Early Devonian rift-related felsic igneous rocks in the western Looe Basin, South-West England

L.R.G. Penfound-Marks and R.K. Shail

Penfound-Marks, L.R.G. and Shail, R.K. 2015. Early Devonian rift-related felsic igneous rocks in the western Looe Basin, South-West England. *Geoscience in South-West England*, **13**, 471-482.

The Looe Basin records the extension of South-West England continental lithosphere during the Early Devonian. Its syn-rift infill, comprising the essentially non-marine Dartmouth Group (?Lochkovian-Pragian) and largely marine Meadfoot Group (Pragian-Emsian), includes low volume bimodal intrusive and extrusive igneous rocks that are predominantly mafic. Felsic igneous rocks are rare and have been described from several locations in the eastern Looe Basin, most notably the area around Whympston, south of Modbury, where they have also been investigated for their mineralisation potential. In the western Looe Basin a single occurrence, the poorly exposed Hendra Felsite, was recognised by Ussher during re-mapping of the Bodmin sheet at the beginning of the 20th Century. Previously undescribed Early Devonian felsic igneous rocks, defined here as the Hoblyn's Cove Felsite, crop out in the structurally complex coastal section through the Start-Perranporth Zone between Ligger Point and Holywell Bay. The felsites exhibit bedding-parallel contacts with the host Trendrean Mudstone Formation (Meadfoot Group), share its Variscan high strain composite S1/S2 fabric, and are interpreted to have originated as horizontal quartz- and feldspar-phyric rhyolite sills. Thinly-bedded crystal-lithic volcaniclastic sandstones, sandy mudstones and possible felsic pyroclastic rocks occur in the host rock succession in the vicinity of the intrusive felsite sheets and suggest that felsic magmatism was both contemporaneous with sedimentation and had a volcanic expression. Contemporaneous felsic magmatism is compatible with previous suggestions of a sedimentary or volcanic exhalative origin for the earliest sulphide-rich paragenesis of the nearby Perran Iron Lode. The felsite whole-rock trace element geochemistry is similar to that reported for Early Devonian felsites from the eastern Looe Basin. The Hoblyn's Cove Felsite and associated volcaniclastic and pyroclastic rocks were re-orientated, during latest Carboniferous-early Permian post-Variscan extension, to their sub-vertical attitude within the steep limb of the large-scale S-verging monoformal F3 fold that defines the Start-Perranporth Zone. Early Permian elvans are readily distinguished from the Early Devonian felsites by their lack of Variscan foliation and distinctive trace element whole-rock geochemistry (low Zr, high P_2O_5 at low TiO_2).

Camborne School of Mines, College of Engineering, Mathematics and Physical Sciences, University of Exeter, Penryn Campus, Penryn, TR10 9FE, U.K.
(E-mail: R.K.Shail@ex.ac.uk)

Keywords: rifting, bimodal magmatism, Devonian, Variscan, Rhenohercynian, Start-Perranporth Zone.

Introduction

During the Devonian and Early Carboniferous, much of South-West England comprised a series of rift basins that were infilled with terrestrial and marine sedimentary rocks and subordinate rift-related igneous rocks (Floyd *et al.*, 1993; Leveridge and Hartley, 2006). Magmatism was bimodal but is overwhelmingly represented by mafic igneous rocks that occur as high-level intrusive sheets, lavas and volcaniclastic rocks (e.g. Floyd *et al.*, 1993; Merriman *et al.*, 2000; Leveridge and Hartley, 2006). Felsic igneous rocks are far less abundant and commonly occur as small bodies that are too small to be represented on geological maps. Several occurrences have been described from the eastern Looe Basin where they were first recognised by Ussher during re-mapping of South Devon (Ussher, 1903, 1904, 1912). Some of these locations have attracted further investigation (Durrance, 1985; Jones and Floyd, 2000) and have been evaluated as potential sites of volcanogenic or exhalative mineralisation (Leake *et al.*, 1985, 1992).

The purpose of this contribution is to describe two locations in the western Looe Basin where felsic igneous rocks are hosted by Early Devonian sedimentary rocks of the Meadfoot Group. One of these locations, Hendra, is very poorly exposed and was briefly described by Ussher *et al.* (1909). The other, at Hoblyn's Cove, is very well exposed but occurs within the complexly deformed Start-Perranporth Zone and has not previously been described. At both locations Early Permian post-Variscan felsic igneous rocks also crop out as intrusive microgranite sheets or 'elvans'. Data are presented on the field relations, petrography and whole-rock geochemistry of the Early Devonian felsites that: (i) demonstrate their characteristics and how they can be readily distinguished from the Early Permian elvans, and (ii) allow comparison with more extensively studied Early Devonian rift-related felsites in the eastern Looe Basin.

Previous work

Looe Basin tectonics and stratigraphy

The Looe Basin (Figure 1) was defined by Leveridge *et al.* (2002) and represents the earliest and most southerly rift basin formed during the development of the Rhenohercynian proximal passive margin of South-West England (Leveridge and Hartley, 2006; Shail and Leveridge, 2009). Modern descriptions of the stratigraphy of the Looe Basin have resulted from British Geological Survey re-mapping of the Plymouth sheet (Leveridge *et al.*, 2002), Torquay sheet (Leveridge *et al.*, 2003) and Newquay sheet (Hollick *et al.*, 2006, 2014). Syntheses of Devonian rift basin evolution have been provided by Leveridge and Hartley (2006) and Leveridge (2011).

The lower part of the Looe Basin succession is formed by the essentially non-marine Dartmouth Group (?Lochkovian-Pragian) that is dominated by sandstones and mudstones deposited in alluvial, fluvial and lacustrine environments that were influenced by rifting (Smith and Humphreys, 1991; Leveridge *et al.*, 2002; Leveridge, 2011). The overlying Meadfoot Group (Pragian-Emsian) comprises mudstones, sandstones, limestones and local conglomerates that, in Devon and south-east Cornwall, were largely deposited in offshore to shallow marine environments (Leveridge and Hartley, 2006; Leveridge, 2011). Farther west, the Meadfoot Group includes deeper and/or more distal marine environments that may represent the infill of more southerly half-graben sub-basins (Leveridge, 2008; Hollick *et al.*, 2006, 2014).

Structural geology

During the Carboniferous the Looe Basin succession underwent two episodes of Variscan convergence-related deformation (D1 and D2) resulting in the development of thrust and transfer faults, folds and foliations that are generally compatible with a top sense-of-shear towards the NNW (e.g. Leveridge *et al.*, 2002; Leveridge and Hartley, 2006). All successions have undergone diagenetic to epizone low-grade regional metamorphism (Warr *et al.*, 1991; Leveridge *et al.*, 2002). A third deformation episode (D3) occurred during the latest Carboniferous to Early Permian and resulted from post-Variscan regional NNW-SSE extension that brought about reactivation of earlier thrust faults and the local development of folds and foliations compatible with a top sense-of-shear to the SSE (Alexander and Shail, 1995; Leveridge and Hartley, 2006; Shail and Leveridge, 2009).

The Start-Perranporth Zone (SPZ) represents a structurally complex area, up to 5 km in width, towards the southern margin crop of the Looe Basin, that is characterised by a steeply inclined fabric (Dearman, 1971; Holdsworth, 1989). Several authors have inferred that this steep zone is the short limb of a large-scale southwards-facing monoform that re-orientated earlier fabrics during regional D2 or D3 deformation (Sanderson, 1971; Shackleton *et al.*, 1982; Coward and McClay, 1983) whereas others have emphasised the role of strike-slip or transpressional tectonics in forming primary and secondary steep fabrics (Holdsworth, 1989; Steele, 1994). The most recent interpretations suggest that the steep fabric is composite, comprising bedding (S0), primary (S1) and high strain secondary (S2) cleavages, and was initially formed during Variscan convergence, but re-orientated during the development of a large-scale monoform during regional D3 extensional reactivation (Alexander, 1997; Shail and Leveridge, 2005, 2009; Hollick *et al.*, 2014).

Mafic magmatism in the Looe Basin

Low volume rift-related intrusive and extrusive mafic magmatic activity occurs throughout the crop of the Dartmouth and Meadfoot groups and is mostly considered as approximately contemporaneous (Ussher, 1903, 1904, 1912; Ussher *et al.*, 1909; Reid and Scrivenor, 1906; Leveridge *et al.*, 2002). Thin intrusive sheets of basalt and dolerite predominate but larger bodies do occur as well as rare gabbros (Leveridge *et al.*, 2002). Basaltic lavas and volcaniclastic rocks are generally minor but form a significant component of the Bin Down Formation (Dartmouth Group) where the geochemical analysis of samples from the Widegates Borehole resulted in rocks previously mapped as felsites (Ussher, 1907) being reinterpreted as basaltic tuffs, hyaloclastites and brecciated basalt that had undergone pre-burial silicification (Leveridge *et al.*, 2002). The geochemistry of the mafic igneous rocks shows almost all to be overwhelmingly within-plate sub-alkali, alkali and tholeiitic basalts compatible with generation by rifting of continental lithosphere (Floyd, 1982; Merriman *et al.*, 2000; Leveridge *et al.*, 2002). The geochemical and isotopic data are compatible with either an asthenospheric source that has been modified by crustal contamination or a lithospheric mantle source that had previously undergone enrichment during pre-Devonian subduction (Merriman *et al.*, 2000).

Felsic magmatism in the eastern Looe Basin

Pre-Variscan felsic igneous rocks in the eastern Looe Basin were first tentatively described within the Dartmouth Group at Blackpool Sands, near Dartmouth, by Ussher (1903), although these might be silicified mafic igneous rocks. Other minor occurrences of felsic intrusive igneous rocks within the

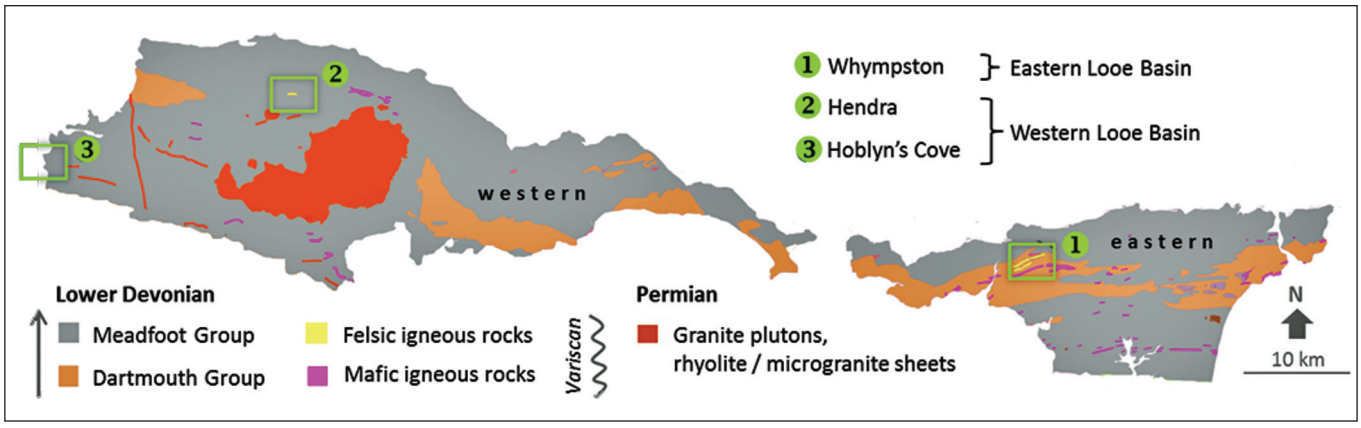

Figure 1. *Simplified geological map of the Looe Basin showing the distribution of Lower Devonian pre-Variscan felsic igneous rocks, primarily Whympston in the east and Hendra in the west, together with the location of the previously undescribed felsic rocks at Hoblyn's Cove that are the focus of this study. Permian granites and the principal associated rhyolite / microgranite sheets ('elvans') are also shown. Geological Map Data ©NERC 2015.*

Meadfoot and Dartmouth groups around Thurlestone and Blackaterry (Bigbury Bay) described by Ussher (1904) were reinterpreted as altered feldspathic tuffs by Durrance (1985). More substantive exposures of sheared and altered felsic igneous rocks, occurring at several levels within the Dartmouth Group were mapped over a strike length of *c.* 4 km around Whympston, south of Modbury (Figure 1), and described in detail by Ussher (1912), who emphasised their pre-folding age and distinctiveness relative to the post-folding elvans. Durrance (1985) provided petrographical detail and whole-rock geochemical analyses and suggested that these rocks originated as rhyolites and rhyolitic tuffs that had undergone variable silicification prior to Variscan deformation. Further geochemical analyses of felsic rocks, derived from boreholes in the Whympston area, were presented by Leake *et al.* (1992) and Jones and Floyd (2000). The latter authors indicated that most rocks corresponded to intrusive medium/high-K calc-alkali rhyolites and dacites and were consistent with an origin as within-plate A-type granites developed during the early stages of rifting.

Felsic magmatism in the western Looe Basin

The Hendra Felsite, interpreted as a quartz porphyry sill, has dimensions of *c.* 1.1 x 0.1 km (Figures 1 and 3) and was recognised and mapped by Ussher *et al.* (1909). It was defined largely using field brash but *in situ* material was confirmed at one location. The quartz porphyry was composed of 'greatly crushed' phenocrysts of quartz and potash feldspar and exhibited a lenticular foliation in part defined by secondary sericitic mica (Figure 2). No tourmaline was observed, in contrast to nearby elvans, and the rock was unequivocally interpreted as being of pre-folding age (Ussher *et al.*, 1909).

Figure 2. *Photomicrograph presented in Ussher* et al. *(1909) of the Hendra Felsite showing foliated porphyritic texture with secondary sericitic mica and fractured quartz phenocrysts. Specimen E5507 in the BGS Mineralogy and Petrology collection. See also E5506 and E5507 at http://www.bgs.ac.uk/data/britrocks.html. Reproduced with the permission of the British Geological Survey ©NERC. All rights Reserved.*

Early Permian post-Variscan magmatism

The generation and emplacement of the Cornubian Batholith occurred during the Early Permian and was accompanied by a suite of steeply inclined intrusive sheets of microgranite and rhyolite ('elvans'), up to 10s of metres in width (e.g. Chen *et al.*, 1993; Scrivener, 2006). The distribution and characteristics of elvans in the westernmost part of the Looe Basin has been described by Reid and Scrivenor (1906), Ussher *et al.* (1909), Goode (1973), Henley (1974b) and Hollick *et al.* (2014). The emplacement of elvans was typically controlled by fault systems developed during the Early Permian post-Variscan extensional tectonic regime (Shail and Wilkinson, 1994) and they do not possess the Variscan fabrics of their Devonian host rocks.

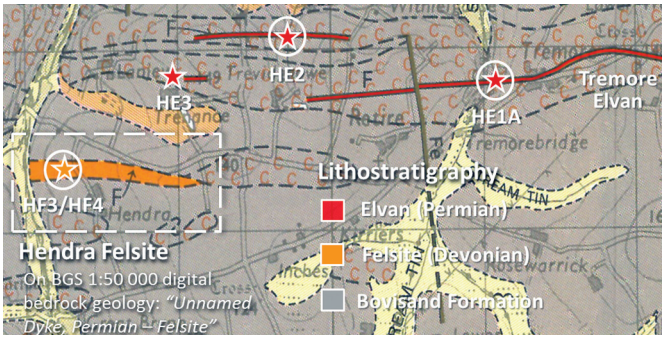

Figure 3. *Map showing the location of the Early Devonian Hendra Felsite and Early Permian elvans, including the Tremore Elvan, identified by Ussher* et al. *(1909). Note the contrast in felsite thickness and geometry with respect to the elvans. The locations of samples used for petrographical and geochemical analysis are shown. Reproduced with the permission of the British Geological Survey ©NERC. All rights Reserved. Contains Ordnance Survey materials © Crown copyright (1974) OS licence number 100040280.*

Field relations

The two study locations are the poorly exposed inland site at Hendra, as described by Ussher *et al.* (1909), and the coastal exposures at Hoblyn's Cove (Figure 1). Both locations are within the Meadfoot Group and also host Early Permian elvans. Emphasis is placed on Hoblyn's Cove as Devonian felsic igneous rocks have not been previously described in any detail from this coastal section. Henley (1974a) suggested that 'a few tuffaceous horizons' were present in the Meadfoot Slates between Penhale Point and Ligger Point.

Hendra Felsite

The Hendra Felsite was sampled from field brash near Hendra Farm (Figure 3). Hand specimens are typically pale brown-grey and possess a weak foliation. A porphyritic texture is exhibited with subhedral-anhedral 3-15 mm diameter plagioclase feldspar phenocrysts (40%) and subhedral 0.5-5 mm diameter quartz phenocrysts (15%) set within a <1 mm brown, partially kaolinised felsic groundmass (45%). Field brash samples of both the felsite and enclosing Bovisand Formation mudrocks and sandstones contain folded quartz veins. Samples of the nearby elvans, including the Tremore Elvan described by Ussher *et al.* (1909), were obtained for comparative petrographical and geochemical analysis (Figure 3).

Hoblyn's Cove Felsite

The previously mapped geology of the area between Holywell Bay and Perran Beach, including Hoblyn's Cove, is shown in Figure 4. The Devonian succession has been re-assigned to the newly defined Trendrean Mudstone Formation of mid-Emsian or younger age (Hollick *et al.*, 2014). A larger-scale sketch section of the principal geological features between Penhale Point and Cotty's Point, including the Hoblyn's Cove Felsite and elvans, is presented in Figure 5. The Trendrean Mudstone Formation comprises three main facies:

1) Uniform mudstone beds, locally pyritic, with sparse silt and very fine sand laminae.
2) Thin- to medium beds of fine, medium and coarse feldspar-rich sandstones (commonly muddy).
3) Thin beds of sandstone with subordinate mudstone and siltstone.

The coastal section between Holywell Bay and Perran Beach forms the westernmost exposure of the Start-Perranporth Zone and the structural geology is dominated by D3 structures. These comprise a series of mesoscale S to SW verging F3 monoformal folds that incorporate smaller S-verging F3 folds with an axial planar, moderately N-, NW- or NE- dipping, S3 cleavage that locally transposes earlier fabrics. The S-dipping S1 cleavage is parallel to bedding (S0) and the S2 cleavage is

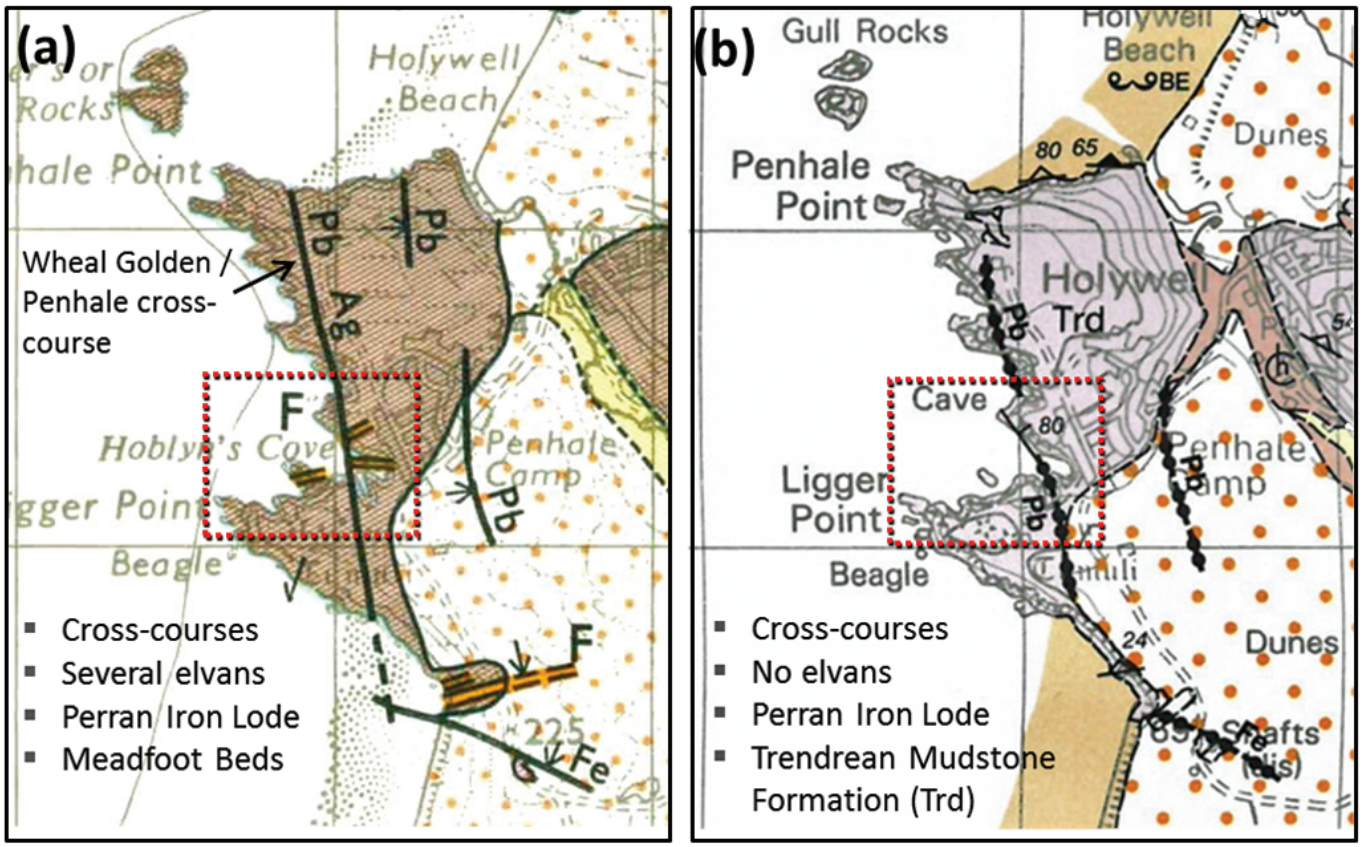

Figure 4. *Extracts of Geological Survey 1:50,000 maps of the Holywell Bay to Perran Beach area showing the location of Hoblyn's Cove (outlined in red) after (**a**) Geological Survey of Great Britain (England & Wales) (1981) and (**b**) British Geological Survey (2012). Pre-Variscan felsic igneous rocks are not distinguished on either map. Elvans recorded on the earlier map are not shown on the latter map. Reproduced with the permission of the British Geological Survey ©NERC. All rights Reserved. Contains Ordnance Survey materials © Crown copyright (1974, 2012) OS licence number 100040280.*

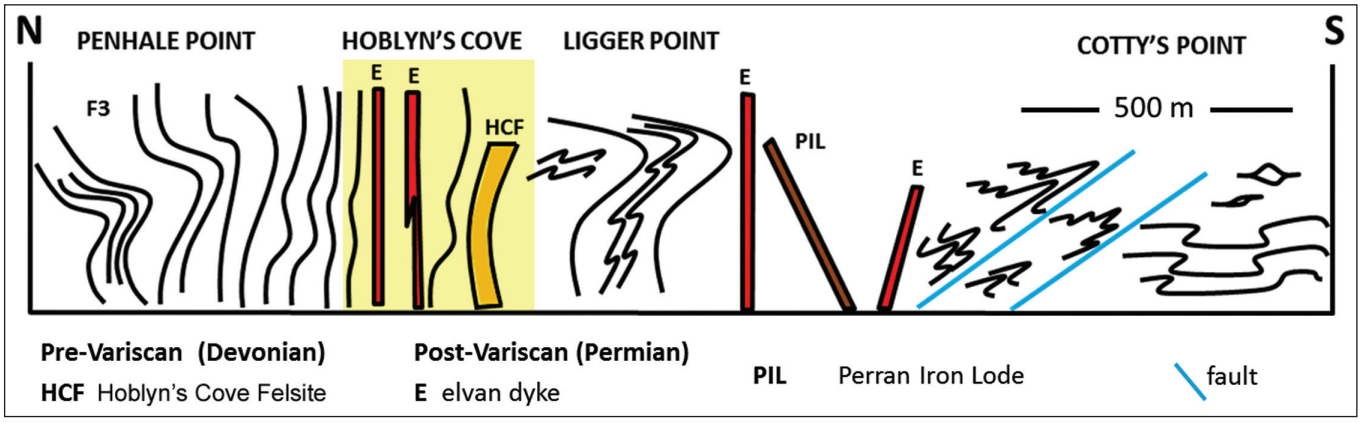

Figure 5. *A sketch section of the principal geological features between Penhale Point and Cotty's Point. The Hoblyn's Cove area is highlighted in yellow and shows the Hoblyn's Cove Felsite (HCF) and elvans (E). The Hoblyn's Cove Felsite (HCF) is parallel to, and folded with, the composite S0/S1/S2 fabric depicted by the black lines. The elvans are not folded and locally cross-cut this fabric.*

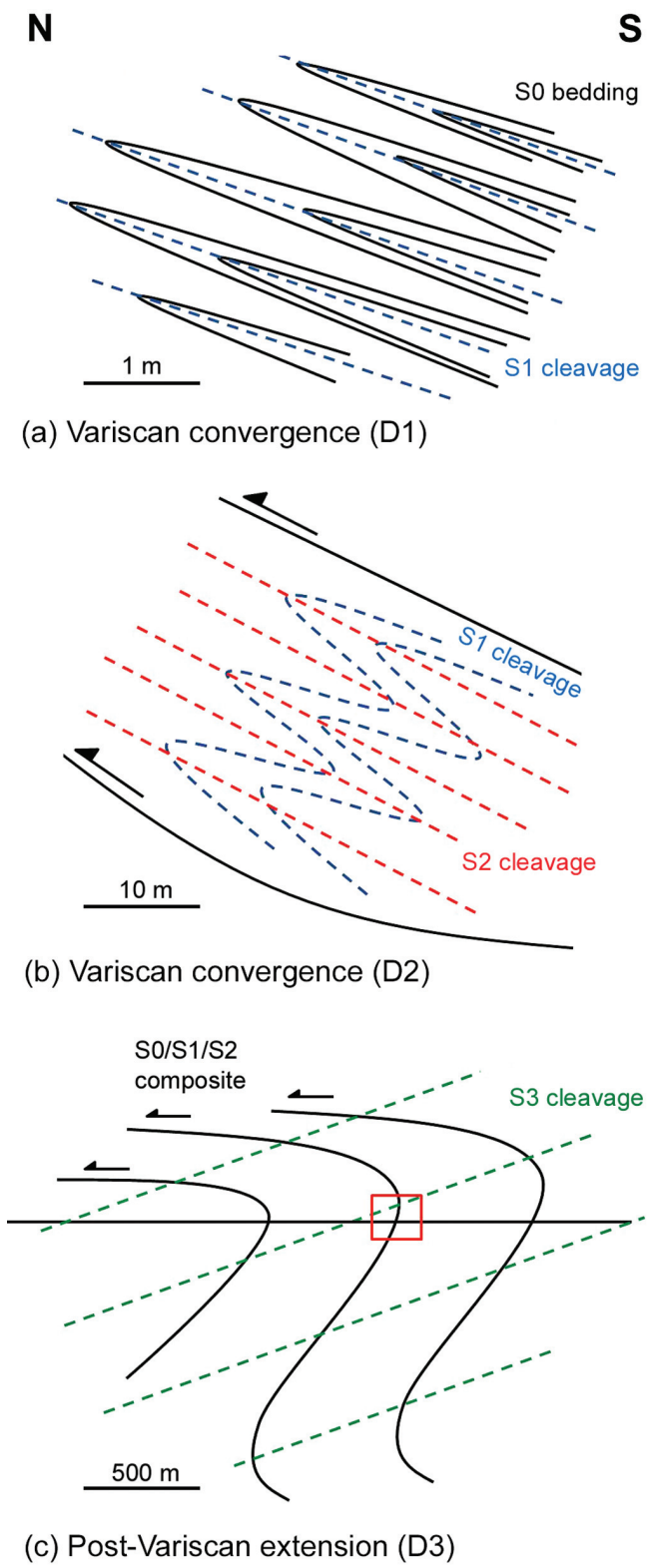

Figure 6. *Summary cartoon of the principal deformation episodes identified between Penhale Point and Cotty's Point.* ***(a)*** *Variscan D1 thrusting to the N generates tight to isoclinal F1 folds and a S-dipping axial planar S1 cleavage (not to scale).* ***(b)*** *Variscan D2 thrusting to the N associated with very high strains that generate F2 folds and a S-dipping axial planar S2 crenulation cleavage and S-dipping thrust surfaces (not to scale).* ***(c)*** *Post-Variscan extension (D3 deformation), with a top sense-of-shear to the S, results in progressive extensional reactivation of earlier thrust faults and development of a large scale monoform of the composite S0/S1/S2 fabric that is associated with a N-dipping axial planar S3 crenulation cleavage (Start-Perranporth Zone). Location of Hoblyn's Cove is shown by the red box.*

generally parallel to S0/S1 other than in lower strain zones near Perran Beach. The N-dipping S3 foliation is consistently axial planar to large scale F3 folds of the earlier composite S0/S1/S2 fabric (Figure 6). The Perran Iron Lode is 12 m wide, forms the hanging wall of a listric fault and marks the boundary between lower strain rocks to the S and higher strain rocks of the Start-Perranporth Zone to the N.

A large-scale geological map of Hoblyn's Cove is presented in Figure 7. The Hoblyn's Cove Felsite dips steeply S and crops out as upper (≤5 m thick) and lower (≤3) m units that thin eastwards and are separated by *c.* 1 m of Trendrean Mudstone Formation. It has been traced over a strike length of 150 m between two locations on either side of the NNW-SSE fault zone controlling the Wheal Golden / Penhale cross-course, across which it exhibits a dextral separation of 70 m (Figures 8 and 9). No substantive separation of the nearby similarly orientated Early Permian elvan dykes occurs across this fault zone (Figure 7). The felsites are dark yellow to white and exhibit localised zones of red iron oxide alteration. The contacts with the adjacent metasedimentary rocks are planar and concordant with bedding (S0) and dip steeply south, parallel to the composite S0/S1/S2 foliation which is locally intense. The metasedimentary rocks and felsites both host pre-D3 metamorphic quartz veins that pre-date the elvans. All lithologies host chalcedonic cross-course veins that post-date the elvans. The metasedimentary rocks in the vicinity of both locations include sporadic thick laminae/very thin beds of sandstone, containing, quartz, feldspar and rock fragments, and mudstone that include sand-sized clasts of felsic material (Figure 10).

The felsites vary markedly in appearance (Figure 10). The lower felsite unit consists of highly altered cream-pale grey competent rock with an intense foliation. Specimens from this unit are composed of 0.5-2 mm anhedral-subhedral quartz phenocrysts (10%) set within a <0.1 mm partially kaolinised quartzo-feldspathic groundmass (90%). The upper felsite unit also exhibits a highly sheared fabric and is more variable, displaying elements of both the enclosing metasedimentary host rocks and the underlying felsite. It has a porphyritic texture and is composed of 5-30 mm subhedral quartz phenocrysts (15%) distributed within an intensely sheared, pale grey, locally kaolinised quartzo-feldspathic groundmass (85%). Specimens can include boudinaged quartz veins.

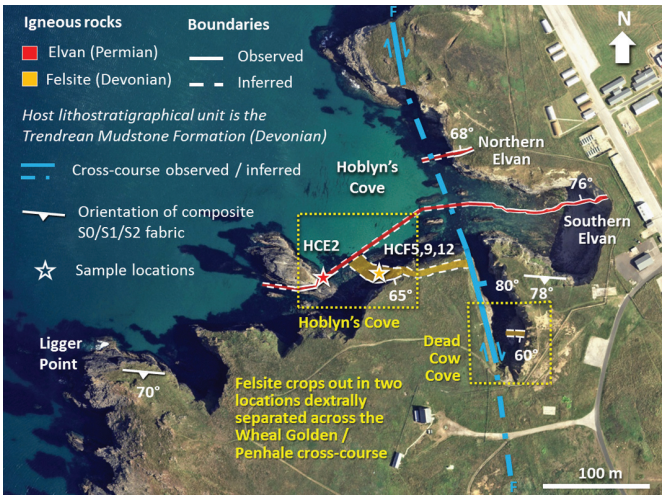

Figure 7. *Geological map of Hoblyn's Cove showing the location of the previously undescribed Early Devonian Hoblyn's Cove Felsite, the southern and northern elvan dykes, and the Wheal Golden / Penhale cross-course vein. The Hoblyn's Cove Felsite thins eastwards into Dead Cow Cove and has a dextral separation of c. 70 m across the fault zone that parallels the Wheal Golden / Penhale cross-course. The Early Permian elvans do not exhibit a separation across this fault. Map data from Google, Infoterra Ltd and Bluesky.*

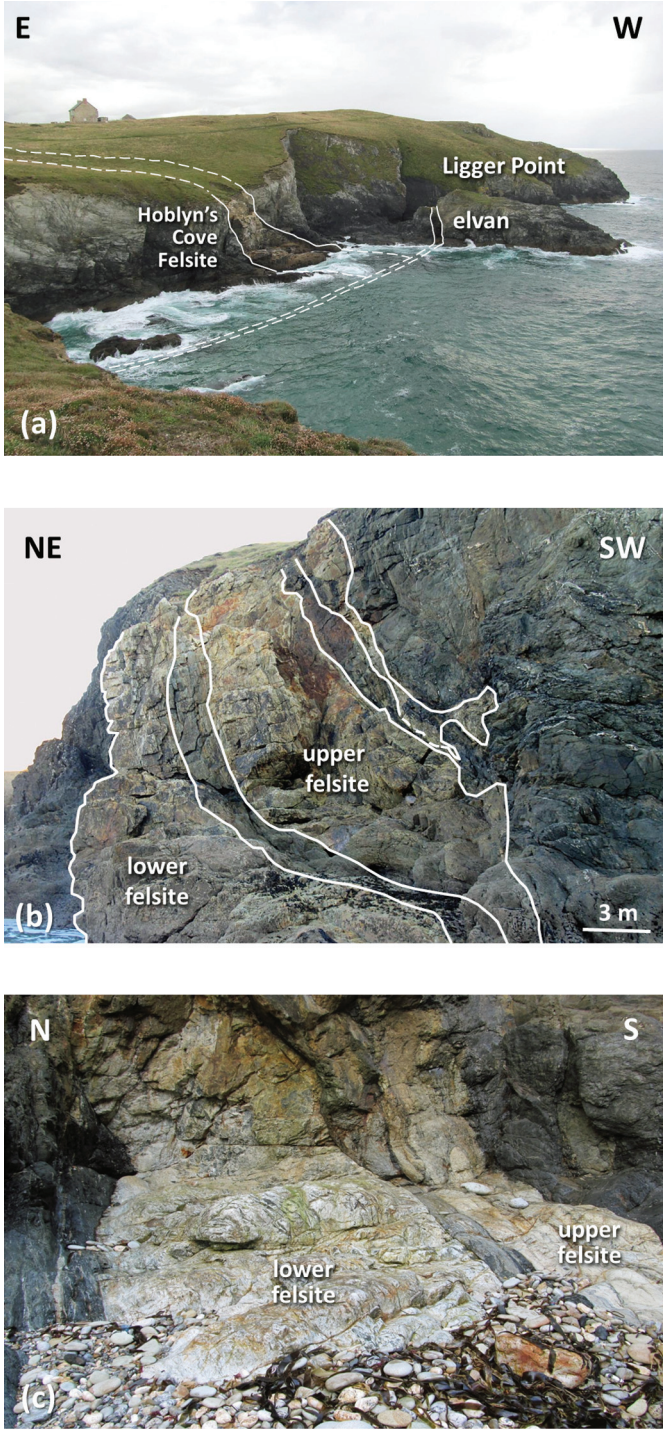

Figure 8. *Field photographs of the Hoblyn's Cove Felsite.* ***(a)*** *View SW across Hoblyn's Cove, the felsite crops out in the cliff and foreshore platform and gives rise to a recessive geomorphological feature trending eastwards to Dead Cow Cove.* ***(b)*** *Steeply dipping lower and upper felsite, separated by metasedimentary rock, exposed in the cliff and foreshore platform on the south side of Hoblyn's Cove. The felsites are parallel to, and folded with, the composite S0/S1/S2 fabric of the Trendrean Mudstone Formation.* ***(c)*** *Strongly foliated lower and upper felsite units exposed on the east side of Dead Cow Cove are separated by metasedimentary host rock (partially obscured by a rockfall in late 2014).*

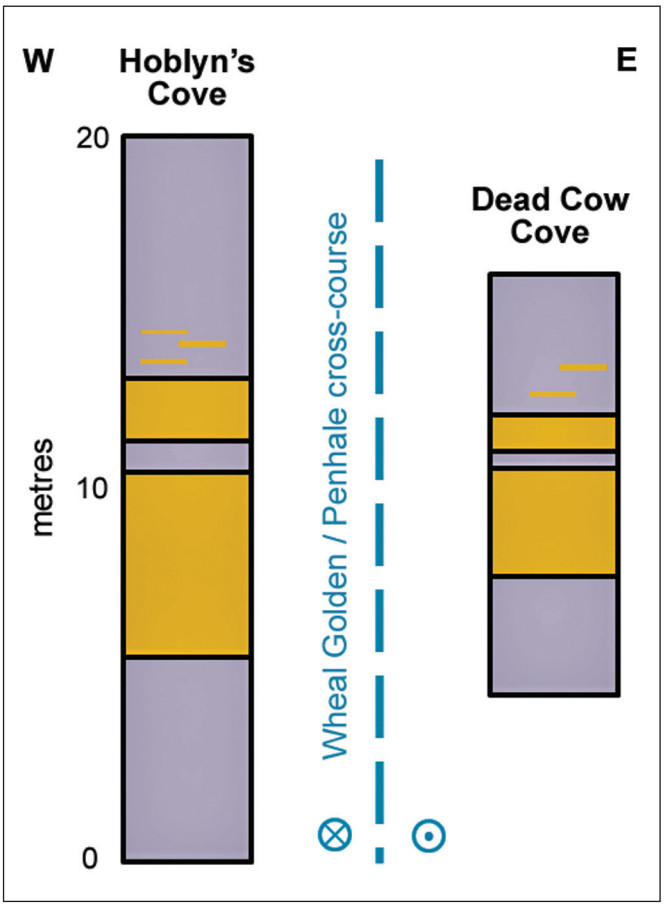

Figure 9. *Lithostratigraphy of the Hoblyn's Cove Felsite. The two felsite units are hosted by the Trendrean Mudstone Formation (lilac) and thin eastwards into Dead Cow Cove and are dextrally separated across the Wheal Golden / Penhale cross-course. The felsites are structurally overlain by quartz-, feldspar- and lithic-rich volcaniclastic sedimentary rocks.*

Petrography

Hendra Felsite and nearby elvans

The Hendra Felsite exhibits a porphyritic texture comprising fractured 0.5-3 mm phenocrysts of euhedral plagioclase feldspar (25%) recrystallised along their margins and 0.1-3 mm subhedral quartz phenocrysts (10%) which are locally stretched parallel to the foliation (Figure 11). The groundmass is formed by an extensively recrystallised fine-grained 0.1-0.5 mm quartzo-feldspathic groundmass (65%). The nearby Tremore Elvan is readily distinguished from the Hendra Felsite as it lacks a tectonic foliation (Figure 11d).

Hoblyn's Cove Felsite and nearby elvans

The Hoblyn's Cove Felsite exhibits a porphyritic texture and is composed of recrystallised 0.1-1 mm anhedral-euhedral plagioclase feldspar phenocrysts (30%) characterised by irregular grain boundaries and 0.1-0.5 mm subhedral quartz phenocrysts (5%) within a <0.1 mm feldspar-dominated felsic groundmass (65%) (Figure 12). Locally, plagioclase feldspar phenocrysts display sericitic alteration within grain fractures whilst 0.1-0.5 mm quartz veins often cross-cut samples. The high strain fabric of the rock is clearly defined as an intense foliation developed within the groundmass (Figure 12). The southern elvan is distinguished from the Hoblyn's Cove Felsite as it lacks a tectonic foliation (Figure 12d).

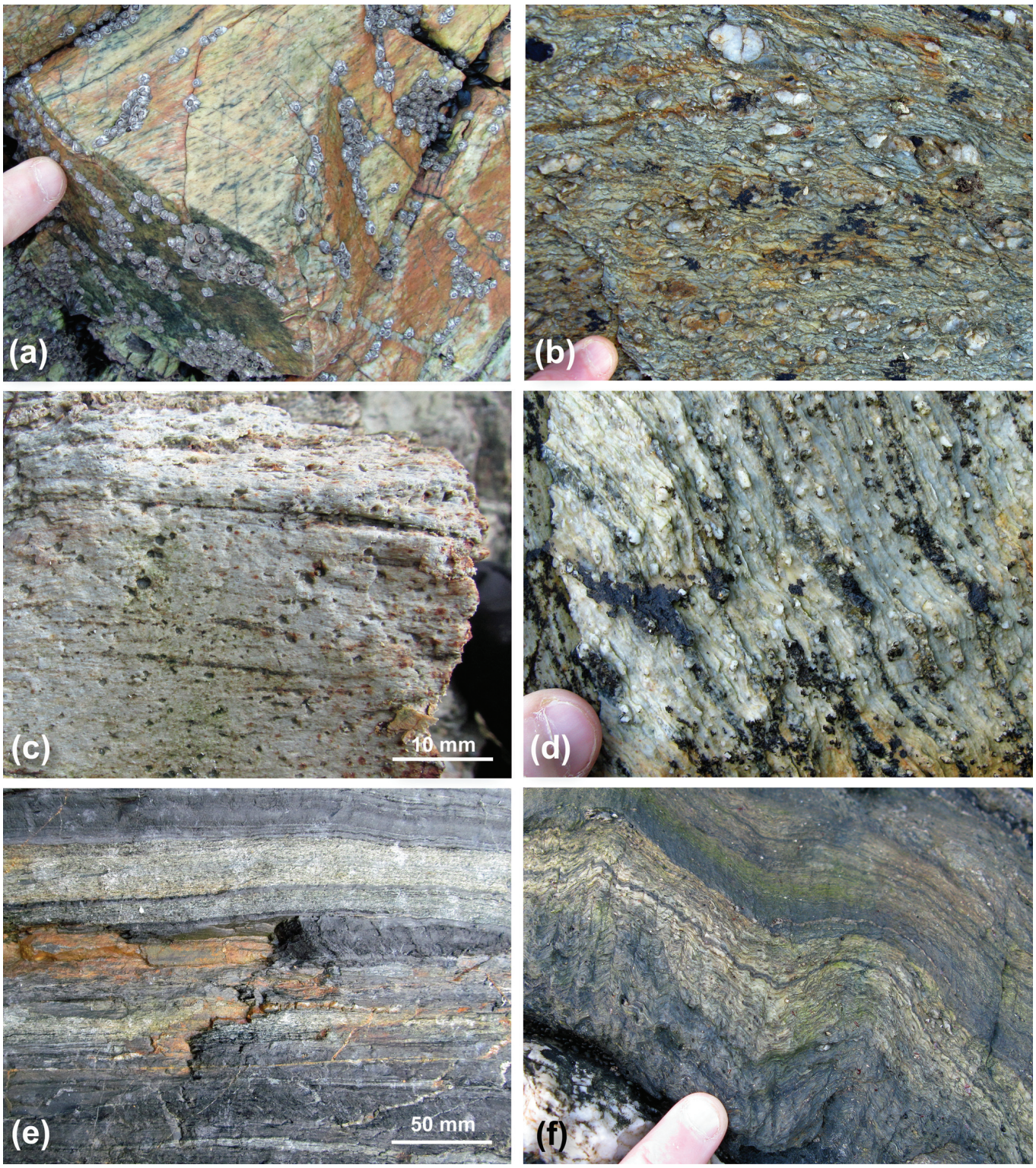

Figure 10. *Field photographs of the Hoblyn's Cove Felsite and associated volcaniclastic rocks.* (***a***) *Lower felsite unit comprised of massive strongly foliated rock.* (***b***) *Upper felsite unit exhibiting intense foliation and vein quartz porphyroclasts.* (***c***) *Porphyritic texture locally developed within the upper felsite unit (partially kaolinised).* (***d***) *Intense foliation within the upper felsite unit and feldspar phenocrysts / porphyroclasts.* (***e***) *Thinly-bedded crystal- and lithic-rock volcaniclastic sandstones and mudstones structurally overlying the felsites.* (***f***) *Thinly-bedded crystal-lithic pyroclastic or volcaniclastic rocks interbedded with mudstone structurally overlying the felsite units.*

Whole-rock geochemistry

Whole-rock geochemical analysis was undertaken on eight samples comprising the Hendra and Hoblyn's Cove felsites and nearby elvans. Samples were ground to a powder (<50 µm), prepared into pressed discs, and analysed by a Bruker S4 Pioneer WD-XRF, using semi-quantitative mode and calibrated to internal standards. The analyses are reported in Table 1. The original whole-rock geochemistry of the Early Devonian felsites is likely to have been modified given the extensive history of fluid-rock interaction spanning pre-, syn- and post-Variscan processes. However, the SiO_2 content of the Hendra and Hoblyn's Cove felsites always exceeds 70% and, given low Fe_2O_3 and MgO (<2.3 wt%), and variable but moderate Na_2O

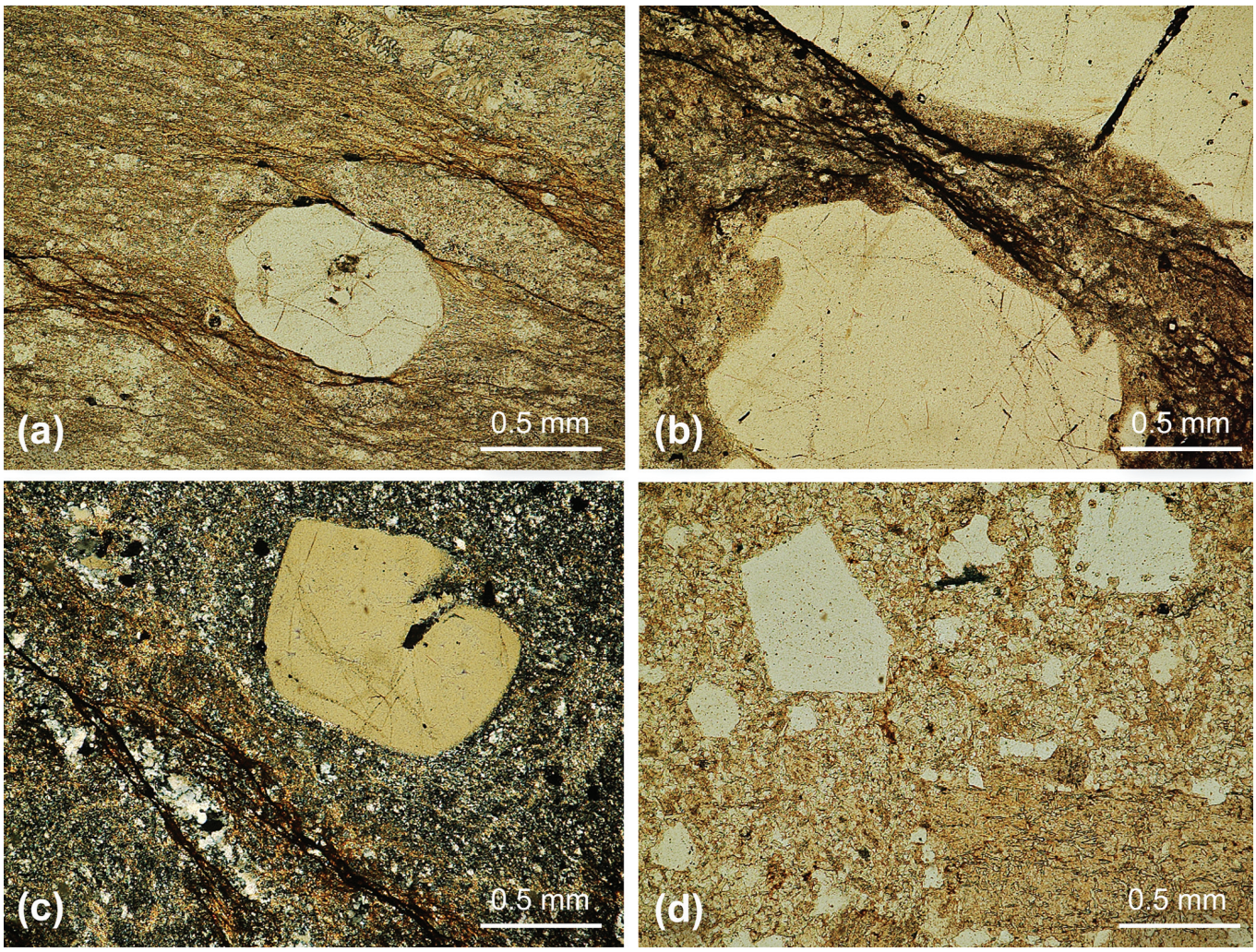

Figure 11. *Photomicrographs of the Early Devonian Hendra Felsite (**a-c**) and an adjacent Early Permian elvan (d) (specimen locations in Figure 3). (**a**) Quartz and feldspar phenocrysts within felsic groundmass displaying intense foliation (PPL); Specimen HF4. (**b**) Strong foliation around quartz phenocrysts (XPL); Specimen HF3. (**c**) Partially resorbed quartz phenocryst within a felsic groundmass; note the increased abundance of mica adjacent to foliation (XPL); Specimen HF3. (**d**) Quartz and feldspar phenocrysts in felsic groundmass lacking foliation (PPL); Specimen HE3.*

and K_2O (3.9-8.3 wt%) supports an origin as rhyolites or, possibly, dacites. The SiO_2 content of the Early Devonian felsites is consistently higher than the Early Permian elvans (Figure 13).

Relatively immobile trace elements are commonly quite robust indicators of original igneous rock type, even after substantial alteration. The sample data have been plotted on a Nb-Zr diagram (Figure 13), previously used to classify Early Permian granites and associated felsic rocks in South-West England (Manning *et al.*, 1996; Manning, 1998). The Early Devonian Hendra and Hoblyn's Cove felsites have Nb-Zr characteristics that: (i) overlap, but generally possess higher Zr values than the least evolved Early Permian biotite granites and elvans, and (ii) fall within the compositional range of the Early Devonian felsites from Whympston-Modbury presented in the analyses of Durrance (1985) and Jones and Floyd (2000). Additionally, the negligible P_2O_5 and low TiO_2 characteristics of the felsites overlap the rhyolite and felsite (but not dacite) fields of the Whympston felsic rocks defined by Leake *et al.* (1992). The Nb-Zr trace element data clearly distinguish the Early Permian elvans from Hendra and Hoblyn's Cove, with low Zr but variable Nb, from the Early Devonian felsites. The classification of Manning (1998) indicates that the Hendra elvans have affinities with the tourmaline and biotite granites whereas the southern Hoblyn's Cove elvan has affinity with the topaz granites. The elvans are also distinguished by their significantly higher P_2O_5 at low TiO_2 (not shown).

Discussion

Early Devonian felsic magmatism in the western Looe Basin

A combination of petrographic and geochemical data, plus comparison with previous studies, indicates that the newly described Hoblyn's Cove Felsite, hosted by the Early Devonian Trendrean Mudstone Formation, is likely to have originated as quartz- and feldspar-phyric rhyolite sills. It shares petrographical and geochemical similarities with the Hendra Felsite, hosted by the Bovisand Formation, originally recognised by Ussher *et al.* (1909) to be a sill of pre-Variscan age and the Whympston felsic rocks hosted by the Dartmouth Group in South Devon (Ussher, 1912; Durrance, 1985; Leake *et al.*, 1992; Jones and Floyd, 2000). Although these Early Devonian felsites have undergone significant local alteration, their whole-rock immobile element geochemistry appears to be robust. High values of SiO_2 are probably influenced by the presence of metamorphic vein quartz as previously suggested by Durrance (1985). The absence of a Variscan foliation from the Early Permian elvans and their trace element geochemistry (low Zr, high P_2O_5 at low TiO_2) allows them to be readily

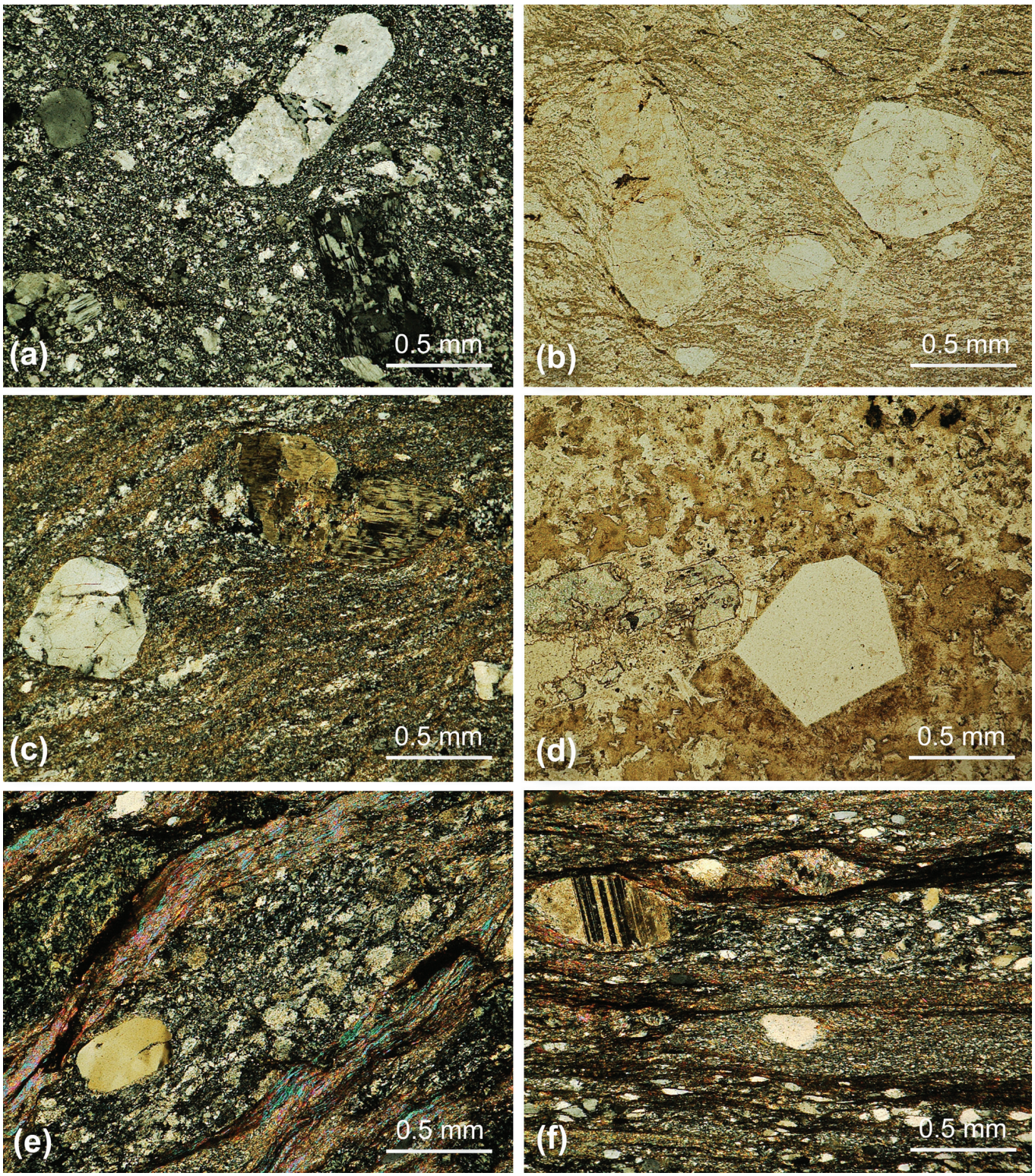

Figure 12. *Photomicrographs of the Early Devonian Hoblyn's Cove Felsite (**a-c**), Early Permian elvan (**d**) and Early Devonian volcaniclastic sedimentary rocks (**e-f**) at Hoblyn's Cove (specimen locations in Figure 7). (**a**) Quartz and feldspar phenocrysts in a felsic groundmass within the lower felsite unit (XPL); Specimen HCF5. (**b**) Composite S1/S2 foliation in lower felsite unit (PPL); Specimen HCF0. (**c**) Highly strained upper felsite unit with quartz and feldspar phenocrysts set in a felsic groundmass with S1/S2 foliation and enhanced mica content (XPL); Specimen HCF0. (**d**) euhedral quartz phenocryst enclosed within felsic groundmass containing biotite and muscovite (PPL); Specimen HCE11. (**e**) Volcaniclastic sedimentary rock with strong S1/S2 fabric containing felsic rock fragment with quartz phenocryst (XPL); Specimen HC4. (**f**) Volcaniclastic sandstone with strong S1/S2 fabric containing clasts of plagioclase feldspar, quartz and felsic rock fragments (XPL); Specimen HC3.*

	HF3	HF4	HCF5	HCF9	HCF12	HE1A	HE2	HCE2
SiO_2	75.05	70.40	76.63	79.60	79.43	69.80	69.82	67.06
Al_2O_3	13.20	9.92	12.50	12.30	13.60	15.50	15.00	18.40
Fe_2O_3	1.74	1.24	1.24	0.50	0.79	1.10	1.29	1.07
CaO	ND	ND	0.08	0.03	ND	0.47	0.48	0.40
MgO	0.51	0.45	0.13	0.14	0.11	0.12	0.21	0.42
Na_2O	0.12	ND	7.93	3.55	0.12	0.62	2.29	0.60
K_2O	7.32	3.91	0.35	1.74	3.98	10.66	9.06	9.24
TiO_2	0.31	0.26	0.11	0.10	0.10	0.09	0.13	0.00
P_2O_5	0.00	0.00	0.00	0.00	0.00	0.47	0.39	0.40
MnO	0.01	0.01	0.03	ND	ND	0.03	0.03	0.10
Cu	ND	ND	ND	ND	ND	ND	48	ND
Zn	ND	ND	56	56	ND	ND	64	68
Rb	252	183	956	567	86	150	ND	1155
Sr	64	25	91	96	63	ND	140	88
Nb	20	20	35	28	24	20	27	59
Zr	188	147	46	77	271	248	273	22

Table 1. *Whole-rock major- and trace element geochemistry of Early Devonian felsites and Early Permian elvans from Hendra and Hoblyn's Cove. HF = Hendra Felsite, HCF = Hoblyn's Cove Felsite, HE = Hendra Elvan, HCE = Hoblyn's Cove Elvan. Major oxides in wt %. Trace elements in ppm. ND indicates below detection limit.*

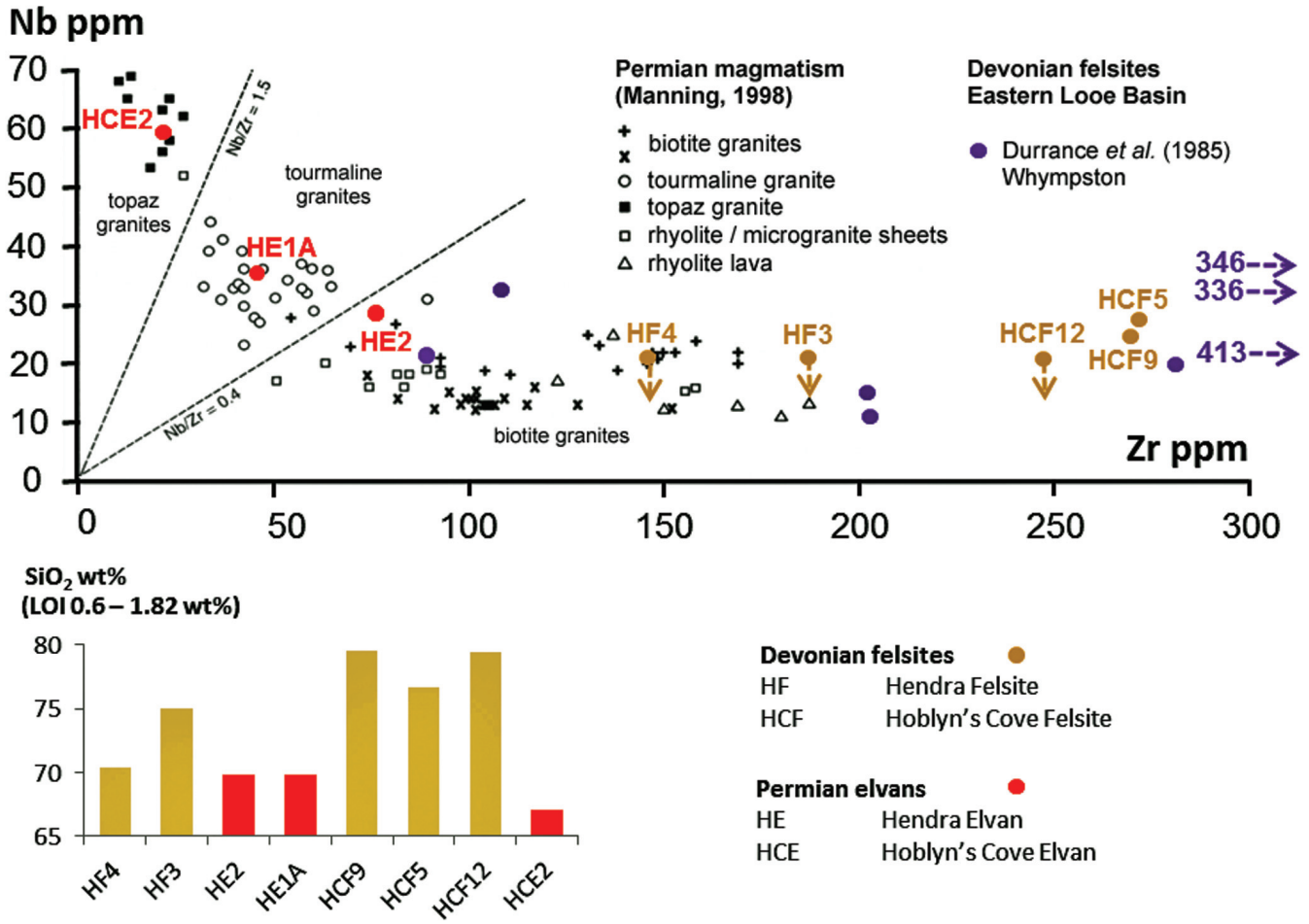

Figure 13. *Whole-rock geochemistry of Early Devonian Hendra and Hoblyn's Cove felsites and Early Permian elvans (data in Table 1).* (***a***) *Nb-Zr diagram showing: (i) representative analyses of Early Permian granites superimposed on fields of biotite, tourmaline and topaz granites (after Manning, 1998), (ii) Hendra and Hoblyn's Cove felsites and elvans, (iii) Early Devonian felsites from Whympston in the eastern Looe Basin (Durrance, 1985).* (***b***) *SiO_2 content of Early Devonian felsites and Early Permian elvans.*

distinguished from the Early Devonian felsites.

The recognition of volcaniclastic sedimentary rocks, and possibly pyroclastic rocks, within the Trendrean Mudstone Formation close to the Hoblyn's Cove Felsite indicates that felsic igneous activity was contemporaneous with sedimentation and had an extrusive expression. These rocks have similarities with the Early Devonian felsites in the eastern Looe Basin first described by Ussher (1904) and reinterpreted as volcaniclastic tuffs by Durrance (1985).

Structural geology

The margins of the Hoblyn's Cove Felsite are bedding-parallel and it exhibits the same composite Variscan S1/S2 fabric as the Trendrean Mudstone Formation. The steeply S-dipping attitude of bedding, felsite sills and the S1/S2 fabric is compatible with their location on the steep limb of the large-scale S-verging monoformal F3 fold, formed during post-Variscan extension, that defines the Start-Perranporth Zone (Alexander, 1997; Shail and Leveridge, 2005, 2009; Hollick *et al.*, 2014).

The *c.* 70 m dextral separation of the Hoblyn's Cove Felsite across the prominent NNW-SSE fault zone is not exhibited by the similarly orientated northern and southern elvans. Almost all displacement on this fault must therefore have occurred before the Early Permian; it probably acted as a strike-slip transfer fault during the latter stages of Variscan thrusting and/or early post-Variscan extension. The development of the Wheal Golden / Penhale cross-course vein system, within the same fault zone, is not associated with any substantial strike separation of the elvans. Similar cross-course vein systems elsewhere in South-West England have been shown to be Mid-Triassic in age (Scrivener *et al.*, 1994) and associated with ENE-WSW extension (Shail and Alexander, 1997).

Syn-rift mineralisation

The syn-rift felsic magmatism identified at Hoblyn's Cove occurs less than 1 km to the north of the Perran Iron Lode. It may provide additional weight to the suggestions that earliest sphalerite-chalcopyrite-pyrite paragenesis recorded in this structure may have originated as VMS / SedEx style mineralisation (Henley, 1971; Scrivener *et al.*, 2006).

Conclusions

1) Early Devonian felsic igneous rocks in the western Looe Basin occur within the Meadfoot Group and are represented by the Hendra Felsite (hosted by the Bovisand Formation) and the newly described Hoblyn's Cove Felsite (hosted by the Trendrean Mudstone Formation).

2) The field, petrographic and whole-rock geochemical characteristics of the Hoblyn's Cove Felsite suggest that it was emplaced as quartz- and feldspar-phyric rhyolite sills. Volcaniclastic and possible pyroclastic rocks occur nearby and imply that felsic magmatism was contemporaneous with the deposition of the mid-Emsian Trendrean Mudstone Formation and had an extrusive expression.

3) The felsic magmatism described in the western Looe Basin is very similar to that more fully described from the eastern Looe Basin (Durrance, 1985; Jones and Floyd, 2000) and is compatible with rifting of continental lithosphere (e.g. Merriman *et al.*, 2000).

4) The recognition of contemporaneous Early Devonian felsic magmatism and sedimentation at Hoblyn's Cove is compatible with previous suggestions of a sedimentary or volcanic exhalative origin for the earliest sulphide-rich paragenesis of the nearby Perran Iron Lode (Henley, 1971; Scrivener *et al.*, 2006).

5) The steeply S-dipping attitude of the Hoblyn's Cove Felsite is due to incorporation of this part of the Trendrean Mudstone Formation into the Start-Perranporth Zone – the steeply-dipping limb of a large-scale S-verging F3 monoform generated during post-Variscan extension.

6) Early Permian elvans occur in the vicinity of the Hendra and Hoblyn's Cove felsites but can be readily distinguished due to their lack of Variscan foliation and distinctive trace element geochemistry (low Zr, high P_2O_5 at low TiO_2). The Nb-Zr characteristics of the elvans indicate affinities with biotite and tourmaline granites (Hendra) and topaz granites (Hoblyn's Cove).

Acknowledgements

Steve Pendray is thanked for making thin-sections from samples that were often less than promising. Malcolm Spence and Gavyn Rollinson are thanked for producing the whole-rock XRF analyses and advice on analytical methodology. The first author is grateful to the Ussher Society for a bursary to defray the costs of participating in the 2015 Paignton Conference and verbally presenting an earlier version of this paper. Brian Leveridge and Richard Scrivener are thanked for their constructive referees' comments and advice on English usage.

References

ALEXANDER, A.C. 1997. *Late- to post-Variscan deformation in south Cornwall.* Unpublished PhD thesis, University of Exeter.

ALEXANDER, A.C. and SHAIL, R.K. 1995. Late Variscan structures on the coast between Perranporth and St Ives, Cornwall. *Proceedings of the Ussher Society,* **8**, 398-404.

BRITISH GEOLOGICAL SURVEY. 2012. Newquay. England and Wales Sheet 346. Bedrock and Superficial Deposits. 1:50,000. British Geological Survey, Keyworth, Nottingham.

CHEN, Y., CLARK, A.H., FARRAR, E., WASTENEYS, H.A.H.P., HODGSON, M.J. and BROMLEY, A.V. 1993. Diachronous and independent histories of plutonism and mineralisation in the Cornubian Batholith, southwest England. *Journal of the Geological Society, London,* **150**, 1183-1191.

COWARD, M.P. and MCCLAY, K.R. 1983. Thrust tectonics of S. Devon. *Journal of the Geological Society, London,* **140**, 215-228.

DEARMAN, W.R. 1971. A general view of the structure of Cornubia. *Proceedings of the Ussher Society,* **2**, 220-236.

DURRANCE, E.M. 1985. Lower Devonian acid igneous rocks of south Devon: Implications for Variscan plate tectonics. *Proceedings of the Ussher Society,* **6**, 205-210.

FLOYD, P.A. 1982. Chemical variation in Hercynian basalts relative to plate tectonics. *Journal of the Geological Society, London,* **139**, 505-520.

FLOYD, P.A., EXLEY, C.S. and STYLES, M.T. 1993. *Igneous Rocks of South-West England.* Geological Conservation Review Series, Chapman and Hall, London.

GEOLOGICAL SURVEY OF GREAT BRITAIN (ENGLAND & WALES). 1981. Newquay Sheet 346. 1:50,000 scale. British Geological Survey, Nottingham.

GOODE, A.J.J. 1973. The mode of intrusion of Cornish elvans. *Report of the Institute of Geological Sciences, London* **73/7**.

HENLEY, S. 1971. Hedenbergite and sphalerite from the Perran Iron Lode, Cornwall. *Proceedings of the Ussher Society,* **2**, 329-334.

HENLEY, S. 1974a. Geochemistry of Devonian sediments in the Perranporth area, Cornwall. *Proceedings of the Ussher Society,* **3**, 128-136.

HENLEY, S. 1974b. Geochemistry and petrogenesis of elvan dykes in the Perranporth area, Cornwall. *Proceedings of the Ussher Society,* **3**, 136-145.

HOLDSWORTH, R.E. 1989. The Start-Perranporth Line: A Devonian Terrane Boundary in the Variscan Orogen of SW England. *Journal of the Geological Society,* **146**, 419-421.

HOLLICK, L.M., SHAIL R.K. and LEVERIDGE B.E. 2006. Devonian rift-related sedimentation and Variscan tectonics – new data on the Looe and Gramscatho basins from the resurvey of the Newquay district. *Geoscience in South-West England,* **11**, 191-198.

HOLLICK, L.M., SCRIVENER, R.C. and BURT, C.E. 2014. Geology of the Newquay district – a brief explanation of the geological map. *Sheet explanation of the British Geological Survey.* 1:50 000 Sheet 346 Newquay (England and Wales).

JONES, R.M. and FLOYD, P.A. 2000. Silicic volcanism in the Rhenohercynian zone: geochemistry and temporal development. *Geoscience in South-West England,* **10**, 29-33.

LEAKE, R.C., BROWN, M.J., SMITH, K., ROLLIN, K.E., KIMBELL, G.S., CAMERON, D.G., ROBERTS, P.D. and BEDDOE-STEPHENS, B.W. 1985. Volcanogenic and exhalative mineralisation within Devonian rocks of the South Hams district of Devon. *Mineral Reconnaissance Programme Report, British Geological Survey,* **79**.

LEAKE, R.C., CAMERON, D.G., BLAND, D.J., STYLES, M.T. and ROLLIN, K.E. 1992. Exploration for gold in the South Hams district of Devon. *British Geological Survey Technical Report* **WF/92/2** (BGS Mineral Reconnaissance Programme Report 121).

LEVERIDGE, B.E. 2008. Geology of the Mevagissey district – a brief explanation of the geological map. *Sheet explanation of the British Geological Survey.* 1:50 000 Sheet 353 Mevagissey (England and Wales).

LEVERIDGE, B.E. 2011. The Looe, south Devon and Tavy Basins: the Devonian rifted passive margin successions. *Proceedings of the Geologists' Association,* **122**, 616-717.

LEVERIDGE, B.E. and HARTLEY, A.J. 2006. The Variscan Orogeny: The development and deformation of Devonian/Carboniferous basins in SW England and South Wales. In: BRENCHLEY, P.J. and RAWSON, P.F. (Eds), *The Geology of England and Wales.* The Geological Society, London, 226-237.

LEVERIDGE, B.E., HOLDER, M.T., GOODE, A.J.J., SCRIVENER, R.C., JONES, N.S. and MERRIMAN, R.J. 2002. Geology of the Plymouth and south-east Cornwall area. *Memoir of the British Geological Survey*, Sheet 348 (England and Wales).

LEVERIDGE, B.E., SCRIVENER, R.C., GOODE, A.J.J. and MERRIMAN, R.J. 2003. Geology of the Torquay district – a brief explanation of the geological map. *Sheet explanation of the British Geological Survey.* 1:50 000 Sheet 350 Torquay (England and Wales).

MANNING, D.A.C. 1998. Granites and associated igneous activity. In: SELWOOD, E.B., DURRANCE, E.M. and BRISTOW, C.M. (Eds), *The geology of Cornwall.* University of Exeter Press, 120-135.

MANNING, D.A.C., HILL, P.I. and HOWE, J.H. 1996. Primary lithological variation in the kaolinised St Austell Granite, Cornwall, England. *Journal of the Geological Society, London,* **153**, 827-838.

MERRIMAN, R.J., EVANS, J.A. and LEVERIDGE, B.E. 2000. Devonian and Carboniferous volcanic rocks associated with the passive margin sequences of SW England; some geochemical perspectives. *Geoscience in South-West England,* **10**, 77-85.

REID, C. and SCRIVENOR, J.B. 1906. The geology of the country near Newquay. *Memoir of the Geological Survey of Great Britain.*

SANDERSON, D.J. 1971. Superimposed folding at the northern margin of the Gramscatho and Mylor Beds, Perranporth, Cornwall. *Proceedings of the Ussher Society,* **2**, 266-270.

SCRIVENER, R.C. 2006. Cornubian granites and mineralisation of SW England. In: BRENCHEY, P.J. and RAWSON, P.F. (Eds), *The Geology of England and Wales.* The Geological Society, London, 257-267.

SCRIVENER, R.C., DARBYSHIRE, D.P.F. and SHEPHERD, T.J. 1994. Timing and significance of crosscourse mineralization in SW England. *Journal of the Geological Society of London,* **150**, 587-590.

SCRIVENER, R.C., GRANT, J.B., HOLLICK, L.M. and SMITH, C.W. 2006. Nature and origin of the Great Perran Iron Lode. *Geoscience in south-west England,* **11**, 255-256.

SHACKLETON, R.M., RIES, A.C. and COWARD, M.P. 1982. An interpretation of the Variscan structures in SW England. *Journal of the Geological Society, London,* **139**, 533-541.

SHAIL, R.K. and ALEXANDER, A.C. 1997. Late Carboniferous to Triassic reactivation of Variscan basement in the western English Channel: evidence from onshore exposures in south Cornwall. *Journal of the Geological Society, London,* **154**, 163-168.

SHAIL, R.K. and LEVERIDGE, B.E. 2005. Large-scale southward facing structures in the Looe Basin (Lower Devonian), SW England (Abstract). *Geoscience in south-west England,* **11**, 164.

SHAIL, R.K. and LEVERIDGE, B.E. 2009. The Rhenohercynian passive margin of SW England: Development, inversion and extensional reactivation. *Comptes Rendus Geoscience,* **341**, 140-155.

SHAIL, R.K. and WILKINSON, J.J. 1994. Late- to post-Variscan extensional tectonics in south Cornwall. *Proceedings of the Ussher Society,* **8**, 162-270.

SMITH, S.A. and HUMPHREYS, B. 1991. Sedimentology and depositional setting of the Dartmouth Group, Bigbury Bay, south Devon. *Journal of the Geological Society, London,* **148**, 235-244.

STEELE, S.A. 1994. *The Start-Perranporth Zone - transpressional reactivation across a major basement fault in the Variscan orogen of SW England.* Unpublished PhD thesis, Durham University.

USSHER, W.A.E. 1903. The geology of the country around Torquay. *Memoir of the Geological Survey of Great Britain*, Sheet 350 (England and Wales).

USSHER, W.A.E. 1904. The geology of the country around Kingsbridge and Salcombe. *Memoir of the Geological Survey of Great Britain*, Sheets 355 and 356 (England and Wales).

USSHER, W.A.E. 1907. The geology of the country around Plymouth and Liskeard. *Memoir of the Geological Survey of Great Britain*, Sheet 348 (England and Wales).

USSHER, W.A.E. 1912. The geology of the country around Ivybridge and Modbury. *Memoir of the Geological Survey of Great Britain*, Sheet 349 (England and Wales).

USSHER, W.A.E., BARROW, G. and MACALISTER, D.A. 1909. The geology of the country around Bodmin and St. Austell. *Memoir of the Geological Survey of Great Britain.*

WARR, L.N., PRIMMER, T.J. and ROBINSON, D. 1991. Variscan very low-grade metamorphism in southwest England: a diastathermal and thrust-related origin. *Journal of Metamorphic Geology,* **9**, 751-764.