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A revised age, structural model and origin for the North Pennine Orefield in the Alston Block, N. England: Intrusion (Whin Sill)-related base metal (Cu-Pb-Zn-F) mineralization

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Abstract: Mineralization and associated fluid migration events in the ca 1500 km² North Pennine Orefield (NPO) are known to be associated with tectonic activity, but the age of these tectonic events and origins of the base metal sulphide mineralization remain unresolved. New fieldwork in the Alston Block shows that mineralization post-dates a weakly developed phase of N-S shortening consistent with far-field Variscan basin inversion during the late Carboniferous. New observations of field relationships, coupled with microstructural observations and stress inversion analyses, together with Re-Os sulphide geochronology show that the vein-hosted mineralization (apart from barium minerals) was synchronous with a phase of N-S extension and E-W shortening coeval with emplacement of the Whin Sill (ca 297-294 Ma). Thus the development of the NPO was related to an early Permian regional phase of transtensional deformation, mantle-sourced hydrothermal mineralization and magmatism in northern Britain. Previously proposed Mississippi Valley Type models, or alternatives relating mineralization to the influx of Mesozoic brines can no longer be applied to the development of the NPO in the Alston Block. Our findings also mean that existing models for equivalent base metal sulphide fields worldwide (e.g. Zn-Pb Districts of Silesia, Poland and Tennessee, USA) may need to be reassessed.

[end]
The world-famous veins and orebodies of the North Pennine Orefield (NPO) have long been considered to be archetypal examples of a Mississippi Valley Type (MVT) deposit (e.g. Halliday et al. 1990 and references therein) and have been exploited since at least the 12th century. The NPO covers an area of ~1500 km$^2$ and by the time mining activities ceased during the early 20th century, approximately 10 million tonnes of ore (Zn, Pb, Ba, Fe, Cu) had been extracted (Dunham 1944, 1990). The orefield lies at the centre of a structural high known as the Alston Block, a ~40 km wide, fault-bounded horst (Fig. 1a). The block is bounded to the north by the Stublick/Ninety Fathom Fault system, to the south by the Lunedale - Butterknowle Fault system, and to the west by the Pennine Fault system. Whilst it is generally agreed that mineralization was contemporaneous with tectonic activity in conjunction with fluid migration, the age of these tectonic events and origin of sulphide mineralisation remain unresolved. Here we integrate detailed field observations, palaeostress analyses of fault slickenline data and Rhenium-Osmium (Re-Os) geochronology and geochemistry on vein-hosted pyrite samples to constrain the style and timing of events relating to the genesis of the NPO and the structural evolution of the Alston Block and adjacent regions of northern England.

Geological Setting

The Alston Block and the North Pennine batholith

The geological structure of northern England is dominated by features associated with basin formation during the Carboniferous. N-S Early Mississippian (ca 359 – 335 Ma) rifting is widely recognised (Underhill et al. 1988; Collier 1989) and is characterised by the formation of a series of fault-bounded basins and structural highs. Of these, the Alston Block, separates the Northumberland Trough to the north from the Stainmore Trough to the south and is bound to the west by the post-Carboniferous Pennine escarpment and Vale of Eden basin (Fig. 1a). The Alston Block preserves a 600m thick sedimentary sequence of Carboniferous cyclothemic sedimentary rocks which range in age from the Late Mississippian to Pennsylvanian (ca 335-300 Ma age). They lie unconformably upon
a basement block of deformed Palaeozoic sedimentary and volcanic rocks intruded by the North Pennine batholith (Dunham 1990; ca. 399 Ma, Re-Os molybdenite, U-Pb CA-ID-TIMS zircon; Selby et al. 2008; Kimbell et al. 2010) (Fig. 1a, b). The erosional non-conformity that separates the North Pennine batholith and the Carboniferous strata (Dunham et al. 1961) rules out any direct genetic link between the NPO mineralization and batholith emplacement. The presence of this low-density granitic core ensured that the Alston Block was underlain by relatively buoyant crust during Early Mississippian rifting, forming a prominent fault-bounded structural high (Critchley 1984). This resulted in a Carboniferous cover sequence across the block that is relatively thin compared to those within the surrounding basins (Collier 1989; Chadwick et al. 1995). Rifting was superseded by thermal subsidence during the Late Carboniferous (Bott et al. 1984).

The effects of Late Carboniferous shortening and inversion are well documented throughout the basins surrounding the Alston Block (e.g. Shiells 1964) and have been attributed by some authors to the far-field effects of the Variscan Orogeny (e.g. Corfield et al. 1996). However, evidence for N-S shortening within the Alston Block has proved to be elusive, leading to suggestions that the underlying North Pennine batholith acted as a shield, protecting the overlying Carboniferous cover sequence from regional compressive stresses (e.g. Critchley 1984). The most obvious evidence of Late Carboniferous inversion is preserved along the southern edge of the Alston Block where the Lunedale Fault (Fig. 1a) has been reactivated as a top-to-the north reverse fault (Cornwell & Wadge 1980, Dunham 1990). Large-scale gentle E-W elongated doming of the Carboniferous sediments, known as the Teesdale Dome (Dunham 1931) has also been interpreted to have formed during the Late Carboniferous due to Variscan shortening (Dunham 1990).

**Early Permian magmatism and the Burtreeford Disturbance.**

The Late Carboniferous to Early Permian was a time of widespread magmatism across NW Europe (e.g. Timmerman 2004). The main manifestation in Northern England is the doleritic Whin Sill Complex (Fig. 1a; Francis 1982), dated at 297.4 ± 0.4 Ma (U-Pb baddeleyite; Hamilton & Pearson 1989).
2011), which formed during a period of large-scale lithospheric extension. In northern England, the ENE-WSW trending Holy Island and High Green dykes (Whin Sill feeder dykes) show en-echelon geometries consistent with emplacement during E-W shortening synchronous with broadly N-S extension. This correlates well with the dextral transtensional deformation documented in the Northumberland Basin during the Late Carboniferous – Early Permian which is considered to be contemporaneous with intrusion of the Whin Sill based on cross-cutting relationships with associated mineral veins (De Paola et al. 2005a).

The Burtreeford Disturbance (Fig. 1b) is a major structural feature of the Alston Block, although, because it is rarely exposed at the surface and has only been penetrated by a very small number of mine workings, it is poorly understood in detail (Dunham 1990). It is a N-S trending, east-facing monocline, which lies between the Tynedale and Scordale plutons and the larger Weardale pluton of the North Pennine Batholith (Fig. 1b). It has an eastward downthrow of up to 150m and has been interpreted as being active both during and after emplacement of the Whin Sill (Hill and Dunham 1968, Astle 1978; Johnson & Dunham 2001). The Burtreeford Disturbance is proposed to represent a northern continuation of the Dent Line which is thought to be the surface manifestation of a much deeper ancient Devonian N-S wrench fault zone (Underhill et al. 1988; Woodcock & Rickards 2003). Similar structures exposed in the Lake District (Moseley 1972) are thought to be related to regional sinistral shear during the Acadian Orogeny. During Late Carboniferous - Early Permian inversion, the Dent Line underwent sinistral transpressional reactivation forming a large monoclinal structure before finally undergoing sinistral transtension during the Early Permian (Underhill et al. 1988; Thomas & Woodcock 2015).

Mineralization of the North Pennine Orefield

The majority of mineralisation within the NPO is hosted by the Carboniferous strata. Little is known of any mineralization characteristic of the NPO within the underlying Lower Palaeozoic basement rocks, although narrow veins of fluorite, quartz and sulphides are observed in the Rookhope...
Borehole from the granite of the batholith’s Weardale pluton (Dunham et al. 1965). Within the Carboniferous, the NPO deposits are hosted within and related to, if not controlled by, regional faults and fractures in four main orientations: NNW-SSE ("Cross veins"); NE-SW ("Lead veins"); ENE-WSW; and WNW-ESE ("Quarter-point veins"), with the NNW-SSE set notably lacking significant mineralisation (Fig. 1a) (Dunham 1990). In addition to vein-fillings, the mineralisation includes numerous strata-bound Pb-Zn-Fe replacement deposits - or “flats” - developed in limestone wallrocks in close proximity to mineralized faults. The deposits of the NPO are characterised by an abundance of sulphide ores, dominated by galena and sphalerite, though with local smaller concentrations of chalcopyrite, pyrite, pyrrhotite. marcasite and rare traces of bismuth, cobalt and nickel sulphides. The main gangue minerals are fluorite, quartz (of various forms), barium minerals, abundant siderite and ankerites of various compositions. Calcite, together with small amounts of aragonite, is widespread, though almost invariably in only minor amounts.

Although it is generally agreed that mineralization was contemporaneous with tectonic activity in conjunction with fluid migration, the age of these tectonic events and origin of sulphide mineralisation in the NPO has remained enigmatic. A number of different techniques used to date this mineralisation have yielded wide ranging dates that vary between 290 and 149 Ma (e.g. Dunham et al. 1968; Solomon et al. 1971; Shepherd et al. 1982; Halliday et al. 1990; Dunham 1990; Davison et al. 1992). As several of the orefield’s vein deposits are hosted in fractures that crosscut parts of the Whin Sill complex, this has commonly been used to infer that mineralisation postdates Whin Sill magmatism (e.g. Dunham 1934, 1990; Cann & Banks 2001). Given that large-scale faults, such as the 90-Fathom Fault System, are also known to offset both the Whin Sill complex and Permian strata (Collier 1989; De Paola et al. 2005b), this could suggest that fault reactivation – and perhaps mineralization - occurred during, or was continuous into the Mesozoic (Cann & Banks 2001).

Perhaps the most conspicuous feature of NPO mineralisation is the marked zonal distribution of major constituent minerals, most notably fluorite and barium minerals. Fluorite
mineralization occurs within an inner zone, centred above the three westernmost plutons of the N Pennine Batholith (Weardale, Tynehead and Scordale); insufficient data exist to infer any relationships with the eastern (Rowlands Gill and Cornsay) plutons, though barium mineralisation is abundantly present in several fracture systems above the latter. Barium mineralization occurs almost exclusively outside the fluorite zone (Fig. 1b) and it was this zonal pattern that guided much of the early thinking on the origins and evolution of the field and of the possible presence of a concealed granitic body (Dunham 1934).

Several genetic models have since been put forward for the age and formation of the NPO. Dunham (1983) advocated classifying the NPO as a fluoritic sub-type of the MVT, a concept developed further by Halliday et al. (1990) who suggested that metals were leached from the Carboniferous host rocks at ca ~200 Ma (Early Jurassic) by circulating proximal connate fluids. This was based on a range of $\varepsilon$Nd values consistent with a Carboniferous source mineralising at 200 Ma, with this age being derived from Rb/Sr isotopic data obtained from fluid inclusions in the Great Sulphur Vein (Fig 1a; Shepherd et al. 1982). An unusual assemblage of magnetite, silicate minerals and ore minerals including niccolite, galena and sphalerite, associated with the NNW-SSE trending Teesdale Fault, was interpreted by Young et al. (1985) as a skarn assemblage resulting from the interaction of metal-rich mineralising fluids with the Whin Sill and its contact rocks very soon after the sill’s emplacement and whilst still at temperatures in excess of 500°C. Crowley et al. (1997) presented isotopic evidence for the derivation of at least some of the sulphur in barite from both the NPO and northern Lake District from deeply buried Carboniferous evaporites in the Solway-Northumberland Basin.

More recently, Cann & Banks (2001) proposed an alternative model in which initial deep fluid movement in the granitic basement below the Alston Block was prevented during the Carboniferous by sealing of pre-existing cracks allowing temperatures to rise to 200°C, up to 100°C hotter than the surrounding country rocks. They hypothesise that Upper Permian tectonic extension
allowed saline waters from the Zechstein Sea to penetrate deep into the basement where theyecame heated to as much as 200°C. This led to a “chimney effect” which generated concentric
zones of increasing temperature fluid and mineralization in the Carboniferous host rocks centred
over the batholith buried at depth. Earlier workers, notably Dunham (1963), had also proposed a
series of ‘emanative centres’ of mineralisation, most notably at a triple junction of veins at
Groverake Mine in Rookhope where temperatures derived from subsequent fluid inclusion results,
together with REE studies, gave strong support to this model (Ixer et al. 1996). In describing the
Great Sulphur Vein of Alston Moor, Dunham (1990) noted that quartz-dominated mineralisation
gives way at depth to a zone rich in iron and minor copper sulphides and suggested that this
reflected a thermal gradient in the upwelling fluids. Very similar changes to vein contents, with a
marked increase in iron sulphide mineralisation, have subsequently been observed at depth in
recent fluorspar workings on the Quarter Point Slitt Vein at Cambokeels Mine in Weardale and
similar features were observed in the deepest workings in the Quarter Point Red Vein system at
Groverake Mine in Rookhope. More recently, Bouch et al. (2006) have pointed out that the inner
boundary of the cooler barium zone does not coincide precisely with the outer boundary of the
hotter fluorspar zone and that they may represent two quite distinct and unrelated mineralization
events. This suggestion is consistent with the observation that across the NPO the occurrence of
fluorspar and barium minerals are almost always mutually exclusive. Bott & Smith (2018) have shown,
based on thermal conductivity and geophysical modelling, that the North Pennine Batholith was
unlikely to have been hot enough to generate the chimney effect proposed. Instead, they suggest
that alkali magma underplating the batholith, associated with the intrusion of the Whin Sill Complex
during the earliest Permian, is the only viable way to account for the observed mineralization.

Many of the uncertainties about the age and genesis of the NPO centre around the issue of
the relative and absolute timings of faulting, mineralization and igneous intrusion in the Alston
Block. In this paper, we combine detailed field, microstructural and geochemical analyses to address
both the timing and affinities of the mineralization and assess its relationship to regional magmatism
of the Whin Sill Complex in northern England. The present study focuses mainly on relationships observed in the inner fluorite zone where barium minerals are absent. The genesis and structural setting of barium minerals – which are generally late in mineralization sequences outwith of the fluorite zone in the Alston Block - are not discussed in detail here.

Field and laboratory methods

Fieldwork

Fieldwork concentrated on key representative localities in a number of abandoned quarries, stream sections and mine workings identified from previous studies. This work focused on the collection of orientation and kinematic data (faults/fractures, mineralised lineations/slickenlines, shear-sense criteria) and oriented samples of mineralized vein fills and fault rocks for thin section and geochemical analysis. All stereonets shown in this paper are equal-area lower-hemisphere plots.

Stress inversion analysis

Fault-slip slickenline data associated with each of the mineralized fault groups identified in the field were used to carry out a conventional palaeostress-inversion analysis (Angelier 1979, 1984; Michael 1984) implemented using MyFault® software following the protocols set out in Holdsworth et al. (2015) and Dichiarante et al. (2020). Importantly, any analysis of this kind is only viable in regions where finite strains are modest and the presence of major fault block rotations can be ruled out. Due to the small (<2 metre) displacements observed along most of the mineralized structures studied, we are confident that regional strain intensities are not large enough to be problematic, and that the degree of rotational strain is negligible (e.g. De Paola et al. 2005; Dempsey et al. 2014). The use of 3D Mohr circles derived from the data additionally allows an analysis of the geometric relationships between faults and fractures measured in the field relative to the orientation and magnitude of the principal stress axes. This can be used to determine which fault and fracture
orientations are most susceptible to failure under given stress and pore-fluid pressure conditions (Alveres et al. 1998).

**Rhenium-Osmium geochronology**

Traditionally the relative ages of different deformation events are established using cross-cutting relationships seen in the field and thin section. Whilst this emphasises the deformation sequence and gives a relative age, the absolute ages of these events remain unknown in the absence of radiometric dating. Pyrite is commonly enriched with rhenium (Re) so that the $^{187}$Re-$^{187}$Os geochronometer can be used to date mineralization and better constrain the timing of brittle deformation (e.g. Dichiarante et al. 2016; Holdsworth et al. 2015, 2020). Furthermore, the determined $^{187}\text{Os}/^{188}\text{Os}$ composition of the sulphide minerals at the time of formation can yield insights into the origins of the fracture-hosted fluids (e.g., Hnatyshin et al. 2015).

For this study, pyrite samples, together with one Whin Sill whole rock sample, were collected *in-situ* from spatially diverse veins within the Alston Block NPO (locations shown in Fig. 1b). Pyrite samples were crushed to 2mm grain size with no metal contact and hand-picked before a final crushing to 75-200 µm. Measurement of the abundance of $^{187}$Re and $^{187}$Os in pyrite samples is obtained by isotope dilution using a mixed $^{185}\text{Re}+^{190}\text{Os}$ tracer solution which was calibrated against gravimetric standard solutions of normal isotopic composition. Approximately 400mg of pyrite/ 2g of Whin Sill (previously dissolved in HF and subsequently dried down to facilitate silica-bound Re/Os to be analysed), plus tracer solution was digested in a Carius-tube with 8mL of inverse *aqua regia* at $220^\circ\text{C}$ for 48 hrs. Rhenium and Osmium were separated and purified by solvent extraction (CHCl$_3$) and micro-distillation (Os) and anion exchange chromatography (Re), and analysed by negative thermal ionization mass spectrometry (NTIMS; Selby et al. 2009). Uncertainties for Re–Os isotopic data and abundances are determined by full error propagation of uncertainties in mass spectrometer measurements, blank abundances and isotopic compositions, spike calibrations, reproducibility of standard Re and Os mass spectrometric values, and weighing uncertainties. Total
procedural blanks were monitored during the three batches of samples run for this study. The average blank measurements over the three batches for Re and Os were 1.7 ± 0.08 ppt and 0.06 ± 0.03 ppt, respectively, with an average $^{187}\text{Os}/^{188}\text{Os}$ value of 0.28 ± 0.03 (1σ, n = 3).

**Structure of the North Pennine Orefield**

The main faults, slickenline and ore vein orientations recorded during the present study are shown in Figure 2. As with previous studies, four main regionally pervasive fault orientations are observed: NE-SW (normal, tensile and dextral) (the ‘Lead Veins’ of the miners); ESE-WNW ‘Quarter Point’ (normal, tensile and sinistral); ENE-WSW “Quarter Point” (dextral); and NNW-SSE ‘Cross Veins’ (tensile and dextral, locally sinistral). Field observations of cross-cutting relationships documented below show that within the NPO of the Alston Block there are at least two phases of fault initiation, here termed Phase 1 and 2. The Phase 1 NNW-SSE and NNE-SSW fractures, many of which host vein minerals, are predominantly dextral and sinistral strike slip structures, respectively, and are associated with contemporaneous N-S tensile fractures (Fig. 2). These fractures and veins are commonly crosscut by Phase 2 mineralized structures (Fig. 2), especially the ESE-WNW veins. There is localised evidence for a later sinistral and dextral reactivation of the NNW-SSE and NNE-SSW structures, respectively, during Phase 2. With a few local exceptions (e.g. Nenthead, South Tyne Valley), the Phase 1 structures are much less mineralized compared to Phase 2. The bulk of mineralization occurs along Phase 2 ESE-WNW (Quarter Point) and NE-SW (Lead Vein) structures, which represent the largest and most continuous features within the Alston Block. Key surface localities analysed during this study are described below. While there are many exposures of mineralized veins within the Alston Block, the locations described here were selected based on the variety of structures exposed, how representative they are of the regional deformation history and/or their suitability for stress inversion analysis (i.e. slickenlines well preserved). A map showing the locations, structures and veins in the NPO is given in Figure 1c.
Conjugate faults and cross-cutting relationships

*Ballihope Quarry* [NY98532 35254] (Fig. 3a) displays an exceptionally well-exposed 20m thick sequence of flat-lying Carboniferous Great Limestone gently folded by several large (80m wavelength) gentle to open folds with shallowly southward plunging (02/175) hinge lines (Fig. 3b). The folds are cross cut by mineralized brittle shear fractures, but a definitive relative age relationship is not clear (Fig. 3a). Fracture-hosted mineralization within the quarry is dominated by calcite and fluorite, with minor amounts of quartz, pyrite, goethite and galena (Figs 3c-f). There are 4 main fracture sets: ENE-WSW dextral; ESE-WNW sinistral; NNW-SSE dextral: and NNE-SSW sinistral (Fig. 3a); where preserved, associated slickenlines are shallowly plunging to sub-horizontal (Fig 3e). Field observations show that the ENE-WSW and WNW-ESE sets are conjugate and consistently crosscut and offset the NNW-SSE and NNE-SSW sets, which are also conjugate. These are interpreted to represent Phase 2 and Phase 1 structures, respectively. The conjugate relationships for each set are identified based on opposing senses of shear and mutually cross-cutting relationships between the fault pairs. These relationships are representative of those seen across the NPO in the Alston Block – the only exceptions occur in those cases where the Phase 1 faults are locally reactivated during Phase 2 (see below).

Quarter Point Veins

The abandoned West Rigg opencut (Figs 4a, b; [NY91122 39208]) is located 1 km north of the village of Westgate. The exposures here within the Carboniferous Great Limestone offer an unprecedented opportunity to view an example of the North Pennine vein systems in 3D (Figs 4c-e). The quarry extracted ‘limonitic’ ironstone formed by the supergene alteration of extensive siderite and/or ankerite replacement deposits within the limestone adjacent to the Quarter Point Slitt Vein. Narrow abandoned stopes, formerly worked underground for lead ore may be seen in the centre of the otherwise barren quartz-fluorite stockwork which stands as a prominent rib which extends for approximately 80 m through the centre of the quarry (Dunham 1990; Bevins et al. 2010). Here the
vein strikes on average towards 120°, but internally contains 3 sets of interconnected shear planes: E-W normal faults; NW-SE sinistral faults; and NE-SW dextral faults (Fig. 4b). These slip surfaces are associated with polished and striated surfaces and mineralized breccias (Figs 4c, d) indicating that fault activity and mineralization were synchronous. The kinematics of these fault sets within the Slitt Vein suggest that the whole system represents a sinistral transtensional brittle shear zone (Fig. 4b). As with almost all NPO veins, no definitive order of mineralization is observed at this location, but large fluorite crystals are commonly overgrown by crusts of euhedral quartz crystals or siderite (Fig. 4e; Dunham 1990). The commonly euhedral forms of the crystals in the vein array suggest that the fluids were often precipitated in open voids likely as a consequence of the extensional/dilatational and relatively near-surface nature of the fault zone deformation (e.g. Woodcock et al. 2014).

The Great Sulphur Vein (GSV) is a 12 km long (at surface), broadly WNW-ESE trending structure composed of a stockwork of numerous smaller, structurally-controlled veins (Dunham 1990). It attains a maximum width of 365 m, but appears to narrow downwards and may represent the root zone for the Quarter Point vein system (Bevins et al. 2010). A characteristic feature of the GSV is a marked vertical zonation in which quartz, both as pure ribs and as extensive replacements of limestone, mudstone and sandstone, dominates an upper zone, beneath which there appears to be a more or less continuous sulphide-rich zone in which abundant pyrite, marcasite and pyrrhotite are locally accompanied by chalcopyrite (Dunham 1990). Galena, sphalerite and fluorite are generally scarce, but occur in local concentrations.

A sulphide-rich portion of the GSV is exposed in the River South Tyne near Sir John’s Mine at Tynehead [NY7604 3756]. Here the vein is hosted within the Tynebottom Limestone where metasomatism has resulted in almost complete quartz replacement in areas up to 10m wide indicating a significant interaction between the vein hosted fluids and the Carboniferous wallrocks. An E-W striking sinistral oblique normal fault exposed below a small waterfall is surrounded by a series of small subvertical veins composed mostly of quartz, with smaller amounts of pyrite and
chalcopyrite. These veins range from 10 cm to 1 mm in width, with the larger veins carrying the majority of the sulphides. NE-SW veins are associated with local brecciation and cataclasism whilst associated N-S or E-W striking veins are dominated by mode 1 tensile opening.

Regionally, the ESE-WNW (Quarter Point) vein fractures are characterized by abrupt changes of strike. Where the orientation is ESE-WNW – as at West Rigg - they are commonly poorly mineralized or barren. Where they assume an almost E-W orientation as at Tynehead - they typically carry wide (locally up to >10 m) mineralised orebodies. This is consistent with their sinistral transcurrent displacement, as recognised by Greenwood and Smith (1977) and was an important factor in the successful location and working of major fluorite orebodies at several mines during the twentieth century.

**Lead Veins**

In the bed of the River South Tyne at *Garrigill*, the ENE-WSW trending Browngill Vein [NY7436 4181] is exposed cutting silicified Tynebottom Limestone wall-rocks (Dunham 1990). This is a typical example of one of the Lead Veins which typically contain varying amounts of quartz, galena, pyrite, marcasite, chalcopyrite and sphalerite. The majority of the mineralisation at Garrigill occurs within a series of NE-SW trending veinlets up to 15 cm wide which are composed primarily of quartz, galena and marcasite. Brecciation of both veins and host rocks is commonly associated with the thicker veins, with small dextral dilatational jogs well preserved along associated smaller veins with the same trend.

The Old Moss Vein is one of several NE-SW trending veins formerly worked underground from Park Level Mine (now Killhope Lead Mining Museum). It is exposed within the Great Limestone in the bed and N bank of Killhope Burn approximately 700 m upstream from the museum [NY 8204 4334]. The vein is here up to 1 m wide and comprises NE-SW trending bands composed of abundant galena and a little sphalerite in a matrix of dark brown partially oxidised siderite and ankerite. The limestone adjacent to both sides of the vein are replaced for up to around 2 m by dense crystalline
ankerite and siderite in which small vugs, locally in bedding parallel bands, are lined with fluorite, quartz and galena (Dunham 1990; Bevins et al. 2010). No definite sense of shear is preserved here.

Cross Veins

The Browngill Vein seen at Garrigill can be traced for approximately 5 kms eastwards from its junction with the NNW-SSE trending Lee House Well Vein [NY7270 4140] to Nenthead. Unlike most of the NNW-SSE Phase 1 fractures across the orefield, the numerous members of this set around Nenthead are unusual both for their richly mineralized fillings and for extensive replacement deposits associated with the development of ‘flats’ in the Great Limestone. The absence of both fluorite and barium gangue minerals is a notable feature of these deposits.

Examples of these flats are well exposed in the waterfall in the River Nent at NY7864 4299 where original bedding, joints, stylolites and some fossils, are replaced by hard crystalline ankerite and quartz with abundant galena and sphalerite and minor amounts of pyrite filling small veinlets and vugs within the altered rock. Limestones exposed in the river gorge downstream of the waterfall exhibit numerous vertical NE-SW trending minor joints, some of which exhibit ankerite and quartz mineralization along NE-SW trending joints (Dunham 1990; Bevins et al. 2010). The main mineralized structures exposed here are sub-vertical NW-SE dextral strike-slip faults. A second set of sub-vertical N-S trending tensile veins filled by ankerite and minor amounts of galena are consistent with the inferred dextral movement along the adjacent NW-SE faults.

Inversion structures, southern margin of the Alston Block

The Lunedale Fault forms the southern bounding fault of the Alston Block (Fig 1a, b) and whilst outside the “fluorite zone” that is the focus of this study, the structures found therein are of importance for understanding the regional structural history of the North Pennines and its associated mineralisation. The main fault is a poorly exposed, steeply southward dipping, E-W trending structure with an along-strike length of roughly 20 km (Dunham 1990) which separates the Alston Block from the Stainmore Trough (Fig. 1a inset). The Lunedale Fault and related structures
and associated mineralisation are exposed at the disused Closehouse Mine [NY 8525 2275], Fig. 5a).

The host lithologies here are Carboniferous limestones and sandstones of the Alston Formation, together with dolerite of the Whin Sill dyke emplaced here within the Lunedale Fault (Dunham 1990; Bevins et al. 2010). Two sets of un-mineralized joints trend N-S and E-W and are likely related to the regional set of jointing observed throughout the NPO. The structure of the area is dominated by an ~100 m wide, E-W striking anticline (Figs 5a, b) crosscut by a series of mostly southward and subordinate northward dipping thrust faults that have been infilled by later quartz mineralisation (Figs 5b, c). Slickenlines preserved on the thrust faults indicate a dip-slip reverse shear sense (Fig. 5a) with offsets that are mostly small (<1 m). Slickenline-bearing bedding planes are also common and appear to be related to flexural slip during folding rather than fault motion. To the north of this structure, a ~20 m wide fault-bounded slice is exposed containing a gently W-plunging anticline-syncline pair (Figs 5a, b). The bounding faults have shallowly plunging slickenlines consistent with sinistral-oblique reverse movement. To the south of the main fold, outcrop-scale antithetic thrusts and associated anticlines are exposed within the limestone (Fig. 5c).

Closehouse Mine is significant for its exposure of an E-W striking altered, dolerite dyke thought to be a feeder to the nearby Whin Sill (Fig. 5a, Dunham 1990; Bevins et al. 2010), although the importance of these “feeder” dykes with regards to magmatism and the associated magmatic fluids is now open to some dispute. Robinson (2020) has proposed a emanative centre for the Whin Sill located close to Cow Green Reservoir (NY 81361 29014) some distance from the horst-bounding structures seen at Closehouse Mine.

**Petrology and microstructures**

Mineralized fractures (faults, veins) in the NPO range in width from millimetres to metres and in length from 1 metre to up to many kilometres. The largest of the Quarter Point veins (Slitt Vein,
Great Sulphur Vein, Red Vein) are in excess of 10km long and 10 m wide. Three main styles of mineralized fracture fills are recognized:

1. Simple tensile/hybrid veins, with slickenlines well developed in strike-slip segments and asymmetric jogs/pull-aparts in more tensile segments, both of which are useful as kinematic indicators. These veins are monomineralic or occasionally bimineralic, with pods of sulphide mineralization intergrown with gangue material (Fig. 6a).

2. Mode I tensile veins with crack-seal textures that can be either monomineralic or polymineralic with common compositional banding (Fig. 6b).

3. Breccia (±minor cataclasis) where all phases of mineralization are present intergrown within a brecciated wall rock fill (Fig. 6c). Slickenlines, Riedel shears and the orientation of associated second-order tensile veins are common kinematic indicators (Fig. 6d). In general, clay gouges were not observed in surface exposures, but are very occasionally observed in underground mine workings. This may reflect the poor preservation potential of such fault rocks or may be due to the relatively minor displacements along many of the structures present.

Examination of thin sections and hand specimens collected for this study reveals that, as established by Dunham (1934), fluorite, quartz, galena, sphalerite, pyrite, marcasite, pyrrhotite, siderite, ankerite and chalcopyrite are the dominant minerals within the orefield’s central fluorite zone, with barium minerals (e.g. barite, witherite) taking the place of fluorite and quartz in the outer barium zone. Pyrite and marcasite appear to be widespread, though in generally modest amounts, throughout the sampled mineralization, with greater concentrations of these and with the addition of pyrrhotite, chalcopyrite and locally very small amounts of bismuth and cobalt minerals in earlier phases of mineralization. The abundance of iron minerals within these early assemblages (Fig. 6e), together with the widely observed occurrence of iron metasomatism of limestone wall-rocks
adjacent to vein fractures of all orientations across the orefield, indicate that iron was a significant and major component of the earliest mineralizing fluids. Occurrences of magnetite, of metasomatic origin, recently reported from the contact zone of the Whin Sill in Upper Teesdale (Young 2017) together with the abundance of magnetite within unique nickel-bearing skarn-type mineralization associated with the Teesdale Fault (Young et al. 1985), are further evidence of early iron-rich mineralizing fluids.

Microstructurally, a huge array of vein textures are preserved within the NPO (Figs 7a-f). Primary crystallization fabrics throughout the orefield include: massive veins (Smirnov 1954); crustiform (Adams 1920); colloform (Rogers 1917); comb (Boyle 1979); and zonal (Smirnov 1954) types, which suggests that the surface-exposed veins retain their original textures and chemistry. Crack-seal textures (both syntaxial and antitaxial) are also widely observed (e.g. Fig. 6b). Deformation fabrics within the mineralized faults of the NPO are dominated by the presence of mineralized breccias (Figs 8a-e). These breccias commonly record multiple deformation and mineralisation events where clasts of fractured/brecciated material are incorporated into subsequent veins or breccias of similar composition (e.g. Fig. 8c); in other cases, brecciated mineral fills are cross-cut by compositionally similar veins (Figs 8b and d). The cyclical nature of these breccias where vein material has been brecciated, healed and then re-brecciated, or crosscut by further veining is indicative of syntectonic mineralisation following hydrofracturing events. The local preservation of cockade textures and open vugs also suggests that, in some cases, fractures were incompletely sealed and cemented allowing repeated periods of fluid flow (Frenzel & Woodcock 2014).

Recrystallization (feathery, flamboyant and ghost-sphere, Adams 1920) and replacement textures (ghost-cubes and skeletal crystals, Morgan 1925) are commonly preserved showing that not all veins have retained their primary mineralogy and fabric (Figs 9a-c). Fluorite microstructures in particular suggest that significant amounts of remobilization and healing/re-precipitation have occurred, e.g. replacement of fluorite by quartz or chalcedony (Young & Hopkirk 2019). Within fluorite crystals,
multiple generations of fluid inclusions are observed. These fluid inclusions highlight the presence of growth zoning and pervasive healed microfractures (Fig. 8e). Optical cathodoluminescence (OCL) shows that recrystallization/healing of fluorite breccias is widespread, illustrating that this mineral is especially prone to dissolution and re-precipitation with overgrowth showing perfect optical continuity (Fig. 10a). By contrast, dissolution and precipitation with optical continuity is not observed in calcite crystals where the textures revealed by OCL are more consistent with those observed using conventional optical microscopy (Fig. 10b).

Results

Stress Inversion analyses

Stress inversion analysis was carried out using all data collected from slickenline-bearing faults and fractures of the Alston Block of the NPO. Field observations at locations such as Bollihope Quarry clearly show that there are two sets of structures developed – an earlier set of Phase 1 NNW-SSE and NNE-SSW faults and fractures and a younger cross-cutting population of Phase 2 ENE-WSE and ESE-WNW structures. Misorientations resulting from block rotations and gentle folding in the Alston Block are negligible. A stress inversion analysis of the earlier NNE-SSW/NNW-SSE faults suggests that they are related to north-south shortening in a contractional reverse faulting or transpressional regime (sigma 3 vertical, Fig. 11a). The younger and more widespread ESE-WNW and ENE-WSW fault sets related to Phase 2 yields N-S extension and E-W shortening consistent with a strike-slip or transtensional regime (sigma 2 vertical, Fig. 11b). The Mohr circle analysis of the earlier NNE-SSW/NNW-SSE Phase 1 structures (highlighted in green) shows they are highly misoriented which suggests that in areas where they have been locally reactivated (e.g. Nenthead), elevated pore fluid pressures would have been required locally during mineralization.

Re-Os Geochronology
The total Re and Os abundances of pyrite range from 3.5 to 228 ppt and 1 to 45 ppt (Table I), respectively. The $^{187}\text{Re}/^{188}\text{Os}$ and $^{187}\text{Os}/^{188}\text{Os}$ ratios range from 0.6 to 97.6 and 0.12 to 0.63, respectively, with the exception of sample RO572-4_BG5A which displays $^{187}\text{Re}/^{188}\text{Os}$ and $^{187}\text{Os}/^{188}\text{Os}$ ratios of 682.2 and 3.7 (Table I). To account for the uncertainties between the $^{187}\text{Re}/^{188}\text{Os}$ and $^{187}\text{Os}/^{188}\text{Os}$ data we present the latter with the associated uncertainty correlation value, $\rho$ (Ludwig 1980), and the $2\sigma$ calculated uncertainties for $^{187}\text{Re}/^{188}\text{Os}$ and $^{187}\text{Os}/^{188}\text{Os}$ (Table I). The regression of all the Re-Os data using IsoplotR (Vermeesch 2018) and the $^{187}\text{Re}$ decay constant ($\lambda$) of $1.666\times10^{-11} \pm 5.165\times10^{-14}$ a$^{-1}$ (Smoliar et al. 1996) yielded a Model 3 Re-Os date of 311.6 ± 19.8 (6.4 %) Ma, with an initial $^{187}\text{Os}/^{188}\text{Os}$ ratio of 0.15 ± 0.01 ($2\sigma$, Mean Squared Weighted Deviates [MSWD] = 0.98; Fig. 12a).

The significant uncertainty in the calculated Re-Os date (6.4 %) is due the low total concentrations of Re and Os in the pyrite and the scatter exhibited in the best-fit of the Re-Os data as proposed by the MSWD value of 0.98. Calculation of initial $^{187}\text{Os}/^{188}\text{Os}$ ratio at 312 Ma indicates the presence of two outlying samples (CB10 and TH1), which have a slightly more radiogenic composition (0.34 ± 0.11 and 0.38 ± 0.11, respectively; Fig. 12b), that ultimately cause scatter about the line of best-fit of the Re-Os data. Regression of the remaining Re-Os data, excluding CB10 and TH1, yielded a Model 1 Re-Os age of 304 ± 20 (6.5 %) Ma with a significantly lower MSWD of 0.14 and an initial $^{187}\text{Os}/^{188}\text{Os}$ ratio of 0.15 ± 0.01 (7.9 %) (Fig. 12c).

The Re and Os abundances of the Whin Sill sample are 472 ppt and 2 ppt, respectively. The $^{187}\text{Re}/^{188}\text{Os}$ and $^{187}\text{Os}/^{188}\text{Os}$ ratios are 4754.2 ± 531.5 and 23.193 ± 1.444, respectively. Based on the geochemistry and petrology, the sill is likely mantle-derived (Thorpe & McDonald, 1985), as such an initial $^{187}\text{Os}/^{188}\text{Os}$ ratio 0.12 ± 0.01 was assumed to calculate a model Re-Os date. On the basis of an initial $^{187}\text{Os}/^{188}\text{Os}$ ratio 0.12 ± 0.01 (Permian mantle $^{187}\text{Os}/^{188}\text{Os}$ composition calculated from Meisel et al. 1996) a Re-Os date of 290.2 ± 29 Ma. The later also indicates that the Os budget in the Whin Sill sample is 99.5 % radiogenic $^{187}\text{Os}$. 
Discussion

A new structural model for the North Pennine Orefield

The four regionally pervasive fault orientations observed within the NPO (Dunham 1990) can be grouped into two broad populations based on observed cross-cutting relationships (Figs. 13a, b): Phase 1) NNW-SSE faults (tensile and mostly dextral) and NNE-SSW faults (sinistral) with associated small-scale N-S trending (<50cm wide) tensile veins; and Phase 2) ESE-WNW faults (normal, tensile and sinistral) with ENE-WSW faults (dextral and tensile) which are commonly associated with larger (<5m wide) E-W striking vertical tensile veins.

Stress inversion analyses indicate that the earlier Phase 1 structures are related to N-S shortening, whilst the later Phase 2 structures are related to a superimposed phase of N-S extension and E-W shortening (Figs 13a, b). The earlier event is consistent with the far-field effects of the Variscan orogeny during the Late Carboniferous (Warr 2012 and references therein). It led to the sinistrally transpressive inversion of the broadly E-W striking faults bounding the Alston Block, as evidenced by the reverse faulting and folding observed associated with the Lunedale fault at Closehouse Mine (Fig. 5). It is consistent with an early dextral transpressional movement associated with the Burtreeford Disturbance, dextral shear along the Pennine Fault to the west (Fig. 13a) and also with the late Carboniferous deformation history of the nearby Dent Fault system located further to the south (e.g. Underhill et al. 1988; Woodcock & Rickards 2003). In detail, however, the NNE-SSW shortening in the Alston Block lies approximately 40° clockwise of the NNW-SSE Variscan direction determined in the SW part of the Askrigg Block (Thomas & Woodcock 2015). The faults in the latter area display larger displacements relative to those measured during the present study. Thus the difference in the late Carboniferous shortening in these two areas may reflect a partitioning of broadly N-S orogenic shortening strain between block interiors (North Pennine Orefield) and block margins (Dent-Craven faults), possibly with a component of deep basement control.
The later phase of N-S extension and E-W compression is consistent with the regional dextral transtensional regime (De Paola et al. 2005a) which is attributed to reactivation of NE-SW Caledonian structures underlying the Northumberland Basin located immediately to the north of the Alston Block. It is suggested that this deformation was synchronous with emplacement of the ca 297 Ma Whin Sill and associated intrusions based on observed cross-cutting relationships seen along the Northumberland coastline. This later phase may have led to localised compressional reactivation of the Burtreeford Disturbance, coeval with monoclinal folding and sinistral reactivation of the Pennine Fault to the west (Fig. 13b). Sinistral transtensional reactivation of the Dent Line fault system in the Early Permian is also recognized south of the Alston Block (Underhill et al. 1988).

The age and origins of the metalliferous fluids

The Re-Os pyrite data (excluding CB10 and TH1) of the North Pennine Orefield yield a date (304 ± 20 Ma) that overlaps within uncertainty with the timing of emplacement and cooling of the mantle-sourced Whin Sill (U-Pb CA-ID-TIMS baddeleyite = 297.4 ± 0.4 Ma; Thorpe & McDonald 1985; Hamilton & Pearson 2011). This temporal relationship may indicate that the NPO sulphide mineralization has a direct genetic link to the Whin Sill complex. The Whin Sill as the progenitor of sulphide mineralization of the NPO is further supported by the similarity in the initial \(^{187}\text{Os}/^{188}\text{Os}\) composition of the Whin Sill (ca. 0.13) and pyrite (ca. 0.15) (this study).

Considering the temporal and genetic link of the Whin Sill to the NPO mineralization the initial \(^{187}\text{Os}/^{188}\text{Os}\) (Os\(_i\)) compositions of pyrite calculated at 297.4 Ma exhibit two distinct populations. Group 1 with a weighted average Os\(_i\) of 0.147 ± 0.010 (MSWD = 0.18; S3, SJM2, S1 and S2) and Group 2 with a slightly more radiogenic weighted average Os\(_i\) of 0.345 ± 0.030 (MSWD = 0.31; BG5A, TH1 and 496CB10). Sample NHM1b possesses an intermediate Os\(_i\) of 0.226 ± 0.04 (Fig. 14a).

The Re-Os data of Group 1 and Group 2 yield Model 1 Re-Os ages of 293.5 ± 20.1 Ma (MSWD = 0.57, Os\(_i\) = 0.152 ± 0.006; Fig. 14b) and 294.8 ± 14.9 Ma (MSWD = 0.19, Os\(_i\) = 0.366 ± 0.047; Fig.
The unradiogenic Os nature of the pyrite coupled with the ca. 294 Ma age strongly supports that Os, and by inference ore metals and fluids were derived from the magmatism associated with the Whin Sill Complex. The Re-Os data further illustrates that fluids migrating from the Zechstein Sea (Permian), or simply leaching from the surrounding Carboniferous host rocks and underlying basement (Palaeozoic) are all unlikely sources as these would lead to much more radiogenic levels of Os. Yet, the more radiogenic Os of Group 2 pyrite and sample NHM1b may represent a slightly more evolved mantle fluid, and/or minor inheritance from the surrounding host rocks.

Reported Sm-Nd fluorite data from throughout the NPO was interpreted by Halliday et al. (1990) to define no definitive age, but was interpreted to suggest that mineralization occurred between the Carboniferous and Jurassic. The Sm-Nd fluorite data from the Slitt, Groverake and Ferneygill veins collectively yield an errorchron (Mean Squared Weight Deviates [MSWD] = 32) postulating a Late Cretaceous age (Fig.15a). The scatter about the best-fit line is largely caused by the Sm-Nd fluorite data of the Groverake and Ferneygill veins, which independently show considerable scatter in $^{147}$Sm/$^{144}$Nd-$^{143}$Nd/$^{144}$Nd space. Thus, they do not provide any meaningful chronological constraints (Halliday et al., 1990).

Eleven of the twenty fluorite samples (8 of 11 from the Slitt vein, 2 of 4 from the Groverake vein and 1 of 5 from the Ferneygill vein) possess similar initial $^{143}$Nd/$^{144}$Nd compositions at ca. 295 Ma (the Re-Os age, see above; Table II). Collectively, the Sm-Nd data for the eleven samples define a Model 3 age of 291.0 ± 39.0 Ma (initial $^{143}$Nd/$^{144}$Nd = 0.511757 ± 59, with the scatter defined by a variation in the initial $^{143}$Nd/$^{144}$Nd of 0.000028 ± 17 (Fig. 15b). Considering only the Sm-Nd data from the Slitt vein, which approximately corresponds to sample CB10 from Cambokeels of this study, with similar initial $^{143}$Nd/$^{144}$Nd at 295 Ma, a Model 1 Sm-Nd age of 293.6 ± 15.7 (MSWD = 5.5). Although the best-fit of the Sm-Nd data exhibits some scatter, the age is within uncertainty of both the sulphide mineralization reported in this study and the emplacement of the Whin Sill (Hamilton &
Pearson, 2011). This is further supported by a Model 3 computation given the degree of scatter about a Model 1 best-fit line to the Sm-Nd data (MSWD = 5.5) which suggests that the deviated scatter is due to geological variations rather than just analytical uncertainty. A Model 3 calculation suggests that the scatter is caused by variation in the initial $^{143}$Nd/$^{144}$Nd of 0.000029 ± 18 (Age = 291.5 ± 46.7; initial $^{143}$Nd/$^{144}$Nd = 0.511758 ± 69) (Fig. 15c).

The nominal agreement of the Sm-Nd fluorite and Re-Os pyrite chronology suggests a penecontemporaneous relationship with the emplacement of the Whin Sill. Recalculating the εNd for the fluorite, the Whin Sill and the Carboniferous sedimentary rocks (Table II) at 291.5 Ma, yield values of -9 to -10 for the fluorite, 1.5 for the Whin Sill and -9.8 for the Carboniferous host rocks, which supports a genetic model that invokes leaching of metals from the Carboniferous sedimentary host rocks (Halliday et al. 1990; Kraemer et al. 2019). This is somewhat at odds with the Os data from the sulphides, but could account for the more radiogenic Os signature observed in Group 2 pyrites (which includes sample CB10 from Cambokeels) where interaction with the host rocks and fluid evolution is likely to have occurred.

Alkali magma underplating of the North Pennine batholith associated with the intrusion of the Whin Sill Complex during the earliest Permian has been proposed as the only viable way to account for the observed mineralization (Bott & Smith, 2018). This proposal is further supported by REE data from fluorite of the NPO which display a large europium anomaly indicating that fluorite from this region must have experienced temperatures >250°C, (Kraemer et al. 2019). This anomaly is absent from the mineralogically similar Askrigg Block and the South Pennine Orefield (Fig 1a inset) located 40 and 120 km to the south of the NPO, respectively. The local presence of exotic minerals in the early stages of mineralization in the NPO of the Alston Block alone - such as bismuthinite (Bi$_2$S$_3$), synchysite (CaREE(CO$_3$)$_2$F$_2$), argentopentlandite (Ag(FeNi)$_8$S$_8$), pyrrhotite, cubanite, cosalite (Pb$_2$Bi$_2$S$_5$), tungsten-bearing cassiterite, monazite, xenotime, adularia, niccolite and magnetite (Ixer et al. 1996;
Young et al. 1985) - have all been ascribed to non “MVT” style mineralization with tentative links to Whin Sill magmatism.

The role of the Burtreeford Disturbance

Recent analysis of the metamorphism associated with the Whin Sill (Robinson 2020) has questioned the traditional view that the Whin Sill magma ascended along feeder dykes located at the edge of the Alston Block. These studies have shown that contact metamorphism, forming an assemblage of grossular garnet epidote, clinopyroxene, hedenbergite, prehnite and datolite, is thickest (up to 20m) towards the centre of the Alston Block, suggesting that an ascending Whin Sill magma and associated high temperature fluids were focussed in this area close to the Burtreeford Disturbance.

The Whin Sill is also emplaced as a small laccolithic mass at Cowshill where the Breckonsike Vein occupies the Burtreeford structure for a surface strike length of approximately 2 km adjacent to which extensive metasomatic replacements of the Great Limestone by siderite and/or ankerite occurs. Two other major mineralized structures diverge from the eastern side of the Burtreeford Disturbance at Cowshill. The NE-SW trending Burtree Pasture Vein was extensively mined here for both lead and fluorspar. Approximately 4 kms to the NE this vein unites with the triple junction of the Red, Greencleugh and Groverake veins of the Red Vein Quarter Point set at Groverake in the Rookhope Valley (Fig. 1c). Although not known to carry significant mineralisation in the near surface strata in the interval between Cowshill and Groverake, this vein could conceivably have channelled mineralizing fluids at depth from the Burtreeford Disturbance towards the Groverake junction which Dunham (1990) suggested to be a major emanative centre of mineralisation, a model for which fluid inclusion and REE data give strong support (Smith 1975; Greenwood & Smith, 1977). It is also significant that the roughly ESE-WNW Sedling Vein, at the western extremity of the Slitt Vein Quarter Point system, also originates from the eastern side of the Burtreeford Disturbance at Cowshill. The possibility that this too could have acted as a significant channel for mineralizing fluids
from the Burtreeford structure is consistent with speculation on the role of Quarter Point veins as important feeders for mineralization.

At Allenheads, approximately 4 kms N of Cowshill, a complex of rich lead-bearing veins and associated ‘flat’ deposits in the Great Limestone, connect with the eastern side of the Burtreeford Disturbance. All were worked at Allenheads Mine, the largest and most productive of the orefield’s lead mines. Although Dunham (1990, p 167) records an underground driveage through the disturbance, no mineralisation was encountered and the limited contemporary evidence was interpreted as indicating that the Allenheads veins terminated against the disturbance. The apparent absence of mineralization within the disturbance here may be due to the driveage being within beds above the Great Limestone that are typically unfavourable to mineralization. It is possible that the Allenheads deposits, together with those associated with their eastwards continuation as the Red Vein Quarter Point system of the Rookhope Valley may, at least in part, have been fed via the Burtreeford Disturbance.

Thus there are a number of lines of evidence to suggest that the Burtreeford Disturbance – or a deep-rooted basement fault at depth that underlies it - acted as a significant conduit for both ascending magma associated with the Whin Sill complex and mineralizing fluids (Fig. 13b). The latter were then channelled away from the monocline into strike-slip related dilatational jogs and associated tensile veins of the ENE-WSW Lead Vein set and in particular the ESE-WNW Quarter Point vein set within the Alston Block.

Mineralization in the Cross-Vein sets

Mineralization associated with Phase 1 NNW-SSE trending ‘Cross Veins’ is generally sparse compared to that within Phase 2 fractures but there are two significant exceptions. Firstly, the Leehouse Well – Sir John’s Vein system of the South Tyne Valley exhibits significant mineralization at several points along its approximately 10 km strike length. The galena is characterised by substantially higher silver
concentrations than are normal for the NPO and the variety of copper sulphides, together with small amounts of bismuth, cobalt, nickel minerals and native silver have been interpreted as evidence of an early high temperature phase of mineralization (Ixer et al. 1996; Fairbairn et al. 2020).

The second exception the Nenthead area where abundant lead-zinc-iron mineralization is present (see above). Although the higher temperature assemblages and more exotic metal content of the Leehouse Well – Sir John’s vein assemblages have not been reported from Nenthead, this may be due to the current level of exposure. The deposits seen in the South Tyne Valley occur in much lower horizons within the Carboniferous succession than those of Nenthead where it is conceivable that similar assemblages may be present at depth; traces of both nickel and cobalt supergene minerals have been reported here (Bridges & Young 1985).

Conclusions

New field and microstructural observations presented here suggest that the faults, fractures and mineralization of the Alston Block of the NPO record two distinct phases of deformation. During Phase 1, which it is suggested to have occurred during the Late Carboniferous due to the far field effects of the Variscan Orogeny, N-S shortening and basin inversion occurred leading to folding and thrusting along the margins of the Alston Block (Fig. 13a). Phase 2 deformation was regionally coeval with Whin Sill magmatism at ca 297 Ma and the main phases of mineralisation of the NPO in the Alston Block. This broad contemporaneity has been demonstrated by Re-Os analyses which suggest that mineralization occurred at ca. 294 Ma, and supported by recalculation of existing Sm-Nd fluorite data. This Early Permian event involved N-S lithospheric extension and E-W compression (Fig. 13b) and appears to be related to regional dextral transtensional reactivation of deep-seated NE-SW Caledonian basement structures as recognised in the adjacent Northumberland Basin (De Paola et al. 2005a). The North Pennine Orefield appears to be centred on the Burtreeford Disturbance, which may correspond to a deep-seated Caledonian structure in the basement that acted as a conduit for ascending metalliferous fluids in the earliest Permian.
The Re-Os isotopic analysis of the sulphide mineralisation indicates that it is likely genetically linked to the same primitive mantle source that gave rise to the Whin Sill magmatism. Previous interpretations of the NPO of the Alston Block as an MVT, or being due to the influx of Zechstein seawater, while understandable given the obvious interactions with sedimentary host rocks during emplacement, are now thought to be incorrect. Based on the findings presented here, it is suggested that the NPO of the Alston Block should be regarded as having formed as a mantle magmatism associated F-rich deposit. The new genetic model proposed here suggests that the Aston Block is distinct from its southern neighbour, the Askrigg Block where mineralization is less diverse, is associated with lower temperatures and seems to lack any clear link to mantle derived fluids (e.g. Bau et al. 2003; Kraemer et al. 2019). This implies that the Alston and Askrigg blocks are genetically distinct and should be treated as two separate orefields.

It is significant that fluorine-associated orefields have been presumed to result from MVT mineralization in several other deposits across Europe and North Africa (e.g. Boiron et al. 2010; Munoz et al. 1994, 1999; Subías & Fernández-Nieto 1995, Subías et al. 1998, Souissi et al. 2010, Dill et al. 2011; Kraemer et al. 2019). It is now apparent that an important part of one of the supposedly archetypal examples is most likely related to mantle-sourced magmatism and fluorine-rich hydrothermal fluids and is therefore not a classic MVT. Reappraisal of other similar orefields worldwide may now be required.

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**Figure Captions**

Figure 1: (a) Simplified geological map and schematic N-S cross section of the Alston Block based on the line of section (white).

(b) The main mineralised faults (red) of the main NPO plotted over the five plutons of the Weardale granite (1 = Weardale Pluton, 2 = Tynehead Pluton, 3 = Scordale Pluton 4 = Cornsay Pluton and 5 = Rowlands Gill Pluton). The depth contours to the top of the granite are also shown in dark grey (deepest) to white (shallowest) (based on Kimbell et al. 2010).

(c) Locations of localities/features mentioned in the text: GG - Garrigill; SJM - Sir John’s Mine; NHM - Nenthead; K - Killhope; SM - Sedling Mine; AH - Allenheads; RV - Red Vein; GR - Groverake Mine; RB -
Redburn; CK - Cambokeels, BQ - Bollihope Quarry; WR - West Rigg workings; WH - Westernhope; SV - Slitt Vein; CHM - Closehouse Mine; CGR - Cow Green Reservoir; TH - Tynehead; GSV - Great Sulphur Vein.

Figure 2: Stereoplots of fault, vein and fracture sets measured during this study, including slickenline lineations and principal ore veins. Senses of shear where known are also shown for shear fractures attributed to Phases 1 and 2.

Figure 3: (a) Aerial view of Bollihope Quarry (©Getmapping 23rd August 2015 using EDINA Aerial Digimap Service). Mineralised fault traced in yellow, fold hinges in red and tensile veins in purple. The quarry sits adjacent to the intersection of a large ESE-WNW mineralised fault with a large NE-SW fault (inset, yellow box shows location of image in a).

(b) Oblique view looking S of gentle folding of bedding surface in the limestones forming floor of the quarry.

(c) Plan view of bedding plane in limestone cut by tensile N-S vein filled with calcite, which has been weathered black.

(d) Sub-horizontal slickenlines with haematite mineralization on NE-SW fault.

(e) Silicified brecciated limestone with chalcedony cement in large NE-SW fault adjacent to the quarry (see inset to a).

(f) 15 m long x 10 m high fully exposed planar NW-SE fault surface with 1-2 cm thick veneer of fluorite (inset).
Figure 4: (a) Aerial view of West Rigg Quarry (©Getmapping 23rd August 2015 using EDINA Aerial Digimap Service) with the fluorite-quartz-galena bearing Slitt Vein highlighted in purple. Dashed black box indicated location of map in b.

(b) Detailed map and stereoplot of shear plane sets exposed in Slitt Vein - E-W normal (blue), NE-SW dextral (green) and WNW-ESE sinistral (red).

(c) View of the central quartz rich stockwork of the Slitt Vein with sub-vertical fault surfaces (red arrowed).

(d) Sub horizontal corrugations on a NW-SE fault surface.

(e) Early fluorite crystals (purple) overgrown by euhedral quartz with iron staining (brown). Location of sample shown in c highlighted by yellow star.

Figure 5: (a) Geological map of Closehouse mine draped over DEM (©Environmental Agency using EDINA Lidar Digimap Service) showing the main structures (faults, folds) and relationship to the associated dolerite intrusions. The edge of the current mine workings shown in is also shown in white. Stereoplot shows shallow-plunging fold hinges (blue) and thrust planes with slickenlines in red.

(b) View of Closehouse mine looking west with the main faults highlighted in red and the associated antiformal structures in yellow.

(c) Antithetic N-dipping thrust fault within the Carboniferous limestones with hangingwall anticline.
Figure 6: The four main outcrop-scale vein types observed within the NPO. (a) Massive monomineralic to polymineralic veins with local dilational jogs indicating shear sense associated with mineralization. River Nent section, Nenthead (NY 7864 4299; Cross Vein set).

(b) Tensile (Mode I) veins ± crack seal banding. South Tyne River section, Tynehead (NY 7604 3756; Quarter Point vein set).

(c) Mineralized breccia containing clasts of wall rock (commonly silicified) and brecciated vein material. South Tyne River section, Garrigill (NY 7436 4181; Lead Vein set).

(d) Brecciated fluorite mineralization (white) cut by dextral strike-slip faults (green) and associated Riedel shears (yellow). West Rigg quarry (NY 9112 3921; Quarter Point set).

Figure 7: Photomicrographs of primary growth textures in veins of the NPO.

(a) Massive monomineralic to polymineralic veins (in this case, pyrite, calcite and quartz) with euhedral to subhedral crystal habits. Sample from Nenthead (NY 78644 42992) (NNW-SSE Cross Vein).

(b) Crustiform to colloform mineralization (chalcedony) with overgrowths of euhedral crystals (fluorite). Sample from Groverake Mine (NY 90370 44138) (ESE-WNW Quarter Point vein).

(c) Cockade/moss veins with zoned spheroids (quartz with chalcedony overgrowths) “floating” in a matrix (calcite). Sample from Groverake Mine (NY 90370 44138) (ESE-WNW Quarter Point vein).

(d) Phase transition growth of related mineral phases – in these case quartz crystals are overgrown by crystals which start as chalcedony, evolve into quartzine before finally growing as quartz. Sample from Tynehead (NY 76037 37549) (ESE-WNW Quarter Point vein).
(e) Primary growth zonation is often visible in quartz (as in this case), fluorite and calcite. This is usually highlighted in optical images by the presence of fluid inclusions or impurities (often microsulphides). Sample from Tynehead (NY 76037 37549) (ESE-WNW Quarter Point vein).

(f) Euhedral quartz with a matrix of anhedral, intergrown metalliferous ore minerals (pyrite, chalcopyrite, hematite). Sample from Groverake Mine (NY 90370 44138) (ESE-WNW Quarter Point vein).

(g) Stacked frequency chart showing of the order of mineralisation observed in thin sections analysis of samples collected from the fluorite zone of the Alston Block. While most phases are seen to be coeval (with the exception of oxide/supergene minerals) it should be noted that calcite and the metalliferous sulphides (pyrite, chalcopyrite, marcasite, galena) are generally earlier.

In (a-c) and (f), LH images are in ppl, whilst RH images are crossed-polars. Images (d, e) are both in crossed-polars.

Figure 8: Photomicrographs of deformation textures observed in mineralised faults of the NPO.

(a) Jigsaw-brecciated fragments of limestone wall rock cemented by intergrown quartz and pyrite. Note that brecciation in this case was potentially explosive and related to transient high fluid pressures rather than brecciation through shear/attrition. Sample from Westernhope (NY 92039 34556) (ENE-WSW Quarter Point vein).

(b) Pervasive microfracturing in fluorite clast (lower part of image) suspended within a heamatite-cemented fluorite cataclasite (upper part of image). Sample from Westrigg (NY 91151 39186) (ESE-WNW Quarter Point vein).

(c) Clast of vein material (chalcedony, quartz) suspended in a fluorite matrix. Sample from Sedling (NY 85922 41110) (ESE-WNW Quarter Point vein).
(d) Alternating bands of crustiform chalcedony and fluorite offset by microfractures and quartz microveins. Sample from Sedling Mine (NY 85912 41093) (ESE-WNW Quarter Point vein).

(e) Fractured quartz vein cross cut by microbreccia cemented with oxides and malachite. Sample from Westerhope (NY 92039 34556). (f) Healed microfracturing in quartz grains with fluid inclusions (Tuttle lamellae); RH image shows a higher-power view. Sample from Tynehead (NY 76037 37549) (ESE-WNW Quarter point vein).

In (a) and (f), LH images are in reflected light, whilst those in (b-d) and (e) are in ppl. RH images in (a-d) are in crossed polars, whilst those in (f-e) are in ppl.

Figure 9: Replacive mineral textures within the NPO.

(a) Hand-specimen of fluorite replaced by silica. Sample from Shildon Mines, Blanchland, Northumberland (NY9625 5080) (NE-SW Lead Vein)

(b) Fluorite replaced with quartz with relict grain boundary still visible as a band of chalcedony/feathery quartz. Upper image in ppl, lower image in crossed polars; Sample from Redburn, Rookhope (NY 93283 43072) (ESE-WNW Quarter Point vein).

(c) “Ghost spheres” are commonly observed replacement texture. Here cockade/moss textures are replaced by silica with optically continuous crystals overgrown the original texture; Sample from Redburn, Rookhope (NY 93283 43072) (ESE-WNW Quarter Point vein).

Figure 10: (a) Optical cathode luminescence (OCL) images of fluorite crystals showing multiple dissolution, precipitation and brecciation events which are not visible using traditional optical microscopy. Samples from Sedling mine (NY 85922 41110 ) (ESE-WNW Quarter Point vein). (b) OCL images of calcite crystals within showing zonal growth and brecciation, but lacking the obvious
dissolution/precipitation textures seen in fluorite. Samples from Nenthead (NY 78644 42992) (ESE-WNW Quarter Point vein). 

Figure 11: Stereoplots with stress inversion analyses, Mohr circle plots and maps for all slickenline-bearing structures of the NPO for (a) Phase 1 and (b) Phase 2 structures. These suggest that Phase 1 was a reverse faulting regime with N-S shortening consistent with far-field Variscan inversion, whilst Phase 2 was a strike-slip/transtensional regime with N-S extension and E-W shortening. Explain what the green planes/points are – I don't follow what you wrote.

Figure 12: (a) Re-Os isochron for all 8 samples collected from the NPO yielding a Model 3 age of 311.6 ± 19.8 Ma (MSWD = 0.98) \((^{187}\text{O}/^{188}\text{Os} = 0.154 \pm 0.006)\). 

(b) Initial osmium ratios for all 8 samples at 311 Ma shows that samples TH1 and CB10 from peripheral areas of the NPO (Tynehead Th1, Cambokeels Cb10) are more radiogenic compared to the other samples.

(c) Re-Os regression of the North Pennine Orefield with outliers omitted yields a Model 3 age of 304 ± 20 Ma (MSWD = 0.14) \((^{187}\text{O}/^{188}\text{Os} = 0.151 \pm 0.006)\)

Figure 13: Map views (left) and 3D models (right) showing the proposed two-stage structural evolution of the NPO.

(a) Phase 1 deformation due to N-S Variscan shortening leading to the reverse reactivation and inversion of the surrounding basins and faults bounding the Alston Block, forming E-W folds and thrusts. Within the block, a series of NNW-SE to NNE-SSW strike slip faults formed with minor calcite-dominated mineralisation and dextral reactivation of the deep seated Burtreeford Disturbance (BD).
(b) Phase 2 deformation occurred penecontemporaneously with the emplacement of the Whin sill at ca 297 Ma with N-S extension and E-W shortening reactivating the faults bounding the Alston Block (Stublick and Lunedale faults) as dextral transtensional faults. Within the Alston Block a series of NE-SW to SE-NW strike-slip faults develop and become heavily mineralised by fluids associated with the Whin Sill rising through the orefield close to the Burtreeford Disturbance. As these fluids radiate out from this structure, they interact with the host Carboniferous rocks and become further enriched, altering their isotopic signature and increasing their economic potential.

Figure 14: (a) Initial osmium values of sulphide samples collected from the NPO compared to initial osmium ratios for the Primitive Mantle (black), the Whin Sill (purple), lower limit, Carboniferous seawater (blue) and lower limit, Permian Seawater (yellow). The sulphides can be divided into two groups, with the Group 1 average corresponding to the Whin Sill, whereas Group 2 is slightly more radiogenic. Note that even the most radiogenic samples fall well below the lower limit Carboniferous and Permian values.

(b) Re-Os regression of Group 1 yield a Model 3 age of 293.5 ± 20.1 Ma (MSWD = 0.57) ($^{187}$O/$^{188}$Os = 0.152 ± 0.006).

(c) Re-Os regression of Group 2 yields a Model 3 age of 294.8 ± 14.9 (MSWD = 0.19) ($^{187}$O/$^{188}$Os = 0.366 ± 0.047).

Figure 15: Sm-Nd fluorite data isochron plots. The Sm-Nd data are from Halliday et al. (1990; Table II). Age calculations were undertaken using IsoplotR (Vermeesch 2018) and a $^{147}$Sm decay constant ($\lambda$) of 6.524 ± 0.024e$^{-12}$ a$^{-1}$ (Gupta & MacFarlane 1970).

(a) Errorchron shown for analysis of all Sm-Nd fluorite data from regionally spaced veins (Slitt, Groverake and Ferneygill).
(b) Sm-Nd plot for samples that possess similar initial $^{143}$Nd/$^{144}$Nd values at 295 Ma.

(c) Sm-Nd plot for only fluorite from the Slitt vein that possess similar initial $^{143}$Nd/$^{144}$Nd values at 295 Ma. See text for discussion.

Table I: Synopsis of the Re and Os pyrite data from the sulphide bearing veins and Whin Sill of the Alston Block.

Table II: Synopsis of the Sm and Nd fluorite from the Slitt, Groverake and Ferneygill veins, Whin Sill and Limestone presented in Halliday et al (1990).
Figure a: 
- Age: $311.6 \pm 19.2$ Ma
- $^{187}\text{Os}/^{188}\text{Os}_{\text{initial}} = 0.154 \pm 0.006$
- MSWD = 0.98

Figure b:
- Samples: S1, S2, BG5A, Th1, CB10, NHM1b, SJM2

Figure c: 
- Age: $304.0 \pm 20.0$ Ma
- $^{187}\text{Os}/^{188}\text{Os}_{\text{initial}} = 0.151 \pm 0.006$
- MSWD = 0.14
Phase 1 - Late Carboniferous
Variscan shortening: N-S compression

Phase 2 - Permian
Dextral transtension: N-S extension / E-W compression & NPO mineralization

Influx of metalliferous fluids associated with Whin magmatism
Model 1 age = 73.2 ± 3.0 Ma (n = 20)
initial $^{143}$Nd/$^{144}$Nd = 0.5120786 ± 63
MSWD = 32

Model 3 age = 291.0 ± 39.0 Ma (n = 11)
initial $^{143}$Nd/$^{144}$Nd = 0.511757 ± 59
dispersion $^{143}$Nd/$^{144}$Nd = 0.000028 ± 17

Model 3 age = 291.5 ± 46.7 Ma (n = 8)
initial $^{143}$Nd/$^{144}$Nd = 0.511758 ± 69
dispersion $^{143}$Nd/$^{144}$Nd = 0.000029 ± 18
Table 1: Synopsis of the Re and Os pyrite data from the sulphide bearing veins and Whin Sill of the Alston Block.

<table>
<thead>
<tr>
<th>Batch/Sample</th>
<th>Re (ppt)</th>
<th>±</th>
<th>Os (ppt)</th>
<th>±</th>
<th>$^{187}$Re/ $^{186}$Os</th>
<th>±</th>
<th>$^{188}$Os/ $^{186}$Os</th>
<th>±</th>
<th>rho</th>
<th>±</th>
<th>308 Ma</th>
<th>±</th>
<th>297 Ma</th>
<th>±</th>
<th>295 Ma</th>
<th>±</th>
<th>290 Ma</th>
<th>±</th>
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<td>RO579-1_NHM1b</td>
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<td>260.3</td>
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<td>0.832</td>
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<td>0.34</td>
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<td>0.37</td>
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<td>0.11</td>
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<td>RO572-6_S2</td>
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Table 2: Synopsis of the Sm and Nd fluorite from the Slitt, Groverake and Ferney gill veins, Whin Sill and Limestone presented in Halliday et al (1990).

<table>
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<tr>
<th>Sample</th>
<th>Sm/Nd ±2σ (abs)</th>
<th>Nd/Sm ±2σ (abs)</th>
<th>Nd/Sm at 291.5 Ma</th>
<th>±</th>
<th>ɛNd at 291.5 Ma</th>
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<td>B5</td>
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<td>0.51221 ±0.00002</td>
<td>0.51180 ±0.00002</td>
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<tr>
<td>B13</td>
<td>0.2232 ±0.0022</td>
<td>0.51218 ±0.00002</td>
<td>0.51175 ±0.00002</td>
<td>-9.9</td>
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<td>B44</td>
<td>0.2513 ±0.0025</td>
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<td>0.51175 ±0.00002</td>
<td>-10.0</td>
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<td>B53</td>
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<td>B75</td>
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*Note that no reported uncertainty in Halliday et al. (1990). We estimate 1% absolute (2σ level) uncertainty.