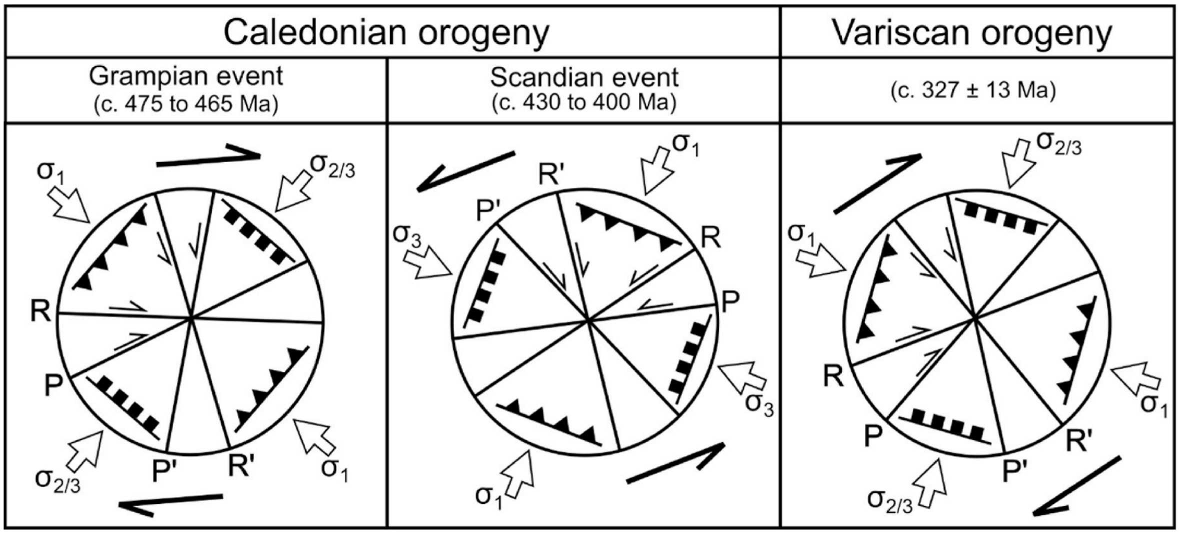


**Fig. 4.** Diagram showing how the main tectonic stresses evolved in the Grampian Terrane of Northern Ireland during the Caledonian and Variscan orogenies; this is: NW–SE-orientated horizontal $\sigma_1$ during the Grampian phase; N–S to NE–SW-orientated horizontal $\sigma_1$ during the Scandian phase; and WNW–ESE-orientated horizontal $\sigma_1$ during the Variscan Orogeny (based on e.g., Alsop and Hutton, 1993a; Mitchell, 2004; Tanner, 2014). Shown also are the respective structures observed in the field or expected based on an idealised Riedel fault and fracture array model.

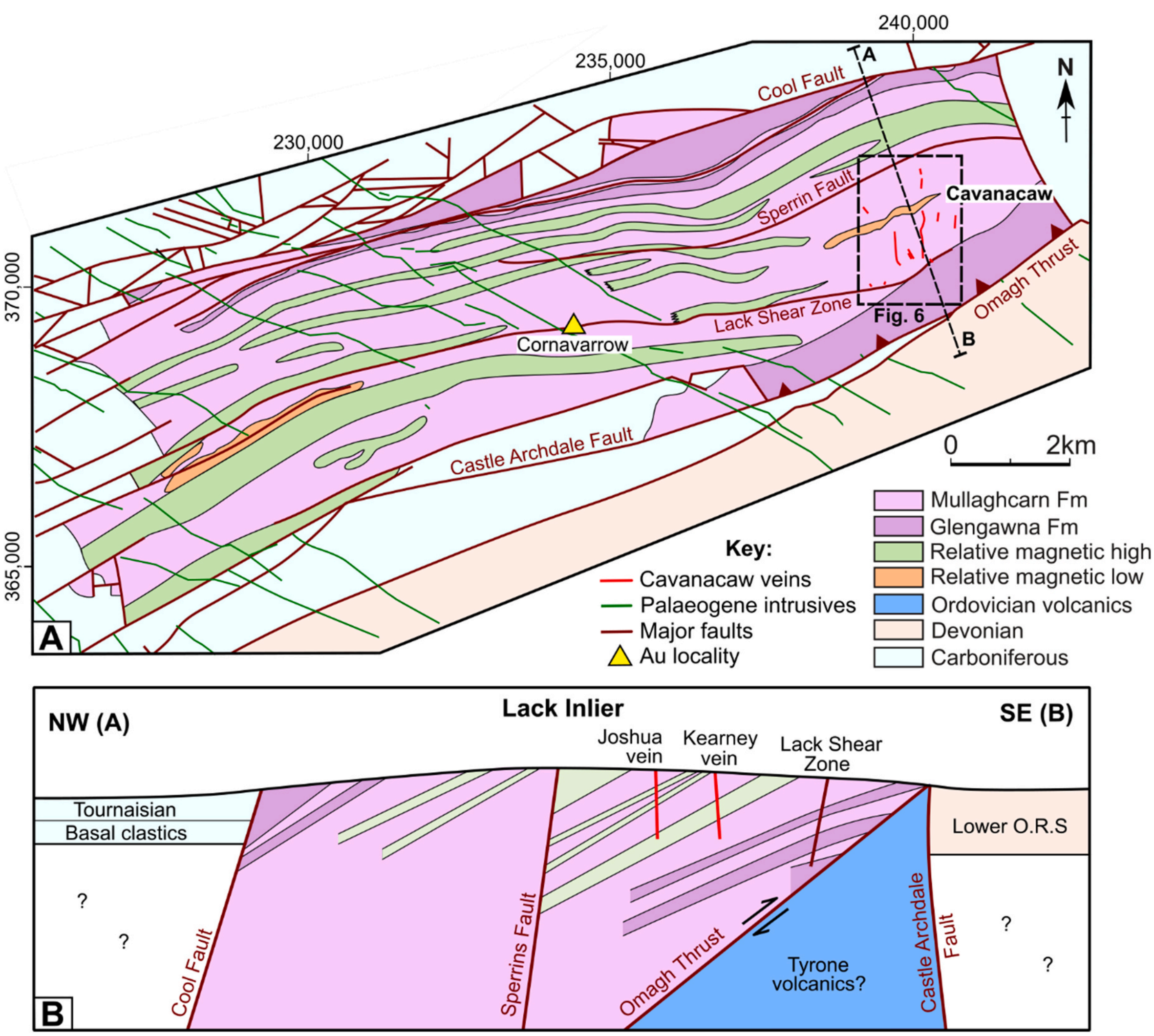


**Fig. 5.** **(A)** Geological map of the Lack Inlier (after McFarlane et al., 2009). The cross-section line section for Fig. 5B is also marked; **(B)** Schematic cross-section through the eastern portion of the Lack Inlier (after Cliff and Wolfenden, 1992). Note that (A) and (B) are not equivalent.

(Leslie et al., 2008). However, the Grampian Terrane was not totally unaffected by the Scandian event. The 'head on' collision may be dated at *c*. 437 Ma (U–Pb zircon age) in the Dalradian Supergroup of Donegal through xenoliths found within a lamprophyre containing a magmatic foliation parallel to that in the host rock (Kirkland et al., 2013). These late-stage regional fabrics are indicative of syn-kinematic emplacement during regional NW–SE compression (Kirkland et al., 2013; Alsop, 1996). The N to NNE-directed Laurentia and Avalonia collision that followed in the mid-Silurian (*c*. 430–425 Ma) emplaced an Ordovician–Silurian fore-arc accretionary complex onto the Laurentian margin (the Down–Longford Terrane in central Ireland and Southern Uplands Terrane in Scotland) (Fig. 2) (Chew and Strachan, 2014; Stone, 2014). This collision was highly oblique, and crustal-scale sinistral strike-slip movement ensued along orogen-parallel NE- to ENE-striking faults and shear zones both within the Grampian Terrane and the accretionary complex to the SE (e.g., Hutton, 1982; Soper et al., 1992; Dewey and Strachan 2003). This event was contemporaneous with the emplacement of voluminous felsic magmatism, possibly during either local or regional transtension interpreted to relate to a slab 'break-off' or delamination (Fig. 2) (Atherton and Ghani, 2002; Cooper et al., 2016; Miles et al., 2016; Anderson et al., 2018). Overall, the regional Scandian, sinistral transpression had been replaced by regional sinistral transtension by the Early Devonian which led to the formation of depositional basins (*c*. 410–395 Ma; Dewey and Strachan, 2003). Deposition was interrupted by the short-lived and northward-directed Acadian (Proto-Variscan) event between *c*. 400–390 Ma where major pre-existing faults and shear zones accommodated sinistral transpression in Scotland (Mendum, 2012).

Apart from Curraghinalt, the only two gold occurrences within the Grampian Terrane that have been dated (Cononish and Rhynie in Scotland) formed during the Scandian event (Fig. 2) (412–407 Ma; Treagus et al., 1999; Mark et al., 2011; Parry et al., 2011; Rice et al., 2012). Cononish, as well as many other metalliferous vein systems such as those at Croagh Patrick and Clontibret – Clay Lake in Ireland, have been interpreted to be hosted by NNE- to NNW-striking Riedel, antithetic Riedel, and tension fractures related to NE to ENE-striking sinistral strike-slip faults and a broadly horizontal, approximately N to NNE-orientated maximum principal stress (see Figs. 2 and 4) (Tanner, 2014; Rice et al., 2018). Most of the known metalliferous vein systems have not yet been studied in detail, but many are spatially related to the post-Grampian to Scandian calc-alkaline granitoids and, at least at Cononish where most data are available, are enriched in metals indicative of a magmatic affinity (e.g., Te, Bi, Mo, Cu, Pb, and Zn) (Curtis et al., 1993; Rice et al., 2018; Spence-Jones et al., 2018).

At least some of the major NE to ENE-striking transcurrent faults were reactivated during the Carboniferous Variscan (Hercynian) Orogeny in response to a broadly WNW–ESE compression (Fig. 4). During the early to mid-Carboniferous, it is interpreted that WNW–ESE-directed compression in Northern Ireland induced a zone of dextral transpression between the Omagh Thrust–Castle Archdale and reactivated Caledonian faults to the southeast, uplifting the Lack and Lisbellaw Inlier basement blocks as a positive flower structure (Mitchell, 2004). The timing of this correlates with the K–Ar model ages (327 ± 13 Ma) presented by Earls et al. (1996) and Parnell et al. (2000) on clay-rich fault-gouge samples collected from across the Sperrin Mountains. The transpression was followed by a switch to extension and the formation of depositional basins (e.g., the Newtownstewart Basin) (Fig. 3; Mitchell, 2004). The end of the Variscan was characterised by a return to oblique-dextral overthrusting along the regional Omagh Thrust Fault (Mitchell, 2004). There seems to have been brittle reactivation of at least some of the metalliferous vein systems during the Carboniferous, responsible for paragenetically late base metal-only mineralisation, particularly at Cononish (Samson and Banks, 1988; Earls et al., 1996; Treagus et al., 1999; Parnell et al., 2000; Lusty et al., 2011). It is notable, however, that the recent geochronology data presented by Rice et al. (2016) suggests that brines of Carboniferous age and origin were not involved in the paragenetically late base metal mineralisation at Curraghinalt as initially proposed by Wilkinson et al. (1999).

## 3. Detailed description of study area

### 3.1. The Lack Inlier

The study area and the Cavanacaw deposit are located within the so-called Lack Inlier, 5 km west southwest of the town of Omagh (Fig. 3). The Lack Inlier is an uplifted and fault-bounded package of Neoproterozoic metamorphic rocks that belong to the Dalradian Supergroup (GSNI, 1995a; Cooper and Johnston, 2004). The foliation within the inlier is parallel to subparallel to bedding and generally strikes ENE–WSW and dips moderately towards to the NNW (Fig. 5) (GSNI, 1995a; Cliff and Wolfenden, 1992). The Lack Inlier consists primarily of schistose psammites, semipelites, and pelites of the Mullaghcarn Formation that are interbedded with basic volcaniclastic rocks of the Largy Volcanic Member (Fig. 5) (GSNI, 1995a; McFarlane et al., 2009). The northern and southeastern margins of the inlier are bounded by the Cool Fault and the Omagh Thrust–Castle Archdale Fault complex respectively, both of which are hosted in the strongly deformed graphitic semipelites of the Glengawna Formation (Fig. 5) (GSNI, 1995a; McFarlane et al., 2009). These ENE–WSW-striking long-lived faults juxtapose the Dalradian Supergroup metamorphic rocks against the younger Upper Palaeozoic sedimentary rocks that surround the Lack Inlier (GSNI, 1995a). A series of other steep ENE–WSW-striking transcurrent faults, such as the Sperrin Fault, are also mapped as internally dissecting the inlier (Fig. 5). Northeast of Omagh, Tyrone Igneous Complex rocks are present in the footwall of the Omagh Thrust Fault (Fig. 3; GSNI, 1995b). The extent of the Tyrone Igneous Complex underneath the Lack Inlier in this area is unknown but a prominent bouguer anomaly (Dromore High; Fig. 3) may indicate its presence at depth (Reay, 2004). A swarm of Palaeogene dykes striking NW to WNW represent the youngest geological feature in the region (Fig. 5) (GSNI, 1995a; Cooper et al., 2012).

### 3.2. The 'Omagh Lineament'

A deep-seated, NNE–SSW-trending crustal lineament has been interpreted to run through the eastern part of Lack Inlier and the Cavanacaw deposit (Fig. 3) (Earls et al., 1996; Parnell et al., 2000; Cooper et al., 2013). This 'Omagh Lineament' is inferred to extend along strike for an overall length of 70 km from Drumahoe in County Londonderry (NNE) to Tempo in County Fermanagh (SSW). The Omagh Lineament is one of many N to NNE-striking deep-seated crustal lineaments that are inferred to exist across Scotland and Ireland that may be as old as 1800 Ma (Russel and Hazeldine, 1992; Hutton and Alsop, 1996; Earls et al., 2000; Cooper et al., 2013). The Omagh Lineament is a rather weak feature on geophysical surveys (e.g., Tellus surveys; GSNI, 2007a) and its existence is largely inferred based on the presence of the N–S-striking Cavanacaw vein system; a significant swing in the strike of the Dalradian metamorphic rocks from ENE–WSW (075°–255°) strikes to NNE–SSW (030°–210°) strikes; the rare occurrence of a basic Palaeogene dyke (Cooper et al., 2012) and the eastern extent of the quartz porphyry 'Sperrin Mountains Suite' of minor intrusions (Cooper et al., 2013); N–S-striking minor faults; and by the approximate location of the eastern margin of the Dromore High bouguer anomaly (Fig. 3) (GSNI, 1997; Reay, 2004; Cooper et al., 2013). The most prominent feature of these is the significant swing in strike of the Dalradian metamorphic rocks across the Newtownstewart region, just north of the Lack Inlier; we call this feature the 'West Sperrin Knee Bend' (Fig. 3). According to our interpretations in this paper, the West Sperrin Knee Bend plays an important role in the development of the mineralisation and regional deformation.

### 3.3. The Cavanacaw resource, ore mineralogy, and paragenesis

The Cavanacaw deposit has a measured resource of 32,202 oz at 7.24 g/t Au, an indicated resource of 147,784 oz at 6.78 g/t Au, and an inferred resource of 341,123 oz at 7.71 g/t Au according to most recent estimates (Galantas Gold Corporation, 2014). Ag is alloyed with the Au, with average assay results ranging between 1 and 2.5 parts of Ag to 1 part of Au (Galantas Gold Corporation, 2014). Assay results further report up to several percent Pb in the veins (Galantas Gold Corporation, 2014). The Au–Ag–Pb resource is structurally hosted by steep 1–3 m wide zones of quartz-sulphide veining, shearing, and sericite alteration that cross-cut the host rock and foliation fabrics (Fig. 6A) (Cliff and Wolfenden, 1992). Most of the resource is hosted by the Kearney vein structure which was historically exploited in an open excavation pit (now mostly infilled) and is currently being mined in a series of underground tunnels (Fig. 6A). The discovery and exploration history of the deposit is detailed extensively in Cliff and Wolfenden (1992) and Galantas Gold Corporation (2014, 2020).

Several sulphide phases are present in the veins but the most common are aggregates of pyrite (Py) and arsenopyrite (AsPy) which are typically intensely brecciated and cemented/replaced by undeformed galena and chalcopyrite (Fig. 6B) (Cliff and Wolfenden, 1992). Minor carbonate can also be found in the quartz veins (Cliff and Wolfenden, 1992). The primary, pre-breccia Py–AsPy dominated stage is suggested to be related to broadly Caledonian (470–400 Ma) fluids with a significant magmatic component by Earls et al. (1996) and Parnell et al. (2000), based mostly on extrapolation of analysis undertaken at Curraghinalt. The secondary sulphide stage is dominated by base metals, particularly galena, followed by a late phase of carbonate-rich mineralisation (Fig. 6B; Earls et al., 1996; Parnell et al., 2000). Analysis of fluid inclusions in the late quartz phases at Cavanacaw indicate high salinity brines which were interpreted to relate to basinal fluids mobilised during the Variscan orogeny (Earls et al., 1996; Parnell et al., 2000). Relatively low fluid inclusion trapping pressures have been interpreted to suggest the mineralisation was precipitated at epizonal crustal depths (<5 km) (Earls et al., 1996; Parnell et al., 2000). The repeated localisation of deformation and fluids into the Cavanacaw vein system is attributed to the structural reactivation of the Omagh Lineament (Earls et al., 1996; Parnell et al., 2000).

Electrum (Au, Ag) is typically anhedral, located along narrow 1–50 μm wide fractures in pyrite and spatially-associated with quartz/Py boundaries, implying that electrum precipitated during the second, breccia-related deformation stage along with base metal sulphides (Cliff and Wolfenden, 1992; Earls et al., 1996; Chapman et al., 2000; Parnell et al., 2000). Au can also be found as trace substitutions within the galena (up to 1.2 at. % Au) (Earls et al., 1996; Parnell et al., 2000). It is currently unclear whether the Au was remobilised from the first-stage Py–AsPy phase during this second deformation stage.

The alteration halos around the larger veins are typically comprised of sericitised and bleached host rock that can extend outwards for several metres before grading into unaltered wall rock (Cliff and Wolfenden, 1992). Black sulphidic clay-rich fault-gouge can also form part of the alteration halo (Cliff and Wolfenden, 1992). These alteration halos are most prolific in quartz-poor metasedimentary host rocks such as graphitic semipelites and are associated with sulphides and veinlets (Cliff and Wolfenden, 1992). McFarlane et al. (2009) identify laterally persistent (up to 4 km long) ENE–WSW-striking zones that show relatively low magnetic responses and are in the field thoroughly sericitised and silicified (Fig. 5A).

### 3.4. The Cavanacaw deposit structural setting

A 150–200 m wide structure that relates to zones of high conductivity identified through an induced polarisation survey, the Lack Shear Zone, crosses the Cavanacaw area, striking ENE–WSW and dipping steeply to the N (Figs. 5 and 6A). The Cavanacaw vein system is dominated by major N–S-striking veins to the north of the Lack Shear Zone (e.g., Kearney and Joshua veins; Fig. 6A). Another important, subsidiary NNW–SSE-striking vein system also exists to the south of the shear zone (e.g., Discovery, Gormley, Sharkey veins; Fig. 6A). These two broad veining zones are hereafter referred to as the 'Kearney zone' and 'Creevan zone', respectively (Fig. 6A).

The N–S-striking veins in the Kearney zone are more continuous along strike, with the Kearney vein drill-tested to continue for at least 850 m and to extend to at least 300 m depth. In the Creevan zone, the vein system consists of a series of NNW–SSE-striking veins with limited along strike continuity (<200 m). The Creevan zone veins and the Lack Shear Zone are located near the lithological boundary between the Mullaghcarn Formation and Glengawna Formations along the Creevan Burn stream section (Fig. 5; McFarlane et al., 2009; Galantas Gold Corporation, 2020).

All veins are vertical or dip steeply (towards east or west) irrespective of strike orientation. Initial workers interpreted the N–S-striking veins to be antithetic principal (P′) shears and the NNW–SSE-striking veins to be subsidiary antithetic Riedel (R') shears within an overall reverse-dextral shear zone system of the Omagh Thrust that formed during broadly NW–SE-directed Grampian compression (Fig. 4; *c.* 475–465 Ma) (Cliff and Wolfenden, 1992). The specific localisation of the vein system was later attributed to partitioning of Grampian strain along the Omagh Lineament (Earls et al., 1996; Parnell et al., 2000). The N–S-striking Kearney vein was interpreted to be hosted by a co-planar shear zone with sinistral displacement, whilst the subsidiary NNW–SSE-striking veins were interpreted to be later structures that cross-cut and displace the principal structure (Cliff and Wolfenden, 1992; Earls et al., 1996; Parnell et al., 2000). This kinematic framework is further reported to be replicated in nearby N–S-striking regional veins, such as the Rylagh gold vein locality which also records sinistral kinematics (Fig. 3; Earls et al., 1996; Parnell et al., 2000). Several regional veins such as Rylagh are hosted on the NNE–SSW-striking limb of the West Sperrin Knee Bend proximal to the Omagh Thrust Fault (<5 km distance) (Fig. 3).

The interpretation of a Variscan phase within the Cavanacaw vein system (by Earls et al., 1996; Parnell et al., 2000) is based on model ages derived from isotope studies (K–Ar and Rb–Sr) on clay-rich fault-gouge sampled from the Kearney vein and low angle thrusts along the Creevan Burn stream section and regionally across the Sperrin Mountains (mean age of 327 ± 13 Ma) (Earls et al., 1996; Parnell et al., 2000). These ages were used to further support the interpretation that the paragenetically late base metal phase of mineralisation was precipitated during the early Carboniferous (Earls et al., 1996; Parnell et al., 2000). Variscan reactivation is also used to account for the interpretation that the Lack Shear Zone apparently displaces the Cavanacaw vein system in a dextral sense, and for dextral movements on several small-scale faults along the Creevan stream section (Fig. 6A; Cliff and Wolfenden, 1992). In this paper, we present a re-interpretation of the kinematic models and inferred ages outlined above.

## 4. Methodology

### 4.1. Data collection and sources

The structural data presented in this study includes observations and measurements collected directly in the field, as well as that compiled from historic exploration data. At Cavanacaw, the historic data includes a collection of trench, stream section, and underground geological maps produced historically by RioFinex North Limited (once a subsidiary of Rio Tinto) in the 1980s (when the deposit was discovered) and more recently by Galantas Gold Corporation (current operators). The Kearney zone was until recently exposed in an open excavation pit (Fig. 7A–F) and historically in a series of major exploration trenches produced by RioFinex and Galantas (e.g., Figs. 9, 10A, and 11B). The pits and trenches are now mostly infilled, and the Kearney zone veins are

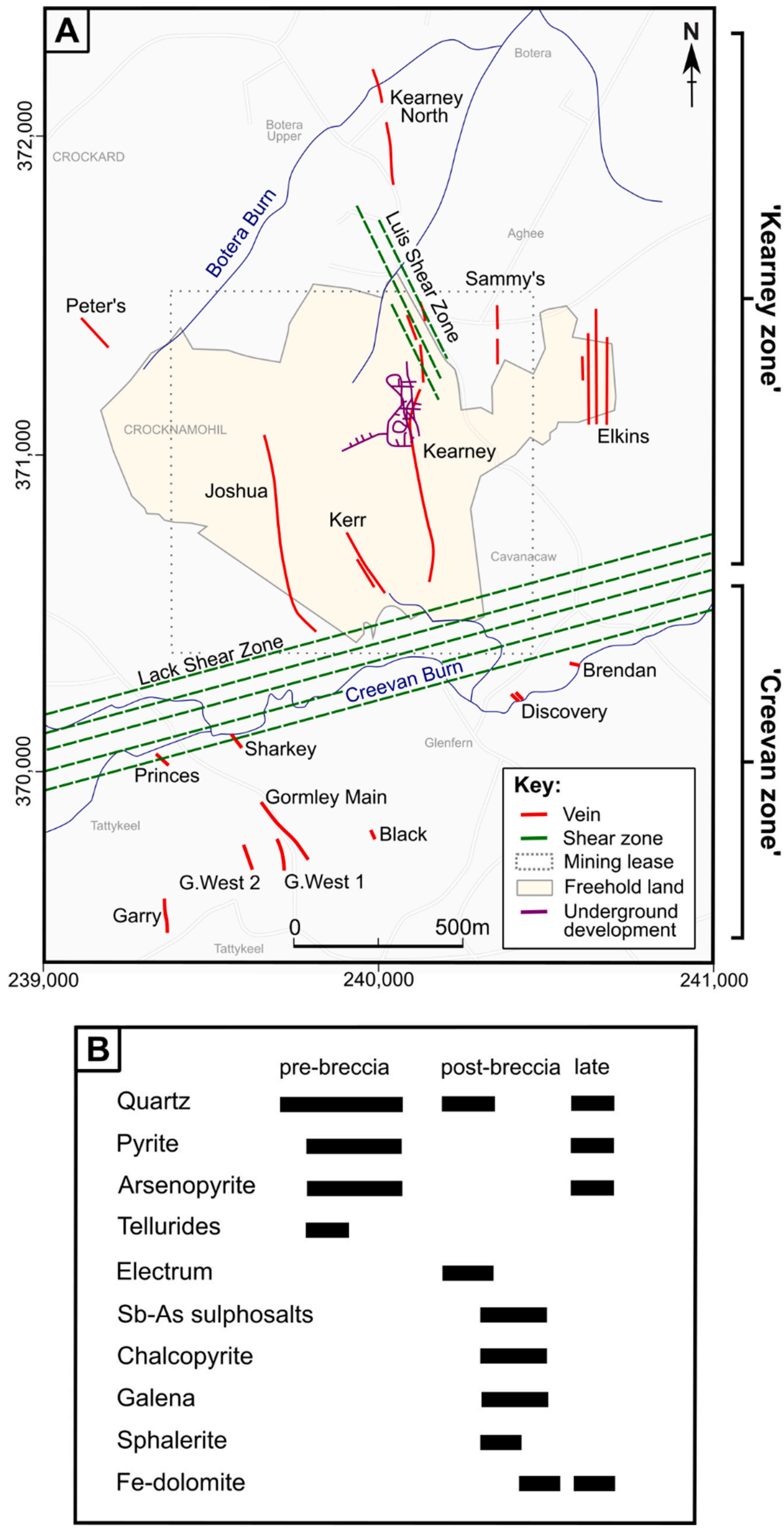


**Fig. 6.** **(A)** Geological map of the Cavanacaw deposit displaying the locations of the major named veins and shear zones (after Cliff and Wolfenden, 1992). The broad locations of the Kearney and Creevan zones are also marked at the side of the map; **(B)** Paragenetic sequence at Cavanacaw according to Earls et al. (1996) and Parnell et al. (2000).

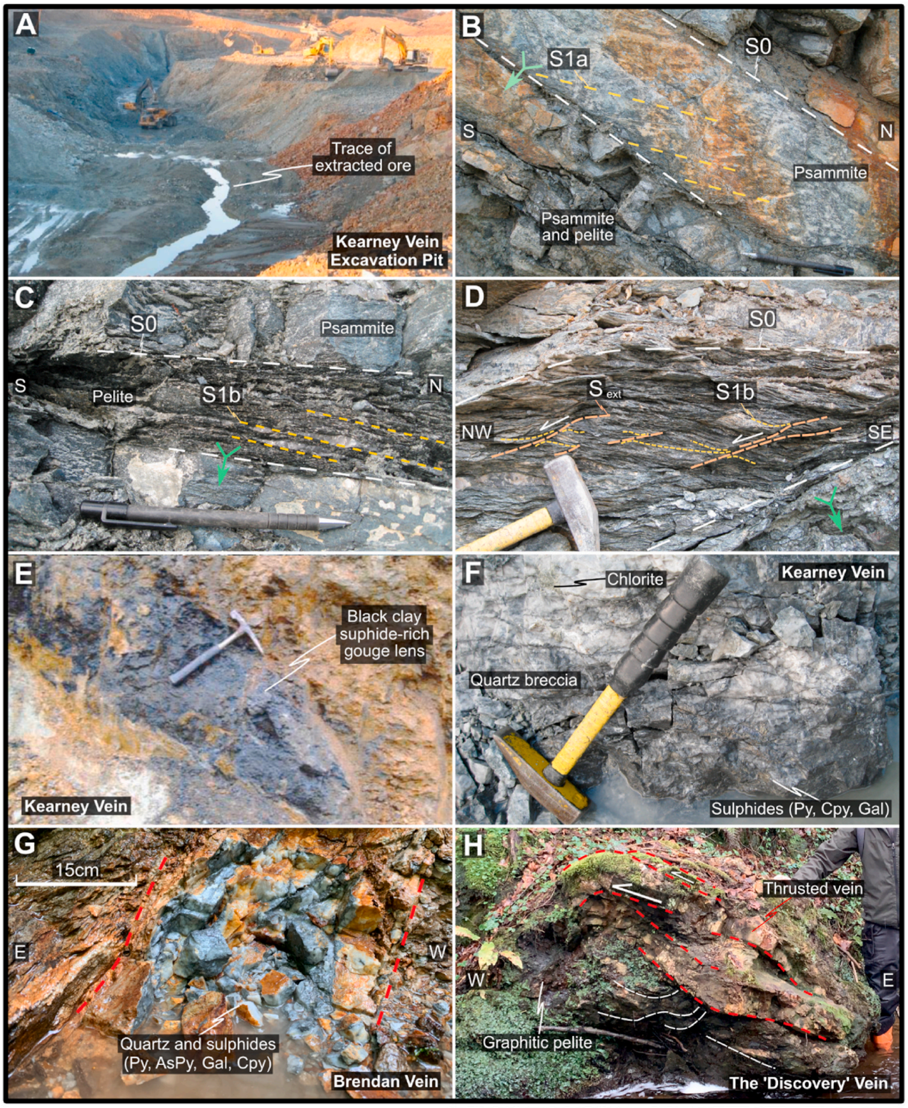


**Fig. 7.** Photographs of **(A)** the trace of the Kearney vein excavation in the open pit in February 2008 (from Galantas Gold Corporation, 2008); **(B)** The relationship between $S_0$ bedding in psammitic host rock and the shallower dipping $S_{1a}$ shape fabric in the Kearney open excavation pit; **(C)** The relationship between interbedded psammites and semi-pelite in the Kearney open excavation pit. Note the $S_{1b}$ fabric is localised in the semi-pelites and dips more steeply than bedding; **(D)** Extensional crenulation cleavage deforming the semi-pelites and $S_{1b}$ fabric in the Kearney open excavation pit; **(E)** Lens of black sulphide clay gouge in the Kearney open excavation pit (from Galantas Gold Corporation, 2008); **(F)** Quartz breccia texture with associated sulphide mineralisation in the floor of the Kearney open excavation pit; **(G)** The Brendan vein along the Creevan Burn stream section with associated quartz and sulphide mineralisation; and **(H)** Internal imbrication of the thrusted Discovery vein along the Creevan Burn stream section.

currently exposed in a series of underground exploration tunnels that exceed 2 km in length over four levels (Fig. 10B). The Creevan zone is primarily exposed for over 2 km along the Creevan Burn stream section which exploits and strikes parallel to the Lack Shear Zone (e.g., Fig. 7G, 7H, and 8). Creevan zone veins were historically exposed in several exploration trenches produced by RioFinex (now all infilled) (Figs. 11A and 11C–F). The authors of the historic exploration data are highlighted where known, however in many cases the authors of the RioFinex trench maps are unfortunately not recorded and the data was found archived at the Cavanacaw mine site. For the most part the trench maps have not been previously published, though a relatively small portion of the northern Kearney exploration trench (part of Fig. 9D) is presented in Cliff and Wolfenden (1992) and the exploration trench maps of the Kerr vein array (Fig. 10A) are presented in Galantas Gold Corporation (2008). The underground maps of the Kearney vein (see Fig. 10B) have recently been published in Galantas Gold Corporation (2020) to document the occurrence of ore shoots. Additional field data include a geological map of the Creevan Burn stream section (Fig. 8A; Galantas Gold Corporation, 2020).

Most of our regional vein data was collected in the field along poorly exposed stream sections. For comparison, we also have structural data from a detailed geological map from another vein system, the Rylagh vein *c.* 5 km NE from the Cavanacaw mine (Fig. 3 and 12). This vein system was visited in the field to ground check the map. Digital structural data provided by the Geological Survey of Northern Ireland (GSNI) has also been compiled to analyse regional structures such as the West Sperrin Knee Bend. This digital data originates from the Omagh, Draperstown, and Newtownstewart 1: 50,000 geological mapping sheets (GSNI, 1995a, 1995b, 2008).

We combine the existing maps and material with our own field observations to propose a new, more comprehensive, holistic interpretation of the structure of the Cavanacaw system. Regardless of where the data was collected or compiled from, particular attention has been paid to host rock foliation fabrics and their relative orientations, the geometry and cross-cutting relationships of the vein and fault structures, the kinematics of the structures (from e.g., displacements and foliation drag), the textures of veins and whether structures are sulphidic and therefore likely to be associated with the metallic mineralisation. This has enabled a deformation sequence to be established for the host rock foliation fabrics, vein and faults systems, and reveals how the economic mineralisation relates to these.

### 4.2. Data analysis

The structural data for the different areas analysed (i.e., the Kearney zone, Creevan zone, and regionally), as well as data for the individual

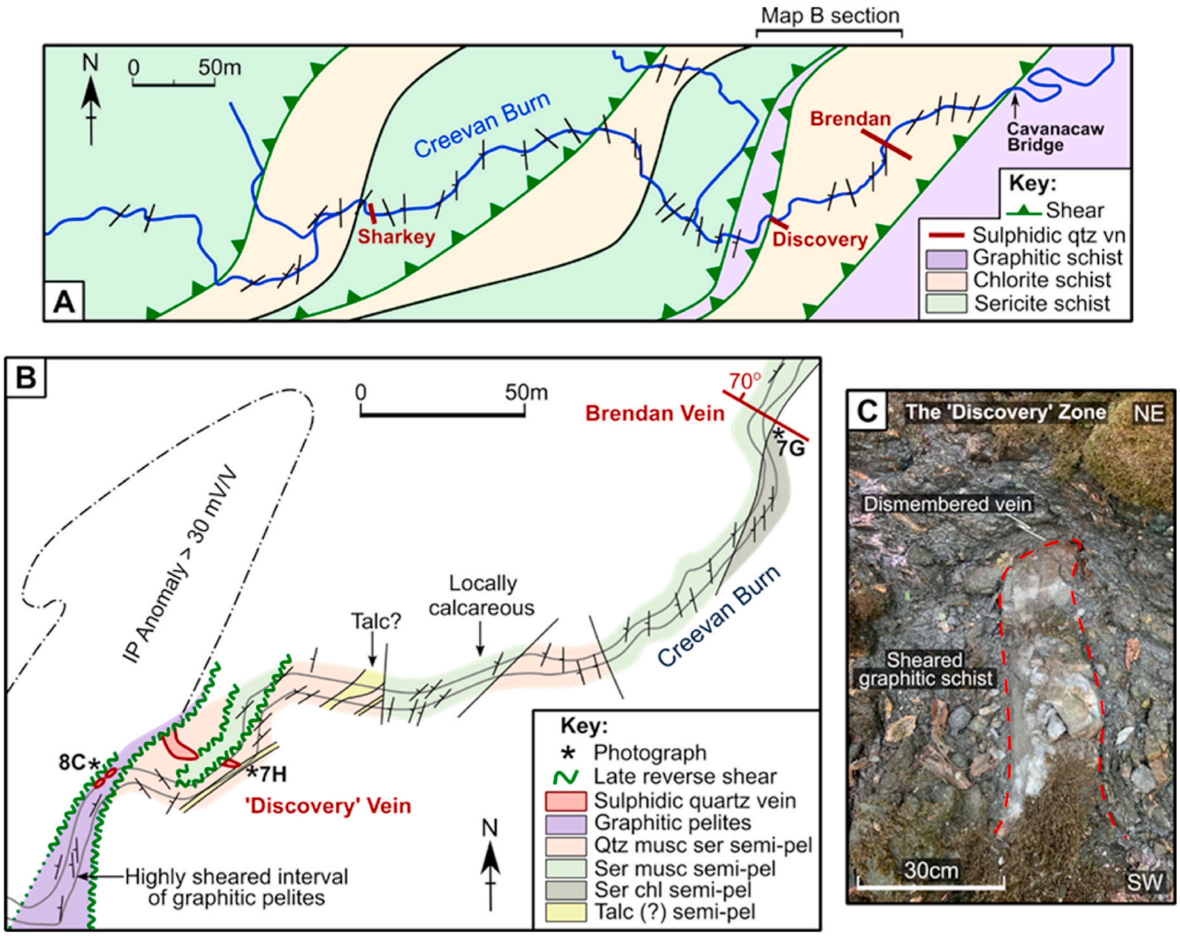


**Fig. 8.** **(A)** Broad geological map of the Creevan Burn stream section (after Dr Sarah Coulter and other Galantas geologists in Galantas Gold Corporation, 2020); **(B)** Detailed geological map of the Discovery vein along Creevan Burn, including the locations of the photographs in Fig. 7G and 7H and Fig. 8C; and **(C)** Photograph of the sheared graphic pelites and an entrained mineralised vein in the Discovery zone.

vein and fault populations, were plotted on equal angle stereonets using Rick Allmendinger's stereonet application (Table 1, Fig. 13). The diagrams also illustrate textural variability and sulphide content (see key in Fig. 13). Mean vectors of the rose diagrams were calculated as well as the 1% area contouring of the calculated poles (Table 1; Fig. 13). Using the stereonets we analyse how the structure orientations and kinematics compare to a theoretical Riedel fault model for transcurrent simple shear (after Wilcox et al., 1973) (Fig. 14). The kinematic analysis allows us to interpret what the orientation of the principal stresses was when the vein and fault systems formed (Fig. 14). This approach has proven successful for confining and interpreting the palaeostress fields responsible for other steeply dipping to vertical auriferous vein and fault systems hosted by the Laurentian Caledonides of Ireland and Scotland (see Tanner, 2014).

## 5. Observations

### *5.1. Cavanacaw host rock lithologies and structural fabrics*

The main host rock lithologies and structures observed at Cavanacaw are consistent with those observed and detailed by Cliff and Wolfenden (1992), McFarlane et al. (2009), and Galantas Gold Corporation (2020). Exposure in the open excavation pit shows heterolithic psammitic and semi-pelitic metasediments dominate in the Kearney zone (Fig. 7B–D). The Creevan Burn stream section transverses through various host rock lithologies (Fig. 8): graphitic pelites, typically interbedded with layers of quartzo-feldspathic semi-pelites, dominate to the east of the Cavanacaw bridge, whilst mixed quartz-muscovite semi-pelites, which can be sericitic and/or chloritic, dominate to the west (Fig. 8). As observed by McFarlane et al. (2009), intervals and disseminations of fuchsite, pyrite, and metacarbonate pods have been identified in the graphitic pelites, whilst intervals of possible talc-bearing metasediments have been observed across all lithologies. An interval of graphitic pelite (up to 15 m thick) is also observed upstream of the Discovery vein and is intensely deformed and exploited by a shallowly NW to WNW-dipping reverse shear zone (Fig. 8). The repetition of units across the area may imply that tectonic imbrication exists in the Creevan zone (Fig. 8A). This interpretation is compatible with the broader geological mapping of the Creevan Burn stream section presented in Galantas Gold Corporation (2020).

The host rock sequence across the Cavanacaw area is inverted, which is evidenced by graded bedding in massive psammite units downwards into relatively heterolithic psammite/pelites (i.e., structurally inverted graded bedding), and sharp lithological changes between psammite-dominated layers and structurally overlying semi-pelite-dominated layers. Two pervasive ductile planar fabrics are identifiable in the host rocks (Fig. 7B and 7C). The first, best developed in the psammitic host rocks, is a pervasive grain-shaped fabric defined by the preferential alignment of mica ($S_{1a}$) and dips more shallowly to the NW than bedding ($S_0$) (Fig. 7B). Elliptical quartz grains in the psammites also defines this fabric. In the semi-pelitic host rocks, a second penetrative, pervasive fabric crenulates the earlier fabric (interpreted as $S_{1b}$) and is marked by the strong parallel alignment of muscovite and chlorite that dips relatively steeper to the NW than $S_0$ (Fig. 7C). $S_{1b}$ envelopes elongated

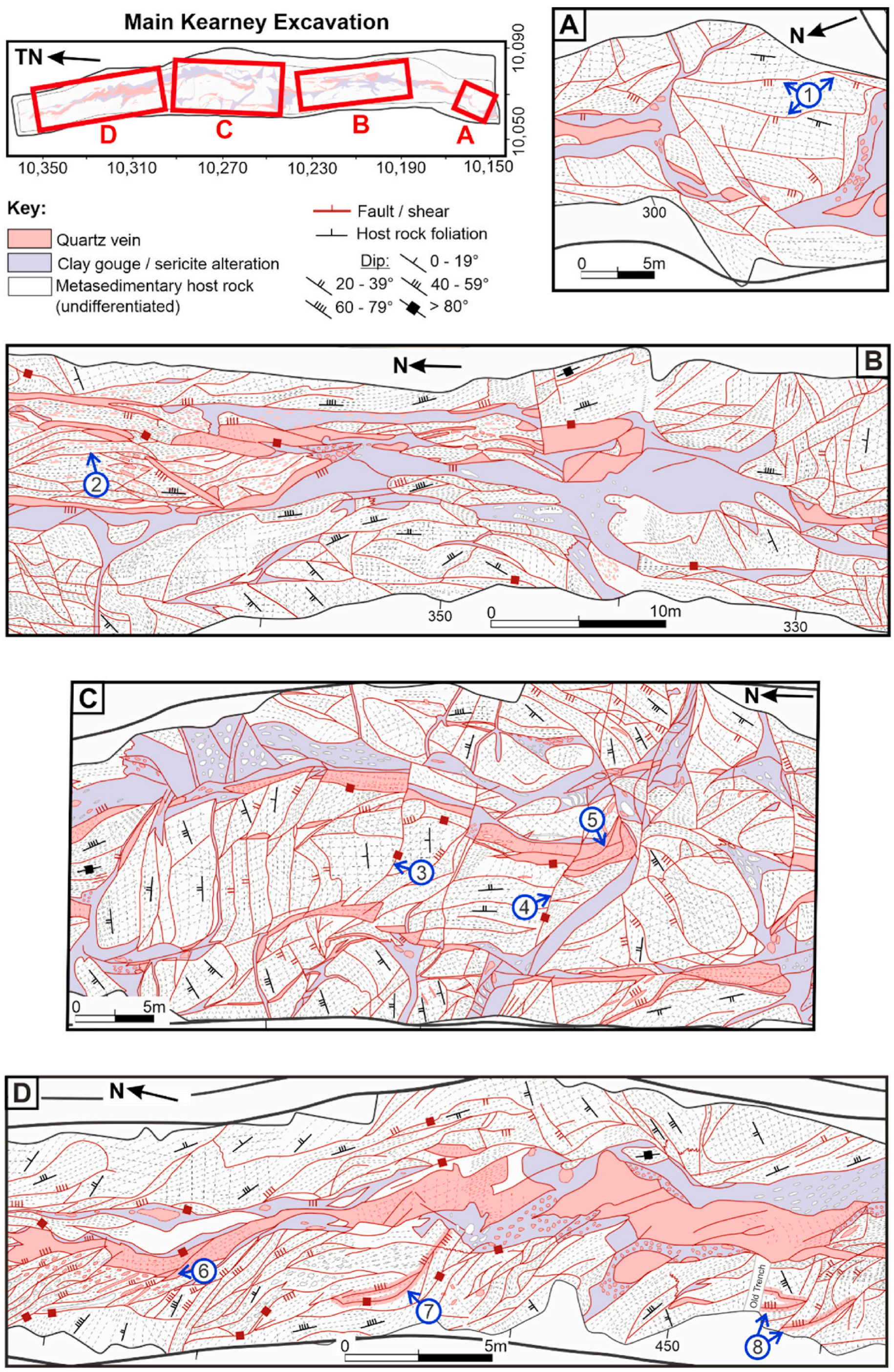


**Fig. 9.** Detailed geological trench maps of the Kearney vein in the so-called northern exploration RioFinex trench (produced by Simon Tear perhaps among others). The locations of each trench map in respect to one another is provided in the key. The blue circles that contain numbers represent specific sites discussed in the text. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

lenticular ribbons and augen of metamorphic quartz vein, whilst cm-scale dark green to black porphyroblasts of chlorite (retrogressed garnet) are also developed along the schistosity. Both $S_{1a}$ and $S_{1b}$ are consistent with overall overturning and thrusting of the Sperrin Nappe. Locally, an extensional crenulation cleavage ($S_{ext}$) can be found to deform $S_{1b}$ in the semi-pelites, suggesting a relatively late episode of top-down-to-NW movement (Fig. 7D).

The average strike of the composite, sub-parallel bedding-foliation fabric in the host rock differs between the Kearney and Creevan zones; these, in turn, differ from the average strike of the host rock bedding-foliation fabric observed regionally across the Lack Inlier (Fig. 13B, 13E, and 13J). Across the eastern and central portions of the Lack Inlier, the composite host rock fabric strikes ENE–WSW (076°–256°) and dips moderately (49°) towards the NNW (Fig. 13J). In the Kearney zone, the strike of the host rock fabric is orientated anticlockwise of that observed in the Lack Inlier and strikes NE–SW (055°–235°) and dips moderately (36°) towards the NW (Fig. 13B). Finally, the strike of the host rock fabric in the Creevan zone is orientated anticlockwise of those observed in the Lack Inlier and Kearney zone, and strikes NNE–SSW (019°–199°) and dips moderately (41°) towards the WNW (Fig. 13E). In the Creevan zone, this produces a marked, low-amplitude s-shaped swing in the strike of the host rock foliation as the Lack Shear Zone is transected

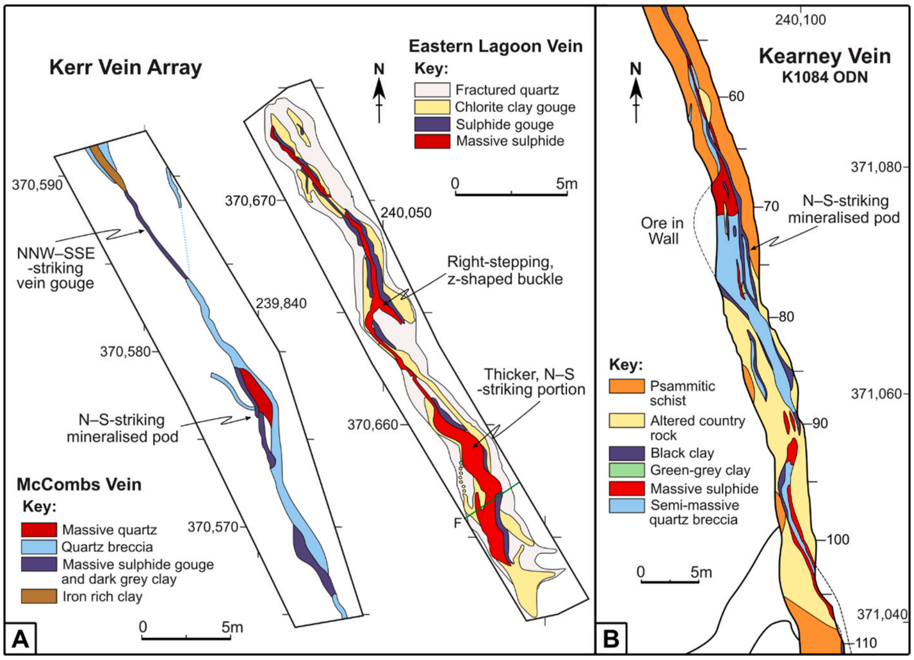


**Fig. 10.** **(A)** Geological trench maps of the McComb vein (left) and Eastern Lagoon vein (right) in the Kerr vein array of the Kearney zone, respectively, including ore textures (after James McFarlane in Galantas Gold Corporation, 2008); **(B)** Underground geological map at chest height of a portion of the Kearney vein that also includes ore textures (after Zoë Brown in Galantas Gold Corporation, 2020). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(hereafter, the 'Creevan swing') (see Fig. 8A). There is no significant change in the dip across the zones, however dip is somewhat shallower in the Kearney (36°) and Creevan zones (41°) than in the eastern and central portions of the Lack Inlier (49°) (Table 1, Fig. 13B, 13E, and 13J).

### 5.2. Cavanacaw mineralised veins

The mineralised vein strikes range from NNE to WNW across both the Kearney and Creevan zones (Fig. 13A and 13D). However, the average vein strike differs between the Kearney and Creevan zones; being N–S (171°–351°) and NW–SE (139°–319°), respectively. The veins are typically vertical to steeply dipping in both zones (on average 69° and 74°, respectively) (Table 1; Fig. 13A and 13D). Note that the mean dip values in Table 1 are likely to be an underestimate as vein dip only seems to have been measured and plotted on the trench maps when deviating from subvertical. The veins range in thickness from mm-wide veinlets to up to 3 m wide tabular veins (Figs. 8–11). They are typically, though not always, enveloped by clay-rich fault-gouge that can entrain clasts of mineralisation derived from the central vein(s) (Fig. 9). A sericite alteration zone that can exceed 5 m in width around the veins is also common, especially around the major veins. Host rock adjacent to the vein can also be mineralised, especially where heavily jointed and/or faulted (Fig. 9B site 2). The major veins in both the Kearney and Creevan zones strike at a relatively high angle to the strike of the host rock foliation (typically ~45°; Fig. 13A and 13B, Fig. 13D and 13E), although the host rock fabric can vary significantly around the veins or swing into parallelism with the vein (e.g., Fig. 9).

The RioFinex trench plans in Fig. 9 present the most detailed vein and host rock maps and data for the Kearney vein which was captured in the northern exploration trench. It is hosted within a complex high-strain shear zone that causes the adjacent host rock to proximally swing into parallelism with the structure (Fig. 9). The Kearney vein is mapped to be continuous along strike in the trench and in underground exposure but does exhibit a classic 'pinch' and 'swell' geometry, ranging from 0.01 to 3 m in thickness (Figs. 9 and 10). The vein is also mapped to occasionally split into arrays of smaller veins (<1 m thick), such as in the centre of the northern exploration trench, before coalescing back into a tabular vein (Fig. 9B and 9C). Although the orientation of the broadly N–S-striking Kearney vein is generally consistent in both the exploration trenches and in underground exposure, variations are common along the strike of the vein, including a prominent z-shaped buckle in the RioFinex southern exploration trench (Fig. 11B). Although less pronounced, similar z-shaped buckles are also mapped by Galantas in the Eastern Lagoon vein within the Kerr vein array (Fig. 10A), and in the Kearney vein underground (Fig. 10B).

Where the internal textures of the veins in the Kearney zone have been mapped in detail by Galantas, it is evident that the vein zones are assembled of relatively thick pods (up to 3 m) of massive sulphide and quartz breccia that are enveloped and connected by thinner (0.1–1 m) veins and zones of black clay-rich fault-gouge (Fig. 10). The mineralised pods are mapped to occur every 55–65 m along the strike of the Kearney vein underground (Fig. 10B). There are subtle differences in the strike of these two internal vein components: with the N–S-striking mineralised pods striking slightly clockwise (179°–359°) of the NW to NNW-striking black clay-rich fault-gouge veins (161°–341°) (Figs. 10 and 13A). In the McCombs vein within the Kerr vein array, and in the Kearney vein underground, this produces an internal low amplitude, right-stepping geometry (Fig. 10). Unfortunately, the host rock foliation has not been mapped underground or in the Kerr exploration trenches to assess how this interacts with the different vein components.

Like the veins in the Kearney zone, the veins in the Creevan zone are strongly deformed, and internally comprise of mineralised quartz pods and veins that are contained within a broader and complex zone of fault-gouge and alteration (e.g., Fig. 11A). It does appear, however, that the textures and kinematics of the Creevan veins change with structural orientation from WNW to NNE-striking (Fig. 13D). The major veins can be internally imbricated by late reverse shears which strike in the same WNW to NW-strike trend (detailed in next section), most evident at the Discovery vein outcropping along Creevan Burn and in the Sharkey vein trench map produced by RioFinex (Figs. 7H and 11E). The veins also appear to drag the foliation in a dextral sense, although no marker horizons are mapped to confirm this is the true shear sense along the structures (e.g., Fig. 11E). Like in the Kearney zone, an abrupt z-shaped buckle is recorded in the NW–SE-striking portions of the strongly deformed Sharkey vein (Fig. 11C). Arrays of mm-wide veinlets striking NNE–SSW (030°–210°) appear to record WNW–ESE (120°–300°) dilational opening vectors in the Sharkey vein trench (Fig. 11E and 11F). Unlike the major veins in both the Kearney and Creevan zones, these subvertical veinlets strike at a relatively low angle to the strike of the

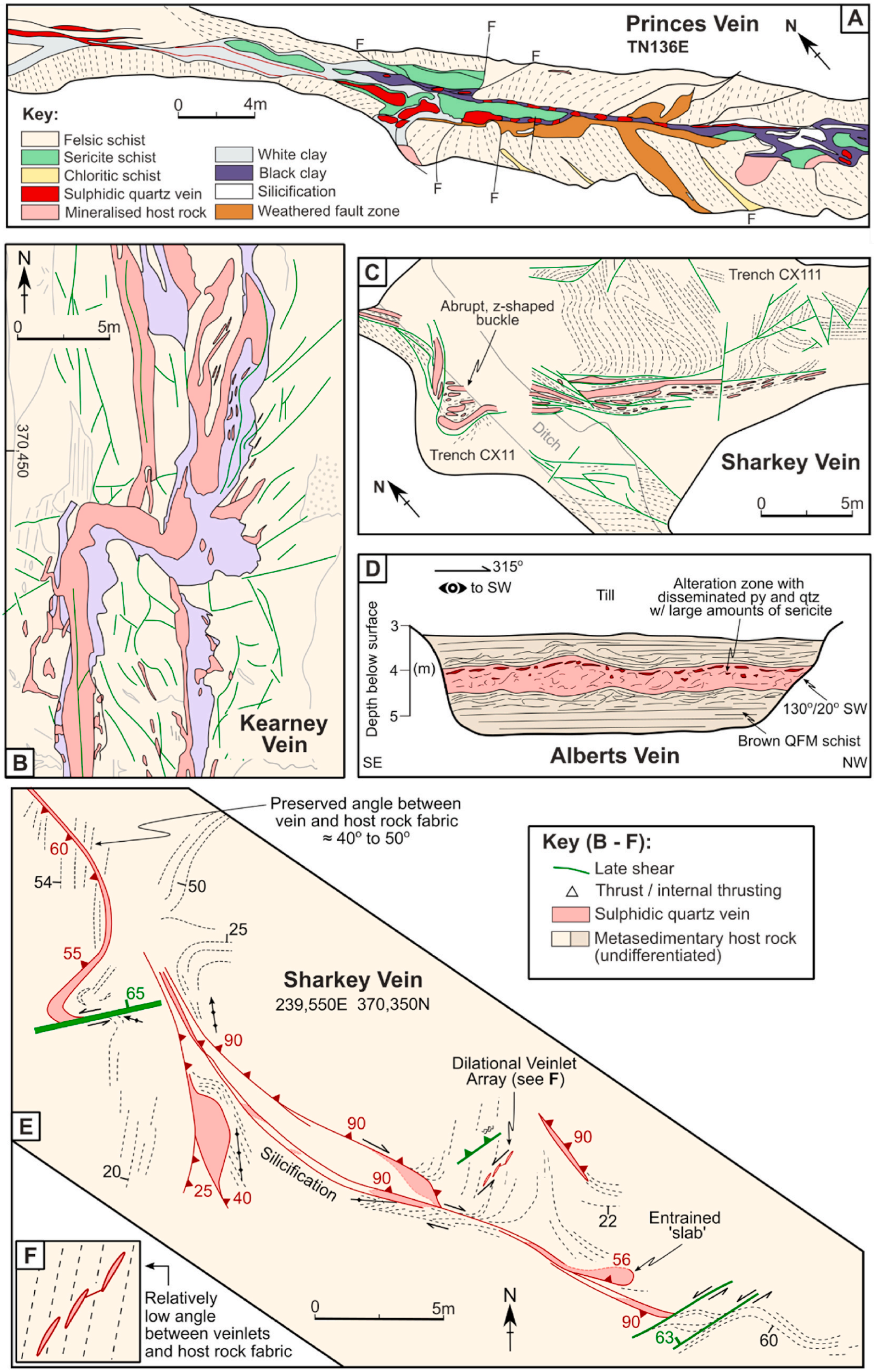


**Fig. 11.** Compilation of geological trench maps produced by RioFinex in both the Kearney and Creevan zones (the authors and dates of many of these are unfortunately not recorded): **(A)** Princes vein; **(B)** abrupt z-shaped buckle in the Kearney vein in the southern exploration trench (produced by Simon Tear perhaps among others); **(C)** Sharkey vein; note again the abrupt z-shaped buckle; **(D)** Map of trench wall of the Alberts vein; **(E)** Sharkey vein; and **(F)** relationship between late dilational veinlets and host rock fabric in Sharkey.

**Table 1**
Summary of the statistical analysis undertaken on the structural orientation data plotted in Fig. 13.

| Zone | Feature | N | Mean Strike Vector | Max Strike Value | Mean Dip | Fisher Mean Vector (for Poles) |
|---|---|---|---|---|---|---|
| Kearney | Host rock fabric | 207 | 055°–235° | 8.7% between 066° and 070° | 36° | 178/69 |
| Kearney | Mineralised veins | 60 | 171°–351° | 25% between 001° and 005° | 69° | 246/44 |
| Kearney | Joints (mineralised and not) | 145 | 158°–338° | 9% between 151° and 155° | 73° | 008/61 |
| Creevan | Host rock fabric | 207 | 019°–199° | 6.4% between 021° and 025° | 41° | 112/62 |
| Creevan | Mineralised veins | 69 | 139°–319° | 13% between 131° and 135° | 74° | 244/35 |
| Both | Dextral strike-slip and reverse shears (mineralised and not) | 100 | 146°–326° | 10% between 161° and 165° | 58° | 234/43 |
| Both | Sinistral strike-slip faults | 26 | 058°–238° | 19% between 051° and 055° | 68° | 150/27 |
| Both | Reverse shears | 56 | 045°–225° | 13% between 046° and 050° | 33° | 132/61 |
| Kearney | Normal-dextral faults | 17 | 118°–298° | 35% between 111° and 115° | 62° | 209/33 |
| Regional | Host rock fabric in eastern and central Lack Inlier | 223 | 076°–256° | 16% between 081° and 085° | 49° | 166/43 |
| Regional | Mineralised veins | 41 | 178°–358° | 12% between 001° and 005° | 74° | 240/68 |
| Regional | Host rock fabric on the West Sperrin Knee Bend | 463 | 029°–209° | 9% between 031° and 035° | 41° | 123/66 |

host rock foliation (~10°–20°) (Figs. 11F and 13D). These veinlets have been observed to cross-cut the major Creevan veins and alteration envelopes in the field and host disseminated pyrite and galena.

### 5.3. Cavanacaw syn-mineralisation structures

Faults that can be sulphide-bearing and auriferous are observed in both the Kearney and Creevan zones. This was perhaps most clearly illustrated in the northern Kearney exploration trench (Fig. 9). Here, a population of WNW to N-striking faults with variable, mostly NE-ward dips were observed to interact with the Kearney vein (Figs. 9 and 13G). The faults relate to the Luis Shear Zone in the north of the Kearney vein (Fig. 6A), but they swing from a NW–SE-dominated trend outside the vein, to an NNW–SSE-dominated and within the vein (Fig. 9D site 6). Many of the faults within the vein are intensely mineralised by sulphides (Fig. 9B site 2, 9D site 7 and 8), indicating that at least the sulphide-bearing faults propagated during the mineralisation; however, some may have been reactivated post-mineralisation as they can displace the subvertical vein in a dextral sense by up to 1 m in the north of the trench (Fig. 9D, site 6). Minor, shallower dipping faults with limited extent can branch from the steep NW to N-striking faults (especially in the NW trend) (Fig. 9D site 8, 13G). These can also be sulphide-bearing, although rarely. The kinematics of these shallow faults is unknown; however, it is notable that the Kearney vein is transected and ‘stacks up’ along faults in this orientation in the centre of the trench, implying reverse kinematic movement (Fig. 9C site 5). Mineralised and unmineralised joints which dominantly strike NNW–SSE and dip steeply are also found across the northern Kearney exploration trench (Fig. 13C).

In the Creevan zone, the Discovery vein exposed along Creevan Burn is internally stacked along NW to WNW-striking and shallowly dipping reverse shears (Fig. 7H). Reverse shears in this orientation are also found in the Sharkey vein trench where they entrain the vein to produce flat lying ‘slabs’ of mineralised vein (Fig. 11E). In both cases, these hangingwall-to-SW to SSW reverse movements are relatively late in respect to the propagation of the veins (Figs. 7H and 11E), although, like similar shallowly dipping faults in the Kearney zone, these faults can also be sulphide-bearing with exploration trench maps uncovering and recording highly altered and auriferous examples (e.g., Alberts vein in Fig. 11D). On average, this composite fault population strikes NW–SE (146°–326°) and dips moderately to steeply (58°) towards the NE across both the Kearney and Creevan zones (Table 1; Fig. 13G).

### 5.4. Cavanacaw post-mineralisation faults

Faults that are barren and clearly cross-cut and displace the mineralised veins are observed in both the Kearney and Creevan zones. In the Creevan zone, a series of NE to ENE-striking (058°–238°) and steeply (68°) NW to NNW-dipping faults, i.e., parallel to the Lack Shear Zone, displace the veins (Fig. 13H). This fault population is best evidenced in the Sharkey vein trench where these brittle faults displace the veins in a sinistral sense by up to 4 m (Fig. 11E). Along the Creevan Burn stream section, foliation drag further indicates that these faults may have been reactivated dextrally following the earlier phase of sinistral movement.

In both the Kearney and Creevan zones a population of reverse shears which strike NE–SW (045°–225°) and dip shallowly towards the NW (33°) cross-cut and entrain the mineralised veins (Figs. 8 and 9A site 1, 13I). When observed, they are typically discreet structures (cm-scale width) that branch from and exploit the penetrative foliation in the host rock. The thrusts produce shear bands within the foliation indicative of a component of dextral movement. These thrusts appear to be responsible for the tectonic repetition created in the Discovery zone (detailed in section 5.1.), with the strongly deformed, shallow NW to WNW-dipping graphitic pelite interval also entraining and dissecting the Discovery vein (Fig. 8).

Finally, a series of WNW–ESE-striking (118°–298°), moderately to vertically (62°) NNE-dipping faults that displace the subvertical Kearney vein branches by up to 1 m in a dextral sense are observed in the central portion of the northern Kearney exploration trench (Fig. 9C, site 3 and 4; 13F). These faults have also been observed in the walls of the open excavation pit where they also have a normal component of movement evidenced by displaced marker host rock horizons. No examples of these faults have been observed in the Creevan zone.

### 5.5. Regional veins

To the east-northeast of the Cavanacaw site, several in-situ auriferous quartz veins outcrop north and east of Omagh town along the Rylagh, Erganagh, Glencurry, Glenhordial, and Mullaghcarn Burn stream sections (Fig. 3). These ‘regional’ veins typically outcrop in the banks of poorly exposed stream sections and vary in width from mm-thick veinlets to 0.5 m (e.g., Fig. 12). The regional veins have strikes ranging from NNE to NW with an average of 178°–358°, and average dips of 74° towards either east or west (Fig. 13K). All the regional veins observed cross-cut the NNE–SSW-striking (029°–209°) and moderately (41°) WNW-dipping limb of the West Sperrin Knee Bend, although the relative angles in which these veins strike in respect to the strike of the host rock foliation does vary (Fig. 13K and 13L). The thicker veins, such as the N–S-striking Rylagh vein, clearly strike at a relatively high angle of ~45° to the host rock foliation (Fig. 12). Many regional veins that strike NW–SE at relatively high angles to the host rock fabric are also internally thrusted and strongly deformed, as is observed at Cavanacaw (Fig. 13K). In slight contrast to the thicker regional veins, mm to cm-wide sulphide-bearing veinlets observed along the Glenhordial and Rylagh Burn stream sections typically strike NNE–SSW at a relatively low angle (~10°–20°) to the host rock fabric (Fig. 13K and 13L). As in the Creevan zone, these subvertical veinlets are recorded in the field to have dilational WNW–ESE (~120–300°) opening vectors from quartz growth crystals and offset markers. Sericite alteration of the host rock is also typically found in the zones of dilational veining. Although exposure is poor, later faults are occasionally found to interact and displace the regional veins, similarly to the Cavanacaw area (Fig. 12). Low angle reverse shears, which share geometric and kinematic similarities to the post-mineralisation, shallow NW-dipping reverse shears observed at Cavanacaw, are observed in the banks of the poorly exposed streams.

## 6. Interpretation: Structural evolution of the Cavanacaw site

Using the observations of geometries, kinematics, cross-cutting relationships, and textures, a deformation sequence has been established for the vein and fault systems observed at the Cavanacaw site (Fig. 14). The host rock lithologies and structural fabrics observed are consistent with the area being located on the overturned limb of the thrusted Sperrin Nappe, therefore, the Grampian event of ductile deformation is not discussed here (instead, refer to Alsop and Hutton, 1993a; 1993b).

### 6.1. A progressive model for the Cavanacaw vein system

As detailed below, the structural observations of the Cavanacaw vein system are compatible with progressive sinistral transpression which, therefore, may relate to either the Scandian or Acadian events of the Caledonian orogeny (Fig. 14A and 14B). Several transcurrent ENE–WSW-striking faults that bound the Cavanacaw deposit and transect the Lack Inlier could have accommodated this sinistral transpression (such as the Cool Fault and Sperrin Fault to the NNW and the Lack Shear Zone and Omagh Thrust–Castle Archdale Fault complex to the SSE; Fig. 5).

The mineralised veins have variable orientations, textures, and kinematics that are compatible with overall progressive deformation within a sinistral shear zone system (Fig. 15). Two main styles of sulphide-bearing veins are observed: (1) Veins that currently strike between N and WNW, show significant asymmetric buckling, dextral shearing, and reverse faulting, particularly in the Creevan zone. Veins in this orientation cross-cut a host rock fabric that is correspondingly rotated anticlockwise with respect to the average orientation of the host rock fabric in the Lack Inlier; and (2) NNE–SSW-striking veins and veinlets showing more dilational textures with little or no shearing and buckling. The undeformed veins cross-cut the deformed veins and rotated host rock fabrics and must, therefore, be relatively younger. The orientation of these undeformed dilation-dominated veins is compatible with the interpretation of an overall NNE–SSW-orientated $\sigma_1$ (Fig. 14A).

We propose that all the veins initially formed in a tensile mode in response to an overall NNE–SSW-orientated $\sigma_1$ (030°–210°) at an angle of ~45° to the shear zone margins (075°–255°) (Fig. 15). This is best supported by rotating the strike of the host rock fabrics that the deformed Cavanacaw veins cross-cut back to the regional ENE–WSW strike (i.e., shear zone parallel) as it respectively rotates the strike of the veins back to ~NNE–SSW (Fig. 15, *cf*. Fig. 1). The z-shaped (dextral-asymmetric) buckling geometries of the deformed veins is compatible with them having originally formed in this orientation and being progressively rotated into their current position (Fig. 15). The buckling indicates that the veins were accommodating shortening along the vein axes and antithetic (i.e., dextral) counter-shearing. Buckles with an asymmetry in the opposite sense to the overall shear direction are well documented in quartz veins that form in progressive shear zone systems (Fig. 1C) (e.g., Ghosh, 1966; Mawer, 1992; Harris, 2003; Lloyd, 2020).

We have not observed veins with intermediate strikes between NNE and N (Figs. 14 and 15). This potentially indicates that propagation of the veins was episodic during rotation rather than continuous (i.e., Fig. 1B and 1C rather than 1A). We explain this through the interplay between rotation, stretching and competence. Only once the quartz veins and their silicified alteration halos, which are rheologically more competent than the surrounding unaltered metasediments, were rotated into the orientation of maximum stretch (i.e., perpendicular to the $\sigma_1$ axis), could a new set of dilational veins form; this is best seen in the Creevan zone (Fig. 15). Our progressive model allows the veins at Cavanacaw to dilate at different times relative to each other but, overall, within the same deformation phase rather than two separate events.

In detail, the relative motions are reflected within the deformed veins that show pinch-and-swell geometries, with quartz-rich sulphide-mineralised pods delimited by layers and shears of intensely deformed

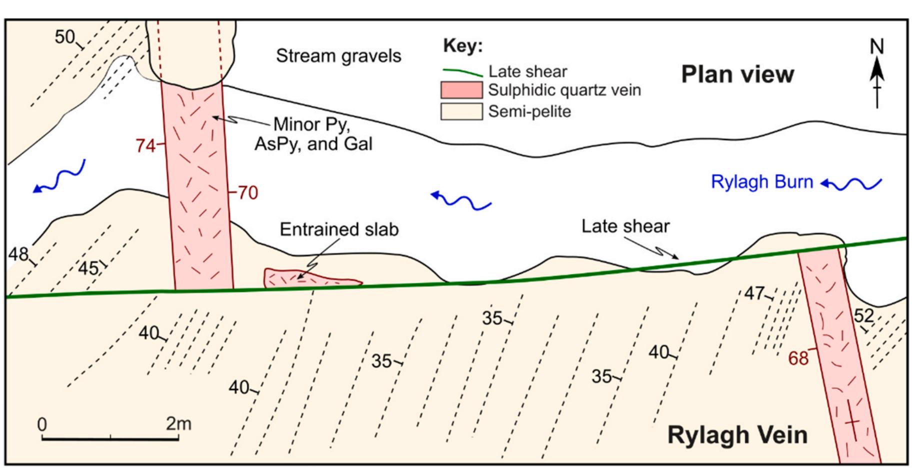


**Fig. 12.** Geological plan view map of the major veins exposed in the banks of the Rylagh Burn stream section and how these are displaced by a late flat shear. The map is a more detailed adaption of the figure presented in Earls et al. (1996) and Parnell et al. (2000).

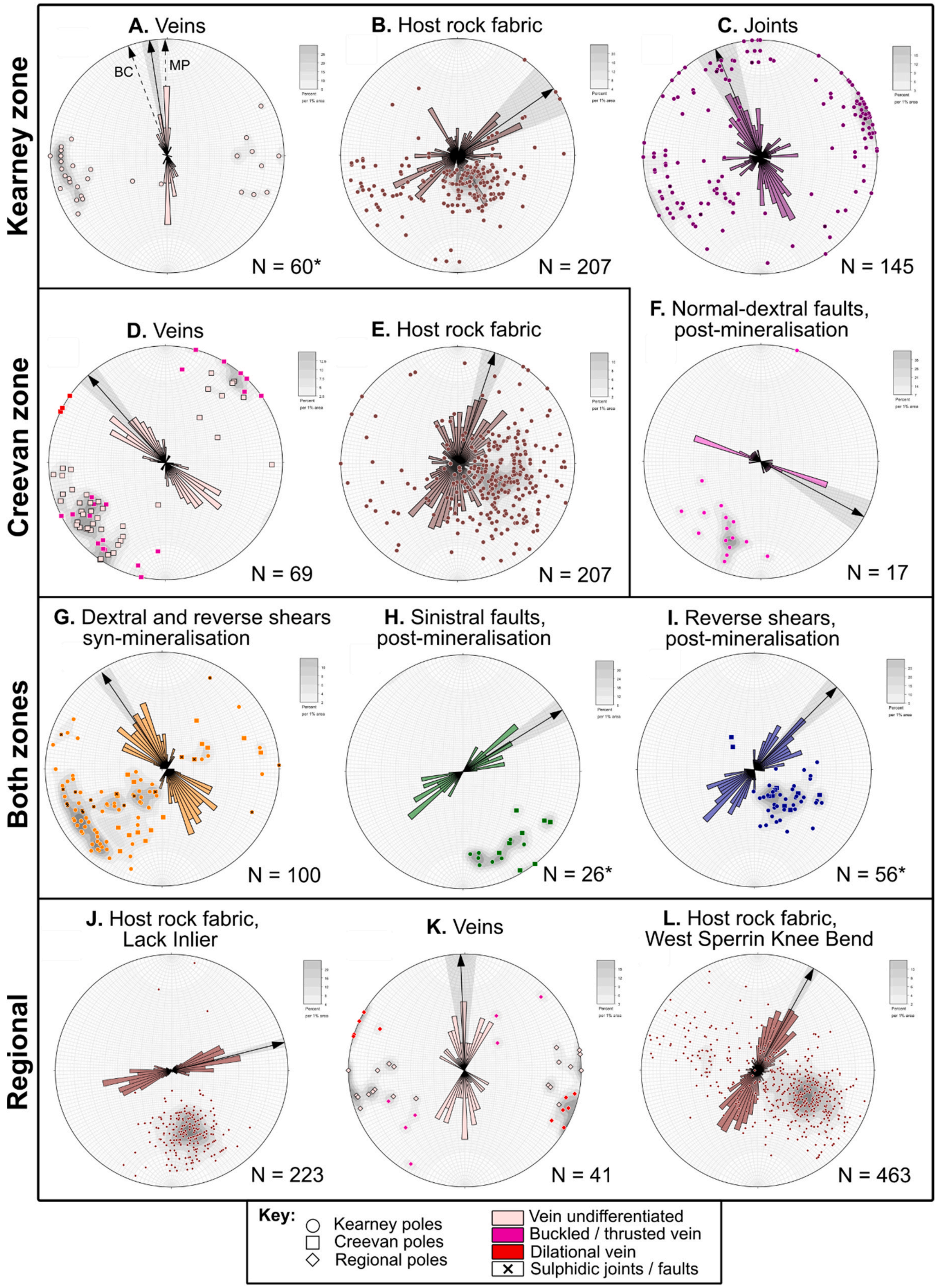


**Fig. 13.** Compilation of equal angle stereonets displaying the structural data for each of the vein and fault populations observed and defined in the Kearney zone, Creevan zone, and regionally. In (A) the abbreviations MP: Massive quartz pod and BC: black clay vein. The structural data is plotted as poles with associated rose diagrams overlain to display strike information. The arrows associated with the rose diagrams shows mean strike. The * next to N represents where compiled strike data without any corresponding dip data has been used to plot the rose diagrams.

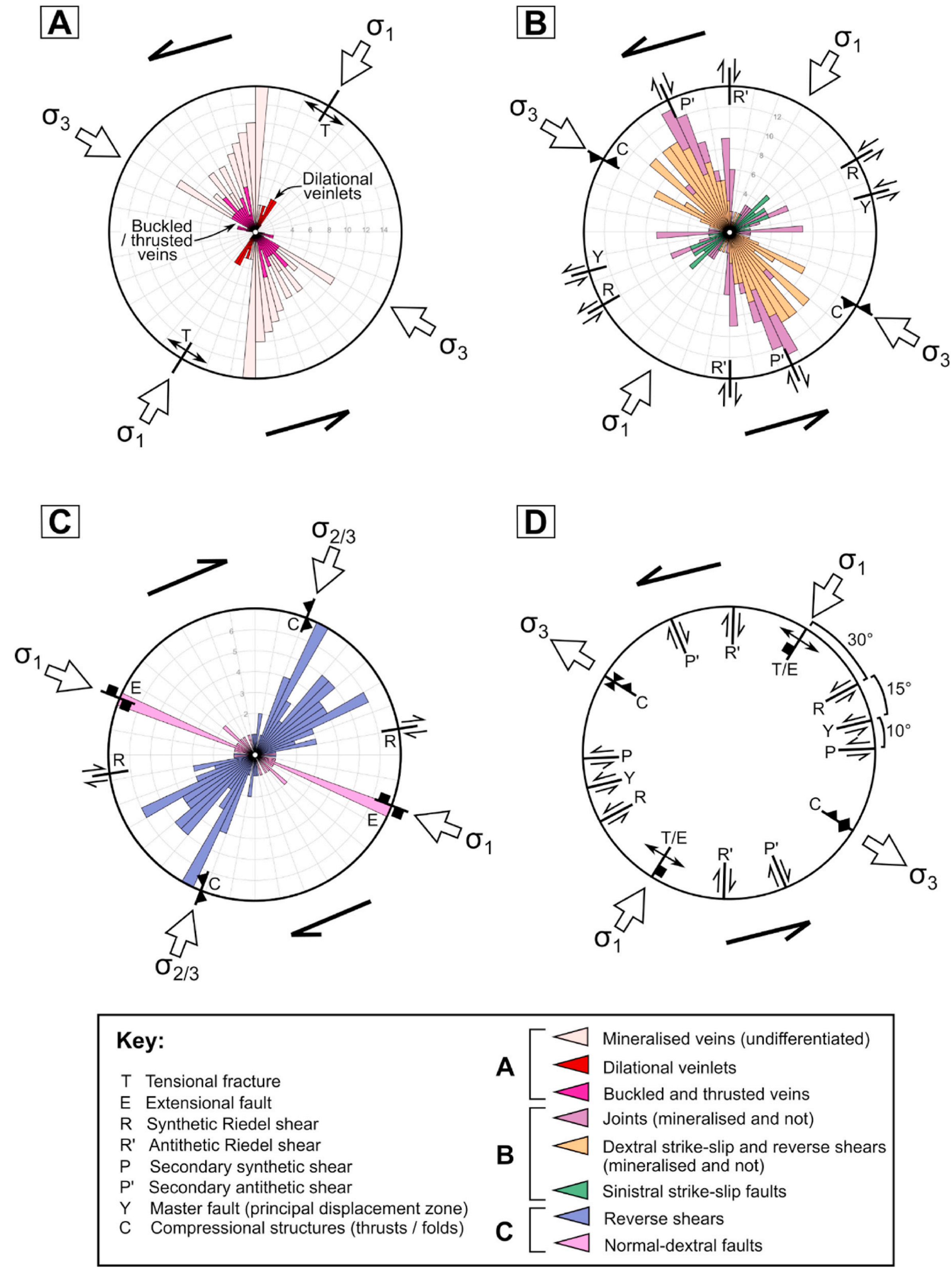


**Fig. 14.** Palaeostress analysis for the Cavanacaw vein and fault systems. **(A)** The strike orientations of the different vein textures observed at Cavanacaw in respect to the modelled palaeostress field; **(B)** The strike orientations of faults and joints (which can also be mineralised) that are interpreted to have formed under the same palaeostress field as the veins; **(C)** The strike of the post-mineralisation faults systems at Cavanacaw in respect to the modelled palaeostress field; and **(D)** an idealised Riedel fault and fracture array model.

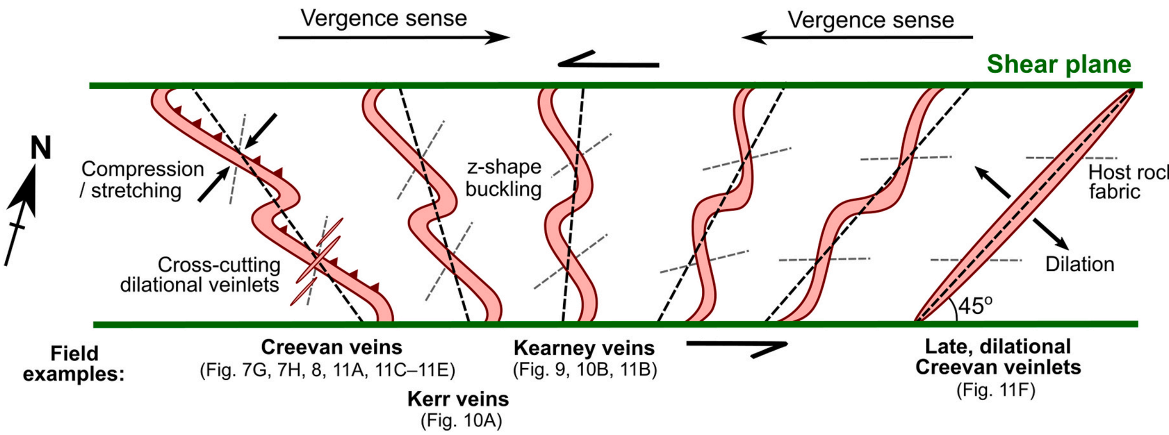


**Fig. 15.** Schematic diagram displaying the interpreted progressive evolution of the Cavanacaw veins within an ENE–WSW-striking shear zone system. The passive rotation of the host rock foliation associated with progressive vein evolution is also shown. From right to left: initial opening of dilational veins in response to an overall NNE-SSW-orientated horizontal $\sigma_1$; progressive rotation and deformation of the veins results in a highly deformed vein system, within which new NNE–SSW-striking dilational veins may open.

clay-rich fault-gouge. The pods are systematically orientated slightly clockwise with respect to the shears (e.g., Figs. 10 and 13A). This is compatible with the enclosing, right-stepping shears preferentially accommodating the bulk of the counter-shearing during the rotation. In contrast, the more competent pods appear to have buckled during rotation. Although the broad geometry of the swollen pods and pinched gouge veins could mistakenly be interpreted as stretching and boudinage, their spatial association with the z-shaped buckling suggests shortening, not extension.

The veins and host rock fabrics in the Creevan zone experienced the greatest degree of anticlockwise rotation (Figs. 8, 13D, 13E, and 15). The rotation is particularly strong at the Sharkey and Princes veins at the southern margin of the Lack Shear Zone (Figs. 6A, 11A, 11C, and 11E). The greater degrees of anticlockwise rotation have orientated the Creevan veins perpendicular to the $\sigma_1$ axis, resulting in the veins showing both later compressional structures (internal imbrication; e.g., in the Discovery vein; Fig. 14A, 14B, and 15) and late dilational veins (e.g., in the Sharkey vein zone; Figs. 11E and 14A). The late structures are associated with the mineralisation as they can be individually sulphide- and gold-bearing and highly altered (Fig. 11D). The Creevan zone is located near the southern margin of the Lack Shear Zone (Fig. 6A). This shear zone must, therefore, have been active during the transpression, accommodating sinistral motion and the rotation within the southern part of the Lack Inlier. The less competent graphitic pelites at the contact between the Mullaghcarn Formation and the Glengawna Formation, probably played an important role in the localisation of strain (Fig. 5).

The overall stress field orientation (Fig. 14B) is further constrained by late strike-slip faults across the Lack Inlier. NW to NNW-striking, steeply dipping faults in the Kearney zone appear to have been reactivated in a brittle dextral sense, compatible with them being antithetic Riedel faults which moved late within the overall shear zone system (Fig. 9D site 6; 14B). A series of brittle, steep, ENE–WSW-striking faults that displace the Creevan veins in a sinistral sense are also compatible with being synthetic Riedel faults in the overall shear zone system (Fig. 14B). These faults strike parallel to and are kinematically compatible with the Lack Shear Zone (Figs. 14B and 15).

In summary, according to our model the Cavanacaw vein system was initiated with mineralised, subvertical tensional veins forming in a ~NNE–SSW-orientation within a progressive, ENE–WSW-striking simple sinistral shear zone system; they were then passively rotated, while internally deforming through counter-shearing (Fig. 14A, 14B, and 15). Our observations and the model explain the formation of the metallic mineralisation with complex vein geometries within a single, progressive episode without the need to evoke separate deformation events.

### 6.2. *Carboniferous structures*

The brittle structures that do not fit the kinematic model related to sinistral transpression, and cross-cut some of the Cavanacaw veins, are evidence of a later episode of deformation. The deformation seems to have reactivated some of the pre-existing structures: e.g., at the Creevan Burn stream section where foliation drag indicates dextral reactivation of some of the ENE–WSW-striking faults which record earlier sinistral movement. This phase also created new structures: e.g., in the Creevan zone this is manifested as shallow NW-dipping, unmineralised reverse shears (top-to-SE) that displace the earlier structures (e.g., the Discovery vein) and create the thrusted tectonic repetitions in the stratigraphy by exploiting graphitic pelites (Fig. 8). The kinematics associated with both the dextral reactivation of the ENE–WSW-striking faults and the top-to-SE directed reverse shears is compatible with a switch back to broadly WNW–ESE-directed compression and shortening, probably due to the peripheral effects of the Variscan (Hercynian) Orogeny (Figs. 4 and 14C; Mitchell, 2004). The reverse shears are also expressed regionally and at Curraghinalt (Earls et al., 1996; Parnell et al., 2000; Shaw et al., in prep). Our interpretation of a Variscan deformation phase is compatible with the published age data from low angle reverse shear clay-rich fault-gouge collected along the Lack Shear Zone and regionally (K–Ar model ages of 327 ± 13 Ma) (Earls et al., 1996; Parnell et al., 2000).

In addition to the described structures, steep WNW–ESE-striking normal-dextral transtensional faults displace the Kearney vein (e.g., Fig. 9C sites 3 and 4). Their orientations may be compatible with the extensional, orogen-oblique component of the broadly WNW–ESE-directed Variscan compressional regime (Fig. 14C) or the later Carboniferous extensional event that also created e.g., the *c*. WNW–ESE-striking Newtownstewart Basin half-graben (Fig. 3); but further data is needed to better constrain these structures and their significance.

The structures associated with the late deformation are not auriferous or sulphide-bearing (excluding where earlier sulphide-bearing veins are locally entrained). Therefore, it seems unlikely that Carboniferous gold mineralisation, whether local remobilisation or the introduction of new gold, occurred at Cavanacaw as proposed by Earls et al. (1996) and Parnell et al. (2000).

## 7. Regional model and discussion

From the interpretations outlined above, we have demonstrated that the Cavanacaw vein system initiated and was rotated within a progressive NE to ENE-striking sinistral shear zone system that was governed by an NNE–SSW-orientated $\sigma_1$ related to the Scandian or Acadian event (Fig. 14A, 14B, and 15) (Soper et al., 1992; Dewey and Strachan, 2003). From this, and the regional analysis presented (e.g., Fig. 13J, 13K, and 13L), we further suggest that the West Sperrin Knee Bend found to the north of Cavanacaw also formed simultaneously. The geometry of the West Sperrin Knee Bend is remarkably like the Creevan swing found locally at the south of Cavanacaw (Fig. 8). The regional, anticlockwise rotation of the foliation across the Newtownstewart region is compatible with progressive sinistral shearing within an overall NE to ENE-striking shear zone system; specifically, between the shear zone pair defined by the Pettigoe Fault and the Sperrin Fault–Cool Fault system (Figs. 3 and 17). A mid-Silurian (U–Pb zircon age of 426.69 ± 0.85 Ma; Cooper et al., 2013) minor calc-alkaline intrusive suite, "the Sperrin Mountains Suite", is spatially associated with the West Sperrin Knee Bend (Fig. 16). Cooper et al. (2013) documents that the orientation of the Sperrin Mountains Suite mainly reflects that of the country rock on the rotated NNE–SSW-striking (029°–209°) limb of the West Sperrin Knee Bend (see also e.g., GSNI 2007a; 2007b, 2008, and 2013). This is compatible with magma intrusion into the tensional domain (030°–210°) of the overall stress system (Fig. 14A, 14B, and 17). The dating and the setting of the Sperrin Mountains Suite imply that the formation of the West Sperrin Knee Bend and, by implication, the Cavanacaw deposit was largely complete by the mid-Silurian and are therefore, Scandian structures rather than Acadian (*c.* 427 Ma) (Fig. 16). As there are indications of 'head on' Scandian NW-SE compression in the Dalradian Supergroup at *c.* 437 Ma in the north of Ireland, the West Sperrin Knee Bend and the Cavanacaw deposit must have formed after this (Alsop, 1996; Kirkland et al., 2013). It is interesting to note that the age of the Sperrin Mountains suite overlaps with the reactivated fault movements dated at the nearby Curraghinalt deposit ($^{40}Ar/^{39}Ar$ sericite age of 424.4 ± 2.8/3.6 Ma; Fig. 16; Rice et al., 2016). The Sperrin Mountains Suite age is also broadly similar to the age of the Tullagh Point Granite, northern Donegal, interpreted to be associated with a phase of relatively ductile sinistral shearing (U–Th–Pb zircon age of 422 ± 2 Ma; Fig. 16; Kirkland et al., 2008). In addition to the geochronological constraints outlined above, the relatively 'late' timing of the Sperrin Knee Bend during the Caledonian orogeny is further supported by: (1) the lack of any cross-cutting structures or fabrics compatible with Grampian deformation; and (2) the absence of any sedimentation patterns or facies changes to imply the structure has an even earlier, pre-Caledonian origin (both observations are also noted by Earls et al., 1996).

As with the Cavanacaw veins, it appears that the propagation of the auriferous quartz veins hosted within the West Sperrin Knee Bend (e.g., Rylagh, Glenhordial) occurred simultaneously with the anticlockwise rotation of the Dalradian rocks during overall sinistral shearing (Figs. 15 and 17). This is best evidenced by the relative angles in which the subvertical gold veins strike in respect to the rotated NNE–SSW-striking strata (Fig. 13K and 13L). For example, the major Rylagh vein currently strikes broadly N to NNW at a relatively *high* angle (~45°) to NNE–SSW-striking foliation (Fig. 12). If the strike of the foliation along Rylagh is restored clockwise to the regional ENE–WSW-trend, this would reorientate the strike of the vein to NNE–SSW, which is parallel to $\sigma_1$ interpreted at Cavanacaw and consistent with the vein initiating as a tensional fracture (e.g., Fig. 14A, 14B, 15, and 17). This further implies that the propagation of the main Rylagh vein occurred prior to, or in the early stages, of the passive rotation and the formation of the West Sperrin Knee Bend (Fig. 17). In contrast to this, the dilational veinlet arrays observed along Glenhordial and Rylagh Burn strike NNE–SSW at a relatively *low* angle (~10–20°) to the Dalradian strata. The vein orientation here is parallel to the modelled $\sigma_1 - \sigma_2$ plane at Cavanacaw and implies that the propagation of the sulphidic veinlets occurred after, or during the final stages, of West Sperrin Knee Bend formation (Fig. 14A, 14B, and 17). Regardless of their relative timings, both vein systems are broadly compatible with the progressive deformation model presented in this paper, and are likely to be coeval with Cavanacaw, i.e., mid-Silurian.

Rather than invoking an enigmatic and poorly constrained "Omagh Lineament", we instead attribute the formation of the West Sperrin Knee Bend to spatial heterogeneities in the physical properties of the

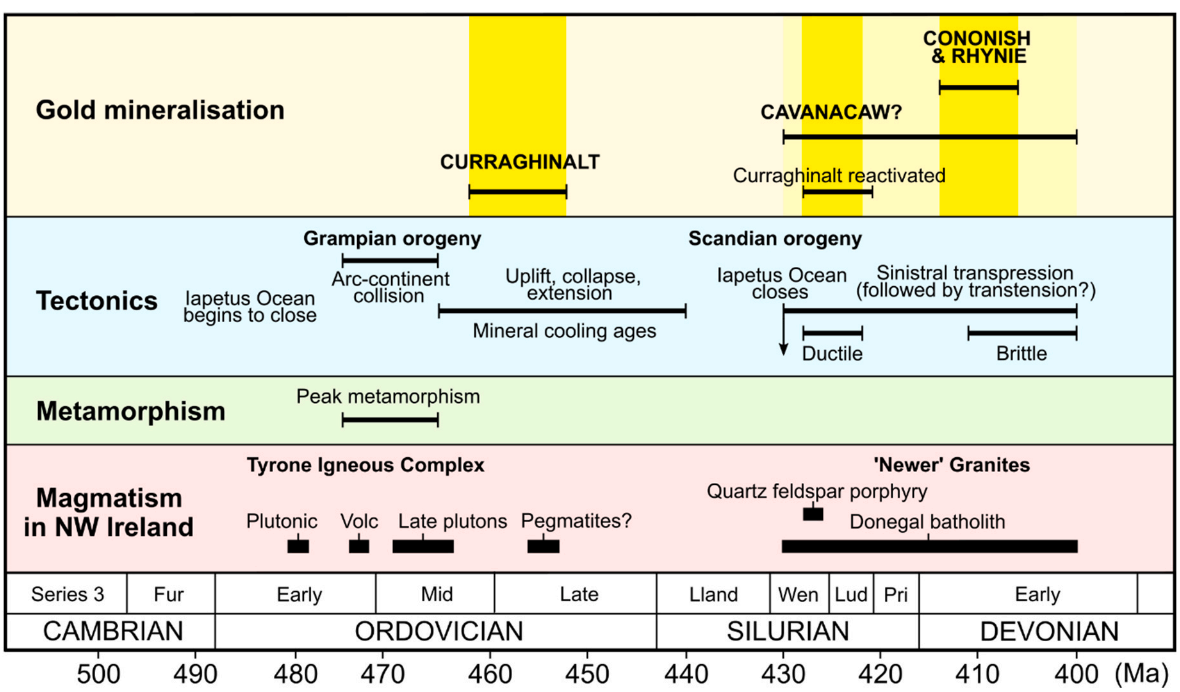


**Fig. 16.** Timeline of the major tectonic, magmatic, metamorphic in the Grampian Terrane of northwestern Ireland (adapted from Rice et al., 2016), as well as the timing interpretations made for Cavanacaw in this study and geochronological data for Curraghinalt (Rice et al., 2016) and Cononish and Rhynie (Treagus et al., 1999; Mark et al., 2011; Parry et al., 2011; Rice et al., 2013). The ductile and brittle phases of the Scandian event is displayed using data from Kirkland et al. (2008). The quartz feldspar porphyry age is from Cooper et al. (2013) on the Sperrin Mountains Suite in Newtownstewart.

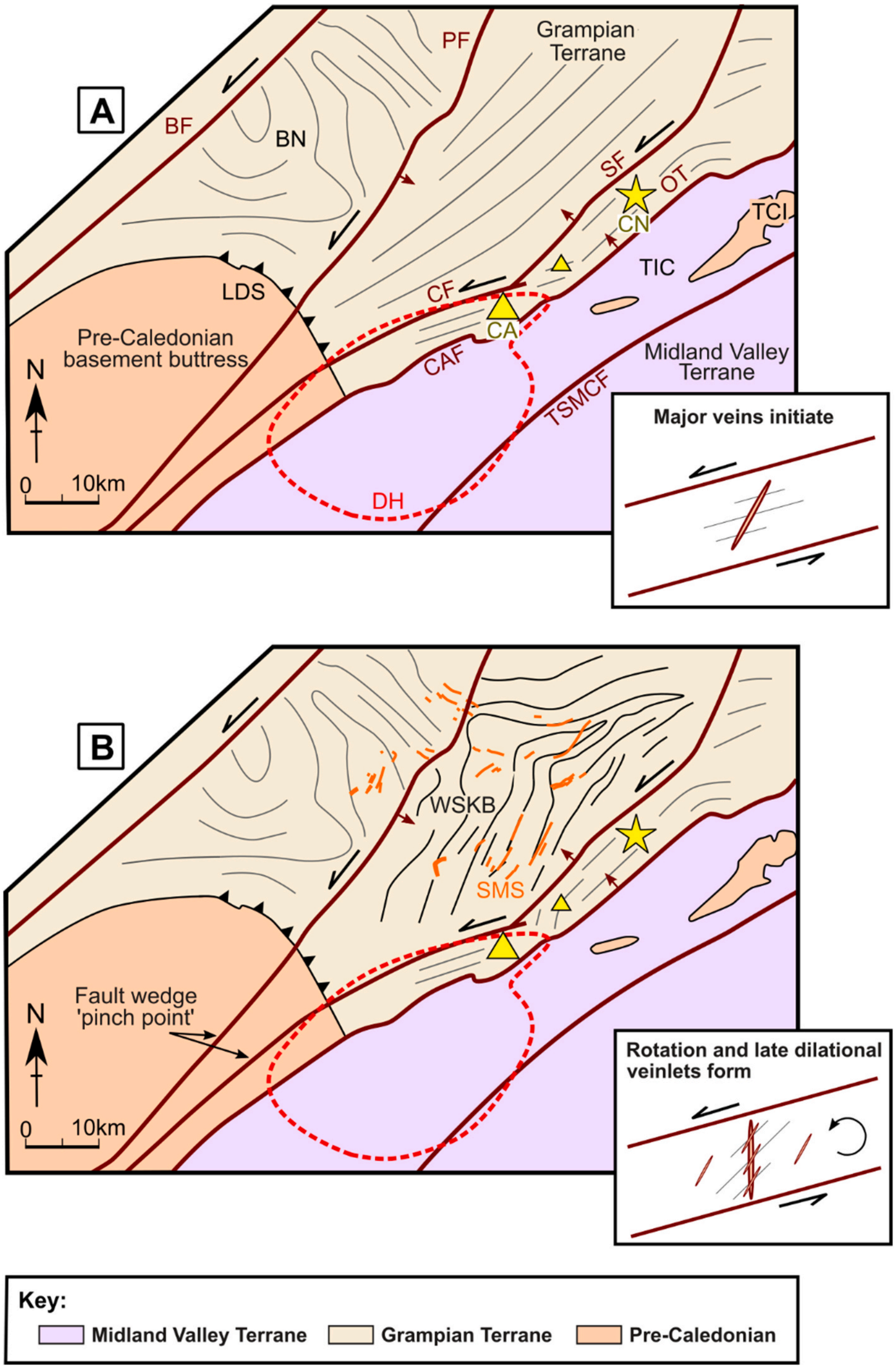


**Fig. 17.** Schematic diagram showing the formation of the West Sperrin Knee Bend which includes all the key geological features and structures interpreted to have been important in northwest Ireland during the Scandian event. The abbreviations are as follows: **CA:** Cavanacaw deposit; **CN:** Curraghinalt deposit; **TIC:** Tyrone Igneous Complex; **DH:** Dromore High anomaly; **SMS:** Sperrin Mountains suite; **WSKB:** West Sperrin Knee Bend; **TCI:** Tyrone Central Inlier; **BN:** Ballybofey Nappe; **TSMCF:** Tempo-Sixmilecross Fault; **OT:** Omagh Thrust Fault; **SF:** Sperrin Fault; **CF:** Cool Fault; **CAF:** Castle Archdale Fault; **PF:** Pettigoe Fault; **BF:** Belshade Fault; **LDS:** Lough Derg Slide.

overriding Sperrin Nappe as it was accommodating orogen-parallel, sinistral shearing (Fig. 17). To the southwest of the West Sperrin Knee Bend, the inverted Upper Dalradian cover rocks of west Tyrone and south Donegal are juxtaposed against the pre-Caledonian basement gneiss of the Lough Derg and Ox Mountains Inliers (Figs. 2 and 17). In contrast to the amphibolite-facies Dalradian cover sequence, the rocks of the inliers have experienced granulite facies metamorphism and were exhumed from the lower crust (Max and Long, 1985; Sanders et al., 1987; Cooper and Johnston, 2004). From this, we suggest that the Lough Derg–Ox Mountain Inlier block was relatively rigid and acted as a 'buttress' to the Dalradian cover rocks to the northeast as they were accommodating margin-parallel, sinistral shearing during the Scandian event (i.e., the 'buttress effect' after Beck et al., 1993) (Fig. 17). In this model, the outboard sliver of Dalradian rocks will have 'locked up' against the buttress and subsequently folded through the anticlockwise rotation of the strata, forming the West Sperrin Knee Bend across the Newtownstewart region (Fig. 17). The West Sperrin Knee Bend does not extend southeast of the Glengawna Formation/Sperrin Fault and the Cool Fault into the Mullaghcarn Formation and Lack Inlier, with only local rotation found in these zones (e.g., across the Lack Shear Zone) (e.g., Fig. 17). We interpret that the strongly deformed graphitic pelitic rocks that largely define the Glengawna Formation/Sperrin Fault and the Cool Fault may have, therefore, acted as a décollement (Fig. 17). This accounts for why the late/post-Grampian Curraghinalt deposit, which is largely hosted by the Mullaghcarn Formation structurally below the Glengawna Formation décollement, does not appear to have experienced significant mid-Silurian structural reactivation or to have been rotated anticlockwise following its initiation (Rice et al., 2016; Shaw et al., in prep). To the northwest, the West Sperrin Knee Bend is further bounded by the Pettigoe Fault, which separates the structure from Grampian fold complexes farther northwest such as the Ballybofey Nappe (Alsop, 1992; 1994). Together, the ENE-WSW-striking and NNW-dipping Glengawna – Cool Fault – Sperrin Fault complex, with the NE–SW-striking and SE-dipping Pettigoe Fault, form a pinch point at the northern end of Lough Erne, and define a wedge in which the West Sperrin Knee Bend could form (Fig. 17). It is notable that this 'pinch point' is bounded by the Lough Derg Inlier to the northwest and the Dromore High bouguer anomaly to the southeast, indicating that the 'pinching' geometry of the Caledonoid faults could potentially have been controlled by pre-existing and underlying structures and/or rigid blocks (Figs. 3 and 17).

The interpretation that the West Sperrin Knee Bend formed during the Scandian event implies that not all the strain associated with the event was compartmented as sinistral strike-slip movement along orogen-parallel faults with little deformation between the faults, as previously assumed by e.g., Soper et al. (1992), Dewey and Strachan (2003), Chew and Strachan (2014). Instead, the West Sperrin Knee Bend indicates regional ductile deformation of this age in the Grampian Terrane of Ireland and Scotland (Fig. 17). The West Sperrin Knee Bend does exhibit remarkable geometric similarities to regional strike swings mapped in the Dalradian Supergroup rocks of Scotland: the most prominent of these is a 20 km-amplitude, s-shaped 'knee bend' mapped in the Dalradian strata between Braemar and Tomintoul in Aberdeenshire, northeastern Scotland (Stephenson and Gould, 1995; Stephenson et al., 2013). Like the West Sperrin Knee Bend, this major feature has also been interpreted to be relatively 'late' as it is not clearly associated with any minor folds or axial planar cleavages (Stephenson et al., 2013). Another 'knee bend' feature is a less abrupt strike swing that is mapped in the Dalradian rocks of southwest Argyll in western Scotland. Like the West Sperrin Knee Bend, this strike swing has also been historically attributed to an enigmatic and deep-seated, NNE–SSW-striking crustal lineament (the 'Argyll Lineament') (Hutton and Alsop, 1996). Future work is needed to assess whether these regional strike swings in the Dalradian rocks of Scotland can also be accounted for by regional progressive rotation during Scandian sinistral transpression.

## 8. Implications for the evolution and metallogeny of the Grampian Terrane

The indirect dating of the West Sperrin Knee Bend and the gold-sulphide mineralisation through field relationship and age data from the Sperrin Mountains Suite, combined with the stress field and deformation model for all the discussed veins, strongly supports a mid-Silurian Scandian event age for most of the gold mineralisation in the western Sperrin Mountains (Fig. 14A, 14B, 15, 16, and 17). The Sperrin Mountains Suite age (*c.* 426.69 ± 0.85 Ma; Cooper et al., 2013) and the overall deformation style and compressional structures in all vein systems suggest that the deformation within the Grampian Terrane was transpressional during mid-Silurian (Fig. 14A, 14B, and 18). This is compatible with prevailing models which suggest that sinistral Scandian transpression in the Grampian Terrane began in the mid-Silurian (*c.* 430–410 Ma; e.g., Soper et al., 1992) and was followed by an episode of sinistral transtension in Early Devonian (*c.* 410–395 Ma; e.g., Dewey and Strachan, 2003; Cooper et al., 2016). Early Devonian ages have been obtained from Cononish and Rhynie in the Grampian Terrane of Scotland (Treagus et al., 1999; Mark et al., 2011; Parry et al., 2011; Rice

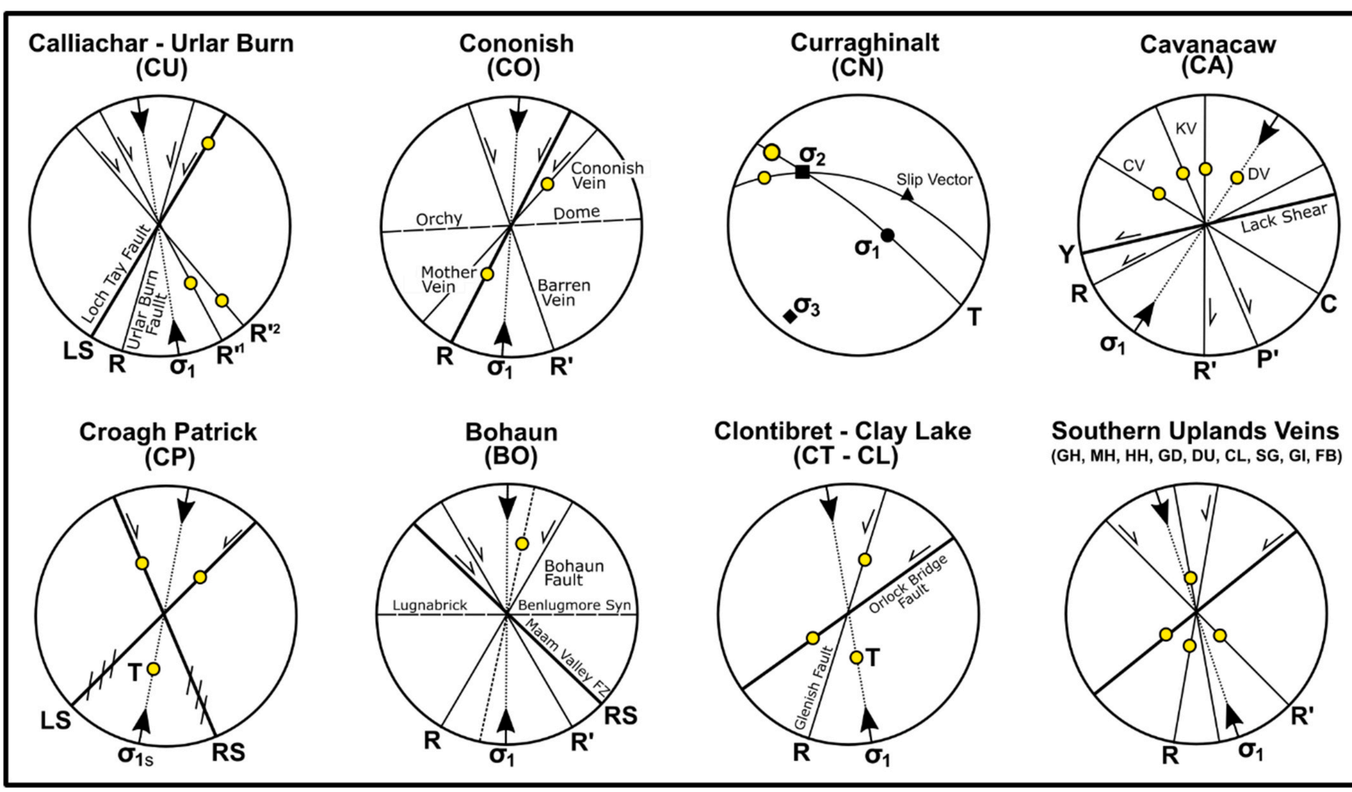


**Fig. 18.** Strike line diagrams and palaeostress reconstruction for major auriferous vein deposits and occurrences in Ireland and Scotland (the location and abbreviations for which can be found in Fig. 2). The yellow circles indicate auriferous/metalliferous structures. Calliachar-Urlar, Cononish, Croagh Patrick and Bohaun are adapted from Tanner (2014). Curraghinalt stereonet is adapted from Shaw et al. in prep. Cavanacaw strike line diagram uses data from Figs. 14A and B and abbreviations DV: Dilational veinlets; KV: Kearney veins; CV: Creevan veins. Clontibret – Clay Lake strike line diagram has been constructed using structural data from Morris et al. (1986), Steed and Morris (1997), Conroy Gold and Natural Resources (2020). The generic strike line diagram constructed for auriferous and polymetallic vein occurrences in the Southern Uplands – Down – Longford Terranes uses data outlined in Rice et al. (2018).

et al., 2012); therefore, they seem to be 10–20 Ma younger than the west Sperrin Mountains gold mineralisation and temporally associated with the onset of regional sinistral transtension (Fig. 16). Although Treagus et al. (1999) favoured a transtensional model for Cononish, Tanner (2012, 2014) suggests that the structures at Cononish are more compatible with a broadly N–S-orientated transpressional stress field, with the broader Cononish vein system further associated with the Periclinal Orchy Dome; a transpressional structure (Fig. 18). It is, therefore, still unclear whether the Cononish vein system formed under transpression or transtension. Regardless of this, both Cavanacaw and Cononish are considerably younger than the Late Ordovician mineralisation age at Curraghinalt (Fig. 16; Rice et al., 2016), which is associated with the late to post-orogenic stages of the Grampian event (Shaw et al., in prep).

Several other auriferous and polymetallic vein systems with remarkably consistent orientations occur throughout the Laurentian Caledonides of Ireland and Scotland (Figs. 2 and 18): broadly N–S-striking vein systems have been identified at Calliachar – Urlar and Coire Buidhe near Loch Tay, Scotland (Pattrick, 1984; Ixer et al., 1997), Croagh Patrick and Bohaun in western Ireland (Johnston and McCaffrey, 1996; Aherne et al., 1992; Wilkinson and Johnston, 1996; Lusty et al., 2011), and Clontibret and Clay Lake in central Ireland (Steed and Morris, 1997). Although comprehensive textural data is lacking to determine the orientation of vein dilation, the structures related to these vein systems imply that they are hosted by NW to NE-striking second-order Riedel, Antithetic-Riedel, and tensile fractures, which like Cavanacaw and Cononish, have kinematic frameworks compatible with overall NE to ENE-striking sinistral shearing and a broadly N to NNE-trending $\sigma_1/\sigma_2$ (Fig. 18) (Tanner, 2014; Rice et al., 2018). Radiometric age data is still lacking from these veins, but their orientations and cross-cutting relationships with surrounding rocks are compatible with either Scandian transpression or late-to post-Scandian transtension, but not with Ordovician structures as with Curraghinalt (Tanner, 2014; Rice et al., 2018).

The implication from our model combined with data from other vein localities is that at least three gold-mineralising episodes, each associated with a specific tectonic and structural setting, occurred across the Grampian Terrane during the overall Caledonian orogeny (Fig. 16). The first episode during which the Curraghinalt deposit formed is confined within a 10 Ma episode in the Late Ordovician (*c*. 463–453 Ma; Rice et al., 2016). The tectonic context at this time seems to have been orogen-oblique dextral transtension due to late-to post-Grampian relaxation of the thickened crust (Shaw et al., in prep). The present study constrains the second mineralising episode with the progressive formation of the Cavanacaw deposit, as well as other nearby gold vein occurrences (e.g., Rylagh, Glenhordial), to a relatively ductile episode of ENE–WSW-striking sinistral transpression during the Scandian event, probably in the mid-Silurian (*c*. 430–425 Ma; Fig. 16). The third episode, so far only dated in Scotland, seems to be 10–20 Ma younger than the "Cavanacaw phase" and may to be associated with an episode of brittle sinistral transpression or transtension along Caledonian faults during the late- to post-Scandian event in the Early Devonian.

Further work is needed to determine whether the other, un-dated vein systems with similar structural architectures to Cavanacaw and Cononish are related to a mid-Silurian event ("the Cavanacaw phase") or an Early Devonian event ("the Cononish phase") in the Scandian. The age information, combined with structural data, across the Grampian Terrane could be very useful in targeting metallogenic vein exploration; but additional age data would also further help to constrain the tectonic evolution of the Grampian Terrane in Ireland and Scotland and the localisation of deformation and fluid flow during the later stages of the Caledonian Orogeny.

## 9. Conclusions

1. The propagation and mineralisation of the economic, structurally complex vein system at Cavanacaw can be explained by a single progressive kinematic model. Rather than linking to two-stage deformation caused by NW–SE-directed Ordovician, then Carboniferous, compression, the formation of the vein system can be more easily explained via progressive deformation and sinistral transpressional shearing along ENE–WSW-striking transcurrent deformation zones. Comparison with regional data strongly suggests mid-Silurian age for this progressive deformation, linking it to the Scandian event of the Caledonian orogeny. All the sulphide-bearing structures in the complexly deformed veins at Cavanacaw and nearby regional localities can be readily explained by our progressive model.
2. The progressive deformation recognised at Cavanacaw may further explain both the occurrence of other metalliferous veins in the Sperrins (except Curraghinalt) and the formation of the regionally significant 'West Sperrin Knee Bend' which has historically been associated with the enigmatic Omagh Lineament. The formation of the regional structure and the structural observations from the veins are compatible with the anticlockwise rotation of the Dalradian strata expected within an ENE–WSW-striking sinistral shear zone system. The age of a calc-alkaline intrusive Sperrin Mountains Suite dated by Cooper et al. (2013), that appear to have been intruded within the tensional domain of this shear zone system, is mid-Silurian and constrains the evolution of the shear zone system associated with the Cavanacaw and other metalliferous veins to *c*. 430–425 Ma. Overall, the West Sperrin Knee Bend and similar structures in Scotland may be proof of penetrative Scandian deformation in the Grampian Terrane of Ireland and Scotland.
3. The interpretations suggest that three mineralising episodes, each associated with a specific tectonic and structural setting, occurred across the Grampian Terrane during the overall Caledonian orogeny. The Cavanacaw deposit is younger (mid-Silurian) than the nearby world-class Curraghinalt deposit (Ordovician); but probably up to 10–20 Ma older than the Early Devonian Cononish deposit and Rhynie gold occurrence in Scotland. The latter two probably formed during a later phase of brittle Scandian transpression or during a switch to transtension. The stress and kinematic regime inferred to be responsible for the veins at Cavanacaw do share similarities with Cononish and with other, un-dated but broadly "Late Caledonian" sulphide veins in the Grampian Terrane of Scotland and Ireland (Loch Tay area; Croagh Patrick; and Clontibret – Clay Lake) but more data, particularly age data, are needed from all vein systems to further investigate the localisation of deformation and fluid flow within the Grampian Terrane during the Silurian and Devonian.

**Author statement**

Shaw JI: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Validation; Visualization; Roles/Writing - original draft, Torvela T: Investigation; Supervision; Writing - review & editing, Cooper MR: Investigation; Supervision; Writing - review & editing, Leslie AG: Investigation; Supervision; Writing - review & editing, Chapman RJ: Investigation; Supervision; Writing - review & editing.

**Declaration of competing interest**

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: James I. Shaw reports financial support was provided by Society of Economic Geologists.

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