



Rb–Sr and U–Pb geochronology of neoblasts and porphyroclasts constrain movements along reactivated segments of the Outer Hebrides Fault Zone, NW Scotland

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Abstract: The crustal-scale Outer Hebrides Fault Zone (OHFZ) (NW Scotland) was initiated as a Stenian–Tonian (1040–950 Ma) ductile thrust, as determined by published U–Pb dating of syn-kinematic apatite. Thrust-related mylonites were then reactivated to form phyllonite belts during successive sinistral strike-slip and extensional displacements. Within the phyllonites, syn-kinematic white mica was formed at temperatures of 150–370°C. New early Devonian (408–396 Ma) Rb–Sr white mica ages from sinistrally deformed phyllonites and an extensionally deformed phyllonite overlap, consistent with broadly coeval development during sinistral transtension. Early Devonian phyllonitization was coeval with sinistral strike-slip faulting along the Great Glen Fault Zone and transtensional development of the Orcadian and Moray Firth Old Red Sandstone basins on and adjacent to the Scottish mainland. Apatites occur as cataclastically deformed porphyroclasts within phyllonites along the eastern margin of the OHFZ, yielding U–Pb ages of 1020–950 Ma. This age signature suggests that the early ductile thrust zone seen onshore in the Northern Segment is located offshore to the east in the Southern Segment and extends the entire length of the Outer Hebrides. Our study highlights the importance of carrying out microstructural analysis of mineral phases prior to isotopic analysis.

Supplementary material: Full Rb–Sr and U–Pb geochronology datasets, SEM-BSE images of apatite grains and associated analytical spot positions, full thin-section scans of JM-21-02/-04 and full petrographic descriptions of all samples are available at <https://doi.org/10.6084/m9.figshare.c.8646672>

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The location of deformation zones within the continental lithosphere is commonly influenced by pre-existing tectonic fabrics and structures such as faults and shear zones and these structures may therefore carry evidence for repeated activation (e.g. [Grocott 1977](#); [White *et al.* 1986](#); [Butler *et al.* 1995](#); [Holdsworth *et al.* 1997, 2001](#); [Hatcher 2001](#); [Ribeiro *et al.* 2023a](#)). Such zones of crustal weakness are important for fluid mobility both upwards from the lithosphere but also downwards from the hydrosphere. Continental fault systems typically incorporate fault rocks formed at different times and depths, often exhibiting cooling histories that reflect their progressive exhumation (e.g. [Wolff *et al.* 2012](#); [Wang *et al.* 2020](#)). Reactivated deformation zones thus enable the study of fault system development at different pressure-temperature conditions. Potentially, it may be possible to constrain the timing of reactivation at mid-crustal levels by applying various geochronological techniques to minerals that formed as neoblasts (new grains) within these fault rocks. Detailed understanding of the *P–T–t* history of fault rocks and integration with microstructural information is required so isotopic ages that correspond closely to the time of deformation can be separated from those that date cooling through a particular closure temperature which only place a minimum age on deformation. If the goal is to constrain primary growth ages, it is therefore important to obtain isotopic ages from minerals that have a closure temperature higher than, or equivalent

to, the deformation temperature within the fault rocks being studied. As examples, the application of U–Pb and U–Th–Pb geochronology to syn-kinematic grains of, respectively, apatite and allanite has proved a powerful tool for dating mid-crustal shear zones within crystalline crustal rocks (e.g. [Centi-Tok *et al.* 2013](#); [Odlum and Stockli 2020](#); [Ribeiro *et al.* 2020a, b](#)). Similarly, recent advances in Rb–Sr geochronology have proven effective in constraining the age of white mica formation in mid-crustal shear zones ([Zametzer *et al.* 2022](#); [Kirkland *et al.* 2023](#); [Ribeiro *et al.* 2023a, b](#)).

The Outer Hebrides Fault Zone (OHFZ) in NW Scotland ([Fig. 1a, b](#)) is a classic example of a reactivated, crustal-scale fault developed within Archean–Paleoproterozoic basement gneisses of the Laurentian craton. The complex kinematic evolution of the fault zone has been well documented by field and microstructural studies (e.g. [Francis and Sibson 1973](#); [Sibson 1977a, b](#); [White and Glasser 1987](#); [Fettes *et al.* 1992](#); [Butler *et al.* 1995](#); [Imber *et al.* 1997, 2001, 2002](#); [MacInnes *et al.* 2000](#); [Osinski *et al.* 2001](#); [Szulc *et al.* 2008](#)). ⁴⁰Ar/³⁹Ar dating of pseudotachylytes from the footwall Lewisian gneisses of the OHFZ yielded ages of c. 1900, 1300–1200 and 700 Ma ([Sherlock *et al.* 2009](#)) but the relationship between these melting ages and the movement history of the fault zone is uncertain. The earliest deformation *within* the OHFZ was associated with top-to-the-NW ductile thrusting that formed a belt of upper-greenschist facies mylonites ([Fig. 1b](#); [Imber *et al.* 2001](#)). U–Pb

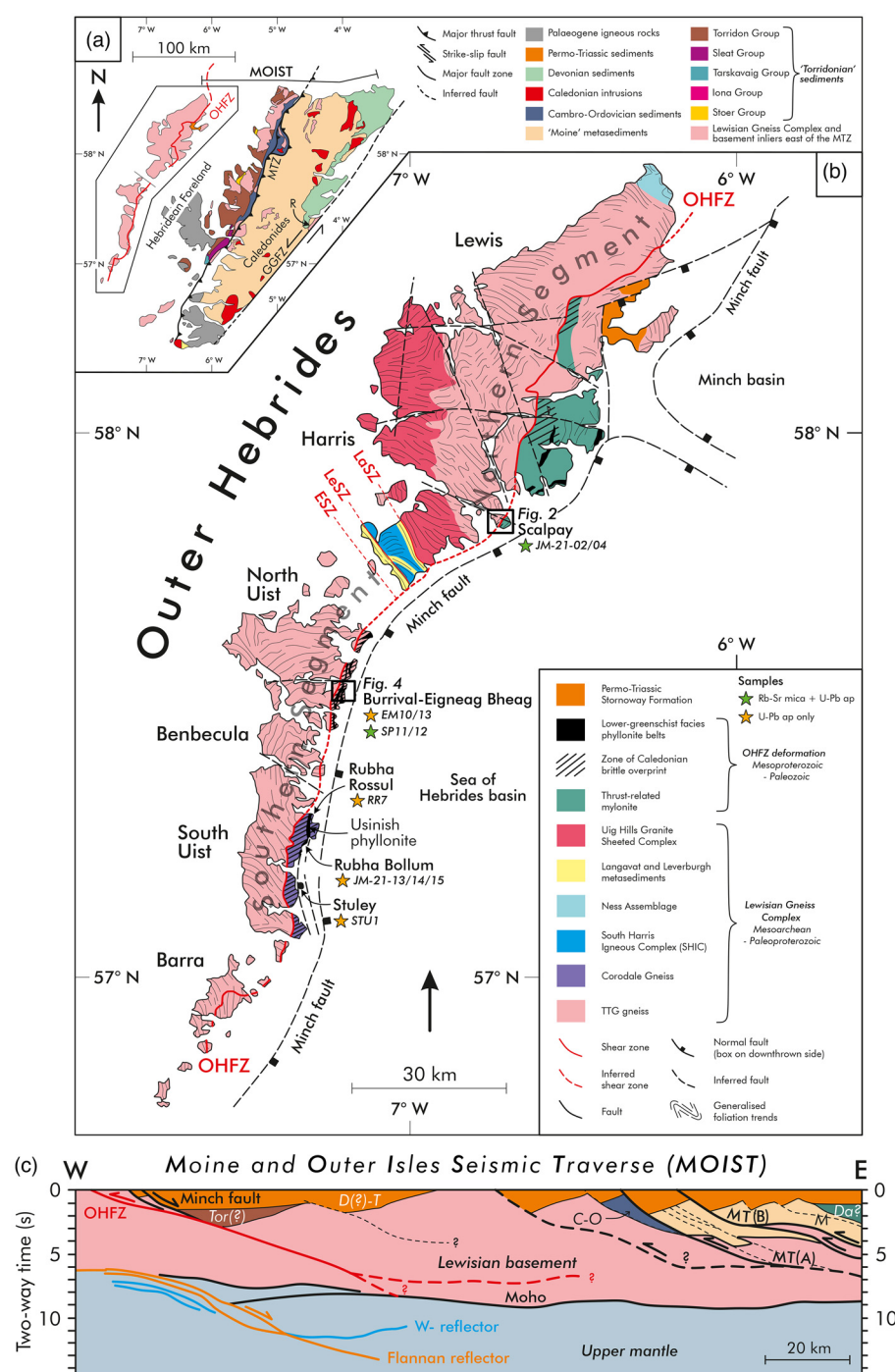


Fig. 1. Simplified geological map of NW Scotland (a) and the Outer Hebrides (b) In (a), the east–west line off the north coast of Scotland represents the trace of the Moine and Outer Isles Seismic Traverse (MOIST; see (c)) and the trace of the Moine Thrust Zone refers to MT(A) in (c). In (b), the margins of the locality maps shown in Figures 2 and 4 are marked by the respective boxes. Abbreviations: ESZ, Ensay Shear Zone; GGF, Great Glen Fault; LaSZ, Langavat Shear Zone; LeSZ, Leverburgh Shear Zone; MTZ, Moine Thrust Zone; OHFZ, Outer Hebrides Fault Zone. (c) Simplified geological cross-section of the upper mantle and crust along the Moine and Outer Isles Seismic Traverse (MOIST see (a)). Positions of the reflectors and geological units are drawn from interpretations made by Brewer and Smythe (1984), Blundell *et al.* (1985), Snyder and Flack (1990), Snyder *et al.* (1997), and Wilson *et al.* (2010). Note the depth of penetration for the Outer Hebrides Fault Zone (OHFZ). Two proposals are made for the lower-crustal geometry of the OHFZ, either a flattening out above the Moho, or a steeper continuation that intersects the upper mantle. The Flannan reflector is interpreted as a deep, mantle-penetrating extensional shear zone, as suggested by Snyder and Flack (1990) and Snyder *et al.* (1997), although it has also been interpreted as a fossilized subduction complex (Warner *et al.* 1996; Morgan *et al.* 2000). Two reflectors are postulated as the Moine Thrust, MT (a) and MT (b), following the interpretations of Brewer and Smythe (1984). The relative positions of the Cambro-Ordovician and Moine sediments assume MT (a) as the Moine Thrust and this is the fault trace shown in (a). Abbreviations: C-O, Cambro-Ordovician sediments; Da, Dalradian Supergroup; D(?)–T, Devonian(?) to Triassic sediments; M, 'Moine' metasediments; R, Rosemarkie inlier; Tor (?), 'Torridonian(?)' sediments. Source: adapted from Metcalfe *et al.* (2024).

dating of syn-kinematic apatite grains within these mylonites yielded ages mostly in the range 1100–900 Ma and initiation of the OHFZ has therefore been assigned to the Grenville–Sveconorwegian orogeny (Metcalfe *et al.* 2024). However, the subsequent reactivation history is not constrained by any reliable geochronological data.

In this study, we report the results of apatite U–Pb and white mica Rb–Sr dating carried out on prominent belts of foliated phyllosilicate-rich fault rocks (phyllonites) that formed during sinistral strike-slip and extensional reactivation of the OHFZ. The microstructural characteristics of apatite grains within the phyllonite belts indicate that they represent pre-kinematic porphyroclasts. These apatite grains yield latest Stenian–earliest Tonian U–Pb ages (1020–950 Ma) which we interpret as recording isotopic resetting of older grains in the footwall of the early top-to-the-NW ductile thrust zone. In contrast, white mica grains are interpreted as neoblasts in the phyllonite belts and these yield Lower Devonian ages (408–396 Ma) for the timing of

sinistral strike-slip and extensional reactivation in an overall transtensional tectonic setting. These results highlight that *in situ* white-mica Rb–Sr geochronology opens a new frontier for dating complex, low-temperature deformation fabrics that are often neglected in the tectonic evolution of complex terranes.

Geological setting

The OHFZ is a 1–15 km-wide NNE-trending belt of fault rocks (mylonites, pseudotachylytes, cataclasites and phyllonites) that is exposed over a strike length of *c.* 170 km along the eastern seaboard of the Outer Hebrides island chain (Fig. 1b; Sibson 1977a, b; Fettes *et al.* 1992). Deep seismic profiling has shown that the fault zone dips at *c.* 25° to the ESE to a depth of *c.* 25 km (Smythe *et al.* 1982; Brewer and Smythe 1984) and it may intersect and possibly offset the Moho (Fig. 1c Blundell *et al.* 1985; Stein 1988). The OHFZ affects the Neoproterozoic to Paleoproterozoic Lewisian Gneiss

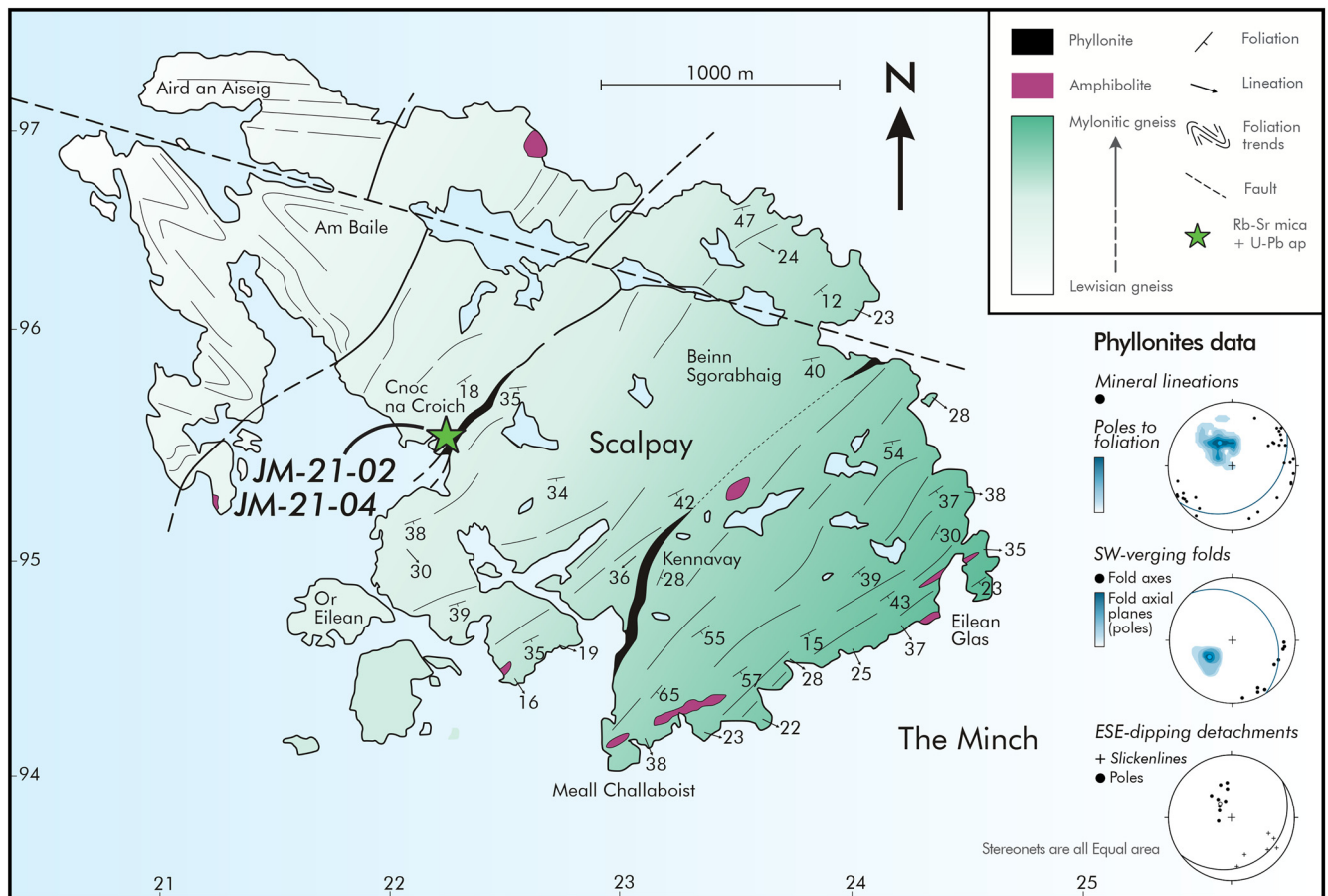


Fig. 2. Simplified geological map of Scalpay. The stereonets present structural data from the phyllonite belts (Butler 1995; Imber 1998). Source: adapted from Metcalfe *et al.* (2024) and references therein.

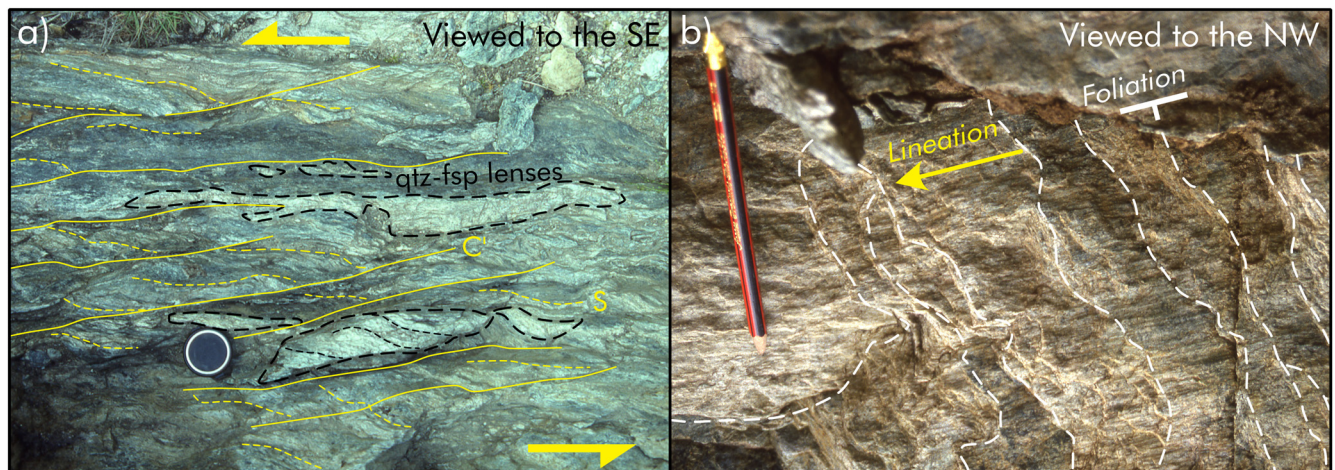


Fig. 3. Field characteristics of the Cnoc na Croich phyllonite belt on Scalpay (NG 224 957). (a) c'-type S-C fabrics indicative of sinistral strike-slip shear, viewed down-dip and parallel to the SE-dipping foliation, (b) mineral lineation plunging gently SW on SE-dipping foliation surfaces, viewed normal to the SE-dipping foliation.

Complex (Cliff *et al.* 1998; Friend and Kinny 2001; Whitehouse and Bridgwater 2001; Mason and Brewer 2004; Mason *et al.* 2004; Mason 2012, 2016). Although the OHFZ is thought to have been initiated during the *c.* 1200–1000 Ma Grenville–Sveconorwegian orogeny (Metcalfe *et al.* 2024), there is no evidence of widespread deformation or metamorphism of this age in Lewisian gneisses that lie in the hanging wall of the fault zone on the Scottish mainland

(Fig. 1). A Grenville–Sveconorwegian orogenic ‘front’ thus likely lies further east buried in the footwall of the Moine Thrust Zone which forms the western margin of the Lower Paleozoic Caledonian orogen (Fig. 1a; Sanders *et al.* 1984; Storey *et al.* 2010; Strachan *et al.* 2020a, 2024; Metcalfe *et al.* 2024).

The Lewisian Gneiss Complex forms the foreland to the Paleozoic Caledonian orogen which resulted from the sinistral

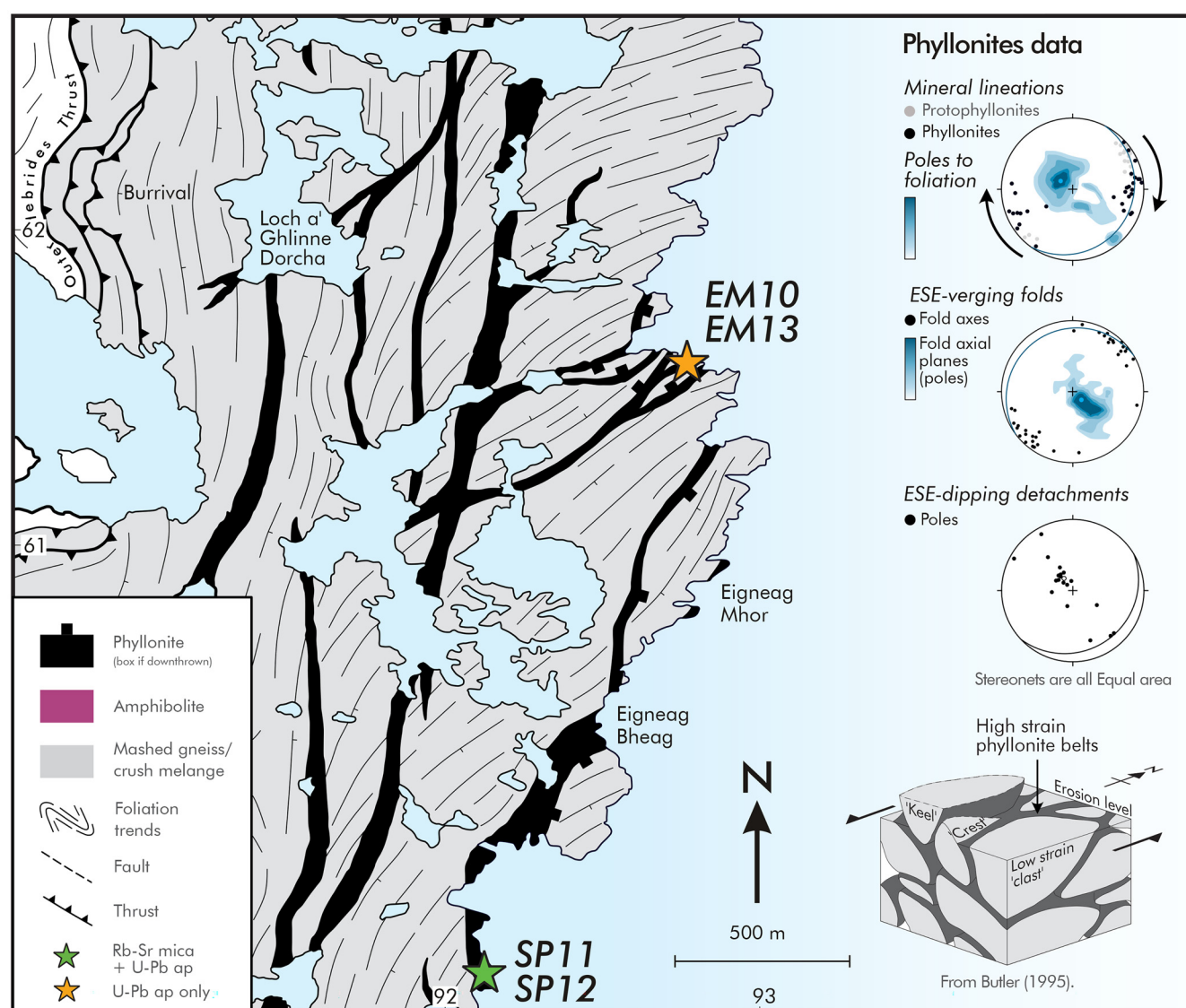


Fig. 4. Simplified geological map of the Burrival–Eigneag Bheag region on North Uist. The 3D block diagram and stereonet data are from [Butler \(1995\)](#) and [Imber \(1998\)](#). The black arrows on the top stereonet plotting mineral lineation data demonstrate the clockwise rotation in orientation of the mineral lineations from NE–SW (strike-slip) within the protophyllonites to east–west (closer to downdip) in the phyllonite cores. Source: adapted from [Butler *et al.* \(1995\)](#).

oblique collision of Laurentia, Baltica and Gondwanan-derived terranes (Ganderia and Avalonia) following the closure of the Iapetus Ocean ([Pickering *et al.* 1988](#); [Soper *et al.* 1992](#); [Dewey and Strachan 2003](#); [Waldron *et al.* 2025](#)). East-dipping reflectors in the eastern section of the Moine and Outer Isles Seismic Traverse (MOIST) are thought to correspond to the Moine Thrust Zone and overlying ductile thrusts ([Fig. 1c](#); [Smythe *et al.* 1982](#)). Caledonian thrusting ceased by *c.* 430–425 Ma ([Goodenough *et al.* 2011](#); [Strachan *et al.* 2020b](#)) and was followed and overlapped by sinistral strike-slip faulting. In NW Scotland, the Great Glen Fault Zone (GGFZ; [Fig. 1](#)) is the most significant of the strike slip faults, with estimates of displacement varying from at least 700 km ([Dewey and Strachan 2003](#)) to *c.* 250–300 km ([Prave *et al.* 2024](#)) and *c.* 100 km ([Kennedy 1946](#); [Searle 2021](#)). From *c.* 410 Ma, the Caledonides went into a regional phase of sinistral transtension to form Old Red Sandstone (Devonian) sedimentary basins. These include the Orcadian Basin on the Scottish mainland and Orkney and form part of a linked system of basins extending north through Shetland and into western Norway and Greenland ([Séranne 1992](#); [Dewey and Strachan 2003](#); [Wilson *et al.* 2010](#); [Dichiarante *et al.* 2020](#); [Utley *et al.* 2023](#)). No known Devonian sedimentary rocks are present onshore in the Outer Hebrides.

The OHFZ was divided by [Butler *et al.* \(1995\)](#) into a ‘Northern Segment’ exposed on the islands of Lewis and Harris, and a ‘Southern Segment’ of the Uist islands and Barra ([Fig. 1b](#)). Up to five deformational events are evident from the study of fault rocks, kinematic indicators, and overprinting relationships ([Table 1](#); [Butler *et al.* 1995](#); [Imber *et al.* 2001, 2002](#)). Each event varies in its development and relative importance and may be absent entirely in some locations. The upper-greenschist facies mylonite belt that formed during early NW-directed thrusting at *c.* 1100–900 Ma ([Metcalfe *et al.* 2024](#)) is only exposed onshore in the Northern Segment. However, both segments were affected by reactivation during the Lower Paleozoic ([Butler *et al.* 1995](#); [Imber *et al.* 1997, 2001, 2002](#)). Reactivation began with NW-directed brittle thrusting which is broadly associated with extensive cataclasite breccias (‘crush melange’ of [Sibson 1977a](#)) and locally common pseudotachylite veins. Biotite grains adjacent to a pseudotachylite vein on Grimsay Island (North Uist) yielded an $^{40}\text{Ar}/^{39}\text{Ar}$ age of 430 ± 6 Ma ([Kelley *et al.* 1994](#)), which was inferred to date thermally activated argon loss from melting of the pseudotachylite vein. Hence top-to-the-NW brittle thrusting may have occurred during the terminal stages of the Caledonian orogeny ([Butler *et al.* 1995](#); [Imber *et al.*](#)

Table 1. Polyphase deformational history along the Northern and Southern Segments of the Outer Hebrides Fault Zone

Northern segment	Southern segment
(1) <i>Top-to-the-NW ductile thrusting</i> North–south to NE–SW trending belt (c. 5 km wide) of upper greenschist facies, SE-dipping mylonites and protomylonites, extending along eastern Lewis and Harris from the southernmost extent in Scalpay towards NE Lewis. c. 1700–430 Ma.	Largely absent? Exposures of mylonites are largely absent. Localized observations (e.g. MacInnes <i>et al.</i> 2000) of ductile top-to-the-NW kinematic indicators on the islands of Gighay and Hellisay off the NE coast of Barra.
(2) <i>Top-to-the-NW brittle thrusting</i> Widescale zones of cataclastic and ‘mashed’ Lewisian gneiss, commonly associated with pseudotachylyte veins and breccias. Top-to-the-NW sense of shear prevails. Potentially associated pseudotachylytes dated at c. 430 Ma by Kelley <i>et al.</i> (1994).	(1) <i>Top-to-the-NW brittle thrusting</i> Widescale zones of cataclastic and ‘mashed’ Lewisian gneiss, with pseudotachylyte-ultracataclasite crush zones and a c. 1 km thick ‘Crush Melange’ (Sibson 1977a, b). Top-to-the-NW sense of shear prevails. Potentially associated pseudotachylytes dated at c. 430 Ma by Kelley <i>et al.</i> (1994).
(3) <i>Top-to-the-NE sinistral strike-slip</i> NE–SW trending, moderately east-dipping discontinuous phyllonitic belts. Essentially lower-greenschist-facies shear zones. Elongate, strike-parallel quartz–feldspar aggregates indicate sinistral strike slip sense of shear. K–Ar ages ranging from 470–394 Ma (D. C. Rex in Sibson 1977a, b).	(2) <i>Top-to-the-NE sinistral strike-slip</i> NE–SW trending, moderately east-dipping anastomosing phyllonitic belts. Essentially lower-greenschist-facies shear zones. Elongate, strike-parallel quartz–feldspar aggregates indicate sinistral strike slip sense of shear. K–Ar ages ranging from 470–394 Ma (D. C. Rex in Sibson 1977a, b).
(4) <i>Top-to-the-SE low-angle dip-slip extension</i> Low-angle faults and SE-verging folds commonly rework the margins of the strike-slip phyllonites. A top-to-the-SE normal sense of shear prevails. Absolute age unknown.	(3) <i>Top-to-the-SE low-angle dip-slip extension</i> Low-angle faults and SE-verging folds commonly rework the margins of the strike-slip phyllonites. A top-to-the-SE normal sense of shear prevails. Absolute age unknown.
(5) <i>Top-to-the-SE high-angle dip-slip extension</i> High-angle, steeply SE-dipping normal faults. Considered likely to be related to offshore fault-bounded basins (Minch and Sea of Hebrides basins). Syn-depositional with the Permo-Triassic Stornoway formation.	(4) <i>Top-to-the-SE high-angle dip-slip extension</i> High-angle, steeply SE-dipping normal faults. Considered likely to be related to offshore fault-bounded basins (Minch and Sea of Hebrides basins). Syn-depositional with the Permo-Triassic Stornoway formation.

After Butler *et al.* (1995), Imber (1998), Franklin (2013) and Metcalfe *et al.* (2024).

2001). Following this, a period of sinistral strike-slip motion was associated with the formation of belts of NE- to north–south-trending, east-dipping phyllonites that were derived from the retrogression of the host gneisses and pre-existing fault rocks (mylonites in the Northern Segment or cataclasites/pseudotachylytes in the Southern Segment). The phyllonite belts are traceable laterally for up to 500–1000 m and are widespread in a zone up to 3 km wide between central Lewis and South Uist (Fig. 1b). Subsequent reworking of these phyllonites occurred during low-angle, mainly top-to-the-south or SE extensional displacements (Sibson 1977a; White and Glasser 1987; Butler *et al.* 1995; Imber *et al.* 1997, 2001; Osinski *et al.* 2001; Franklin 2013). K–Ar whole rock ages of 470–394 Ma obtained from some of the phyllonite belts (D.C. Rex in Sibson 1977a) are broadly consistent with Caledonian reactivation. The youngest phase of reactivation formed high-angle brittle normal faults which downthrow to the SE and are attributed to the formation of the offshore Minch Basin (Butler *et al.* 1995; Imber *et al.* 2001). The sedimentary rocks of the Permo-Triassic Stornoway Formation unconformably overlie intensely faulted rocks of the OHFZ and are bounded to the west by similar steep easterly-dipping normal faults (Steel and Wilson 1975; Stein 1988, 1992; Butler *et al.* 1995). The sedimentary rocks are undeformed and incorporate fault rock clasts derived from the OHFZ, indicating that there were only modest localized displacements along the fault zone onshore since the Permo-Triassic (Franklin 2013).

Field and microstructural evidence from phyllonite belts for strike-slip and extensional displacements

The phyllonite belts comprise a quartz–albite–white mica–chlorite–epidote–actinolite assemblage with minor opaques, consistent with lower greenschist-facies conditions (Imber *et al.* 2001) and temperature estimates of 150–370°C from fluid inclusion studies on syn-tectonic quartz veins hosted within the phyllonites (Osinski *et al.* 2001; Szulc *et al.* 2008). In contrast, the host orthogneisses commonly contain hornblende and biotite; such phases are entirely absent in the phyllonites, where they have been replaced by chlorite,

actinolite and epidote. This retrogression, together with pervasive phyllosilicate growth, has been linked to the ingress of large volumes of hydrous fluids along the fault zone during shearing (White and Glasser 1987; Butler *et al.* 1995). To better constrain the structural evolution of the phyllonite belts, we focus on two exceptional exposures: the island of Scalpay and North Uist (Burruival to Eigneag Bheag) (Figs 2–5). Our structural descriptions draw primarily on Butler (1995), Butler *et al.* (1995) and Imber *et al.* (2001), to which readers are referred to for full details. Samples for geochronology were collected from both localities, together with additional phyllonite belts distributed along the length of the OHFZ (see Fig. 1b).

Scalpay

Phyllonite horizons 10–15 m thick are well developed on Scalpay at Cnoc na Croich (NG 224956) and Kennavay (NG 232950) (Fig. 2; Butler 1995; Butler *et al.* 1995; Imber *et al.* 2001; Szulc *et al.* 2008). The phyllonites on Scalpay carry a prominent foliation and are generally fine-grained, although porphyroclasts of pink K-feldspar up to 10 cm diameter and dm-scale quartz–feldspar aggregates are common (Fig. 3a). The foliation dips c. 40° to the SE, sub-parallel to the older mylonitic thrust-related fabric in the host gneisses (see stereonets in Fig. 2). Within the phyllonites, a mineral lineation defined by aligned quartz ribbons, fibrous chlorite, and pseudo-morphed feldspar aggregates plunges gently (0–10°) to the NE or SW (Figs 2, 3b). Abundant shear sense indicators (σ - and δ -porphyroclasts, shear bands and S-C fabrics) consistently indicate a sinistral (top-to-the-NE) sense of movement (Fig. 3a). Asymmetric, close to tight minor folds appear to have formed during phyllonitization and underwent progressive rotation during intense shear so that their hinge orientations range from transport-normal to sub-parallel to the mineral lineation.

Post-dating the fault rocks derived from both thrusting and strike-slip are a series of extensional structures (Butler 1995; Butler *et al.* 1995; Szulc *et al.* 2008). Late, semi-brittle open folds that verge down-dip to the SE occur locally within the thrust-related mylonites (Sibson 1977a, b; Butler 1995). However, extensional structures are

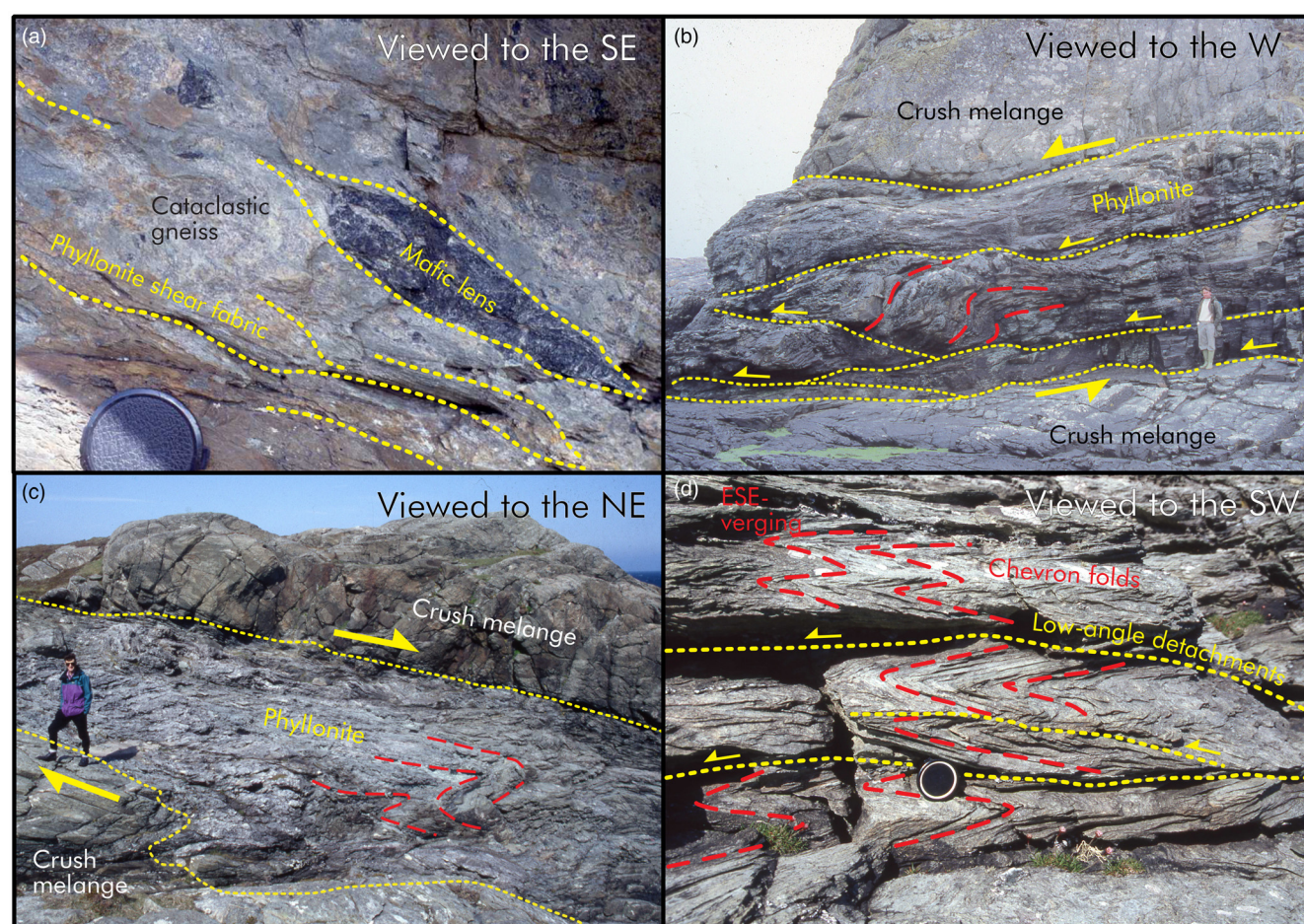


Fig. 5. (a) View to the SE of crush melange overprinted by sinistral strike-slip protophyllonitic fabric at Burrival (NF 909 620); (b) ESE-dipping phyllonite band with ESE-verging folds cuts protophyllonitic crush melange (NF 921 596); (c) Updip view of phyllonite band bound to the top and bottom by protophyllonitic crush melange (NF 921 597). The phyllonite-crush melange boundary is marked by ESE-dipping detachment faults which splay into the phyllonite core (yellow dashes). Extensional displacement has produced ESE-verging folds (red dashes); (d) ESE-verging chevron folds and ESE-dipping detachments within the phyllonites at Eigneag Bheag (NF 921 596).

mainly preferentially localized into the phyllonite belts formed during strike-slip movements. Numerous low-angle top-to-the-SE normal faults ('low-angle detachments' in Fig. 2) occur within, and along the boundaries of, the most extensive phyllonite belts. The normal faults dip parallel to the pre-existing phyllonite foliation which likely exerted an important control on their localization. Within the phyllonites, a series of centimetre-scale asymmetric, close to open SW-verging folds are developed with axial surfaces that are recumbent to moderately inclined to the NE (Butler 1995). Fold axes are gently plunging to the east, SE and south (see stereonets in Fig. 2). The pre-existing NE-trending strike-parallel lineation is folded by these SW-verging structures. A new SE-plunging mineral lineation of quartz and feldspar aggregates and chlorite fibres is generated in phyllonites close to the detachments (see stereonets in Fig. 2). In eastern Lewis, where the phyllonites trend more ENE–WSW, the later extension vector is top-to-the-south. Butler (1995) and Imber (1998) suggest that in the NE–SW trending phyllonites of Scalpay, kinematic partitioning of the overall top-to-the-south displacement has occurred into a relatively large component of dextral (top-to-the-SW) strike-slip (folds) and a relatively small component of top-to-the-SE dip-slip (detachments).

North Uist (Burrival to Eigneag Bheag)

Within the Burrival–Eigneag Bheag region of North Uist (Fig. 4), an anastomosing network of NE- to NNE-trending, mostly SE-dipping phyllonite belts overprint a >1 km thick zone of thrust-

related breccia, cataclasites and pseudotachylytes (the 'Crush Melange' of Sibson 1977a, b; Butler 1995; Butler *et al.* 1995). Note that the three-dimensional form of the phyllonite networks means that they locally dip shallowly to steeply NW (see stereonets and 3D diagram in Fig. 4). In a traverse from west to east, the overall intensity of the phyllonitic fabric increases, although deformation is extremely heterogeneous. The margins of the phyllonite belts pass transitionally into protophyllonites that overprint the orthogneisses or crush melange (Fig. 5a–c). The protophyllonites and the margins of the phyllonite belts contain a subhorizontal to gently, NE or SW-plunging mineral lineation defined by quartz–feldspar aggregates, chlorite fibres and occasionally quartz rods. A sinistral sense of shear parallel to this lineation is indicated by outcrop-scale shear zone foliation asymmetry, asymmetrically wrapped porphyroclasts and mafic lenses, and the general clockwise obliquity between the protophyllonitic fabrics and the margins of the phyllonite belts (Fig. 4; Butler 1995; Butler *et al.* 1995).

The central parts of the phyllonite belts are intensely foliated and retrogressed, the mainly east- to SE-plunging mineral lineation defined by fibrous chlorite, quartz ribbons and stretched sericite feldspar pseudomorphs (Butler 1995). In fully exposed coastal sections, it is evident that the initially strike-parallel lineations are progressively rotated clockwise into a downdip orientation (see stereonets in Fig. 4) in which mesoscopic, mostly top-to-the-SE (i.e. extensional) shear-sense indicators are preserved. Centimetre- to metre-scale folds that verge downdip to the SE and are interpreted to have formed during extension occur within the phyllonites (Fig. 5b–

d). Within the former and the marginal zones of the phyllonite belts, fold axes are parallel to the earlier strike-parallel lineation associated with sinistral strike-slip movement (see stereonets in Fig. 4). In the central parts of the phyllonite belts which display evidence for extensional shear, the fold axes are at a high angle to the superimposed mineral lineation. Linked systems of mainly east- to SE-dipping brittle normal faults are also common within the phyllonite belts and in many coastal sections are seen to form sharp upper or lower boundaries to belts of phyllosilicate-rich fault rocks (Fig. 5b–d).

Summary

The above structural field studies are representative of the later (post-thrusting) history of the OHFZ as a whole (Table 1). These studies highlight that the phyllonite belts everywhere formed during an early phase of sinistral (top-to-the-NE) strike-slip movement that was followed by localized dextral-extensional (top-to-the-SW or south) to extensional (top-to-the-SE, locally -NW) displacements that localized almost exclusively into the pre-existing phyllonites. Top-to-the-SE movements are seen in all sections and are associated with relatively late brittle detachments. The phyllonitic fault rocks formed during both sinistral strike-slip and dextral to extensional phases share essentially the same mineral assemblage, indicating little to no change in metamorphic grade between these displacement episodes. This, in turn, suggests a rapid transition between the deformation regimes.

Geochronological sample details

Eleven samples were selected for detailed microstructural and geochronological analysis. These are described below from north to south along the strike of the OHFZ between Scalpay and South Uist (Fig. 1b), whilst full systematic petrographic descriptions are available in the [supplementary information](#) (Table S1). In contrast to the braided nature of the phyllonite belts on North Uist, the phyllonites on South Uist form a single north–south trending belt, the Usinish Phyllonite (Fig. 1b; Butler 1995; Osinski *et al.* 2001). This dips shallowly to moderately eastwards and is only 10 m thick at its northernmost exposures but at least 40 m thick at its southernmost exposure on Stuley, although it appears wider (*c.* 200 m) due to a more shallowly dipping foliation orientation here (Fig. 1b; Imber 1998).

JM-21-02 and JM-21-04 (Scalpay)

Samples JM-21-02 and JM-21-04 were collected at a prominent roadside exposure within the Cnoc na Croich phyllonite belt (Fig. 2; NG 2241 9564). The samples are fine-grained quartz + sericite + albite + chlorite phyllonites (Fig. 6a, b). As described above, the SE-dipping foliation contains a mineral lineation that plunges gently (0–10°) to the NE or SW (Fig. 3b). Sections viewed down-dip and broadly parallel to the lineation contain penetrative S-C- and C' shear band fabrics that indicate a sinistral strike-slip sense of displacement (Figs 3a, 6a and b; Butler 1995; Butler *et al.* 1995; Szulc *et al.* 2008).

EM 13, EM 10 (Eigneag Mhor) and SP11, SP12 (Eigneag Bheag) (North Uist)

Sample EM 13 (Fig. 4; NF 9260 6059) is a plagioclase (albite-oligoclase) + quartz + sericite + chlorite (possibly replacing hornblende) + epidote + calcite protophyllonite derived from banded gneiss cross-cut by grey-green crush-mélange-related cataclasite. The cataclasite comprises very fine grained (<50 µm) foliated aggregates of epidote and albite with flattened relict clasts of

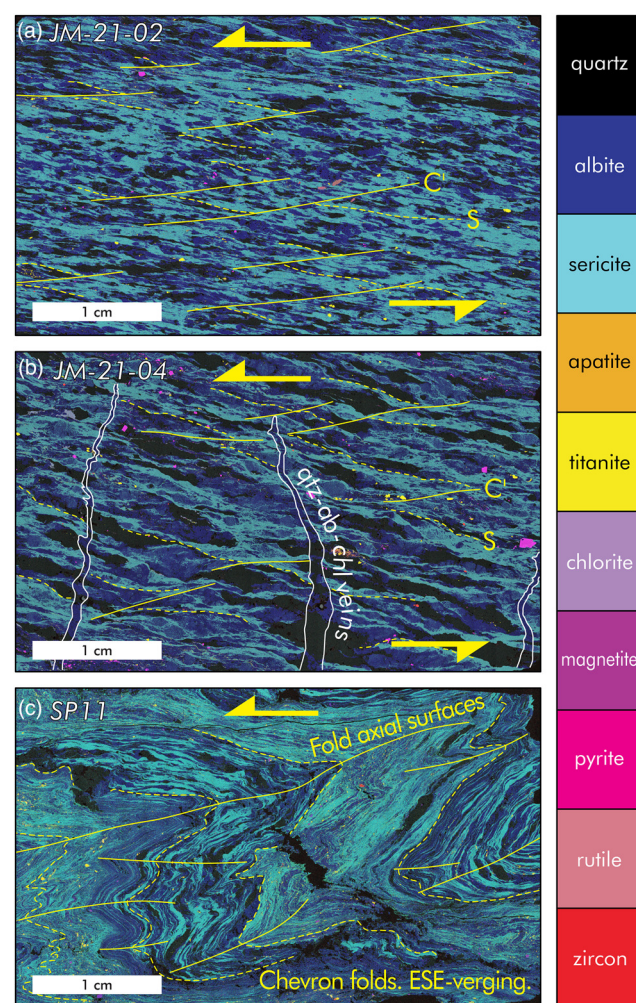


Fig. 6. SEM-EDS elemental maps of thick section samples JM-21-02 (top) and JM-21-04 (middle) from Scalpay, and SP11 (bottom) from Eigneag Bheag. C'-type S-C fabrics in JM-21-02 and JM-21-04 are defined by sericite (white mica) networks wrapping albitized feldspar lenses and porphyroclasts. Quartz–albite–chlorite veinlets cut the shear fabric of JM-21-04. ESE-verging folds in SP11 are defined by interbanded sericite, chlorite and albite.

fractured quartz and sericitized feldspar (>70% of the protolith), which together define the locally NW-dipping protophyllonitic foliation. The foliation is axial planar to folds of the cataclasite seams, vividly illustrating that the protophyllonitic foliation overprints the cataclasite and has formed due to the collapse of the plagioclase load-bearing framework due to sericitization (see also Imber *et al.* 1997, 2001). The lineation here is strike-parallel (055–235°) and mesoscopic (e.g. asymmetric foliations) to microscopic (e.g. bookshelf fractures in quartz domains) shear criteria consistently indicate sinistral senses of displacement (Butler *et al.* 1995; Imber *et al.* 2001).

Sample EM 10 (Fig. 4; NF 9260 6158) comes from the centre of a NW-dipping phyllonite belt dominated by down-dip lineations with extensional top-to-the-NW shear senses including folds. It comprises fine grained aggregates of sericite + quartz + calcite + chlorite which are cross-cut by a series of diffuse top-to-the-NW chlorite-rich shear bands. Relict grains of retrogressed plagioclase and variably recrystallized quartz are wrapped by the foliation whilst occasional pyrite crystals preserve fibrous overgrowths of quartz and chlorite.

Samples SP11 and SP12 are both grey-green phyllonites from the large SE dipping shear zone at Eigneag Bheag (Figs 4, 5c; NF 9210 5980) with variably developed ESE-verging folds on millimetre- to

metre-scales (Fig. 6c). Both samples display strung out layers of fine-grained sericite + chlorite + albite and quartz aggregates (Fig. 6c). The sericite-rich layers show truncations of adjacent aggregates of quartz and feldspar and appear to be sites of preferential dissolution, i.e. pressure solution seams. A large proportion of the protolith feldspar appears to have been recrystallized and/or pervasively sericitized, but isolated porphyroclasts of plagioclase and quartz (<1 mm across) are preserved with fibrous overgrowths of chlorite and quartz. Several show well-developed sigma shapes consistent with top-to-the-ESE shear. In SP12, isolated thin (<1 mm) veinlets of fibrous quartz are reworked by the folds. The folded regions of sericite and chlorite are notably kinked in both samples and regions of localized cataclasis in the hinge zones suggest a brittle–ductile style of folding.

RR7 (Rubha Rossul), JM-21-13, JM-21-14 and JM-21-15 (Rubha Bollum) and STU 1 (Stuley) (Usinish Phyllonite Belt, South Uist)

From north to south, detailed field studies of the Usinish Phyllonite Belt, including both maps and logs have been carried out on the well exposed headlands of Rubha Rossul (NF 858 365), Rubha Bollum (NF 828 284), and on the island of Stuley (NF 830 235) (Fig. 1b; see Butler 1995; Imber 1998).

Sample RR7 comes from the 30 m thick unit of grey-green phyllonite exposed on the north coast of Rubha Rossul (NF 858 365) where it separates the Corodale Gneiss in its footwall to the west from an overlying unit of ‘Mashed Gneiss’ (Butler 1995; Imber 1998). The foliation dips shallowly to the SSE whilst a well-developed mineral lineation plunges shallowly ENE or WSW. Mesoscale folds are locally developed verging ENE and en-echelon quartz veins are present consistent with top-to-the-NE or ENE shear senses. Microfractured porphyroclasts (<1 mm) of plagioclase + epidote + hornblende (largely replaced by fine chlorite and ore) and rarely quartz are set in a fine to very fine (50–100 µm) matrix of sericite + albite + chlorite. Fibrous overgrowths of these matrix phases are common and asymmetrically wrap the porphyroclasts, suggesting sinistral senses of shear. Relict sheared and boudinaged pegmatites are also locally preserved with prominent relict feldspars and epidote, and are consistent with the phyllonite being derived from a Corodale Gneiss protolith (Imber 1998).

Samples JM-21-13, JM-21-14 and JM-21-15 were collected from well exposed coastal sections at Rubha Bollum in South Uist (NF 8302 2843). Here, the NE–ENE trending foliation dips gently to the NW–NNW and contains a strong mineral lineation which plunges gently to the NE–ENE (Imber *et al.* 2001). The phyllonites are fine-grained and comprise a mineral assemblage of albite/oligoclase + quartz + sericite + actinolite + chlorite. Relict, fragmented titanite porphyroclasts sometimes occur and are consistent with these phyllonites being derived from the Corodale Gneiss. In thin sections cut parallel to the lineation, asymmetrically wrapped porphyroclasts (σ -type) indicate a top-to-the NE–ENE sense of shear which might be taken to indicate a dextral strike-slip sense of displacement. However, the gently NW–NNW dipping foliation of these phyllonites is likely to be the result of localized late folding and/or rotation during faulting as the regional sheet dip of the Usinish Phyllonite is to the east. Accordingly, the phyllonitic foliation and lineation are thought to have formed during sinistral shear with a component of extension (see Imber *et al.* 2001).

Sample STU1 (NF 829 231) comes from the island of Stuley where a *c.* 40 m thick unit of flat-lying, platy phyllonite and ultraphyllonite is associated with a predominantly east–west trending mineral lineation (Butler 1995; Imber 1998). Centimetre-scale asymmetric shear bands, mica fish and δ -type quartz and feldspar porphyroclasts (*c.* 1 mm diameter) are consistent with top-

to-the-east extensional shear. STU1 is thought to be derived from the Corodale Gneiss and is composed of very fine grained (<50 µm) polycrystalline albite + quartz + epidote. Both sericite and chlorite are relatively uncommon, the latter sometimes occurring in place of retrogressed hornblende. Recrystallized and locally folded porphyroclasts of quartz are relatively common, whilst dark epidote-rich layers may represent relict cataclasites or pseudotachylytes.

Methods

Microscale characterization

The samples described above were chosen for further compositional and textural characterization and for the identification of apatite and white mica grains using scanning electron microscopy (SEM) techniques. Analyses were performed by a Zeiss EVO MA 10 LaB₆ SEM at the University of Portsmouth. Prior to imaging, samples were carbon-coated to minimize charging effects. An Oxford Instruments X-max 80 mm² EDS detector was used to produce whole-section elemental maps from which apatite and white mica grains were located. The EDS analyses were collected at a working distance of 14.5 mm. High-lateral resolution BSE imaging was subsequently undertaken to investigate the micro-textures and mineral phase relationships, using an accelerating voltage of 20 kV and a probe current of 400 or 500 pA.

In situ mica Rb–Sr geochronology

White mica fabrics from three phyllonite samples were analysed *in situ* on polished thin sections for Rb–Sr isotopes at the GeoHistory Facility (John de Laeter Centre, Curtin University). The analytical setup included an ASI RESOLUTION 193 nm ArF excimer laser coupled to an Agilent 8900 ICP-MS triple quadrupole mass spectrometer using N₂O as reaction gas in the collision cell to enable measurement of Rb and Sr isotopes (Cheng *et al.* 2008; Zack and Hogmalm 2016; Hogmalm *et al.* 2017). The analyses were carried out with a circular laser beam diameter of 64 µm, 7 Hz repetition rate and a laser fluence of *c.* 2.5 J cm^{−2} measured above the cell. The cell was flushed with ultra-high purity He (320 ml min^{−1}), and N₂ (4 ml min^{−1}) to enhance sensitivity in the mass spectrometer (Hu *et al.* 2008). Individual analysis consisted of 30 s baseline acquisition followed by 30 s ablation/data acquisition and 10 s fast wash-out.

Data reduction was performed using Iolite 4 (Paton *et al.* 2011) using an in-house data reduction scheme adapted from Redaa *et al.* (2021). The ⁸⁷Sr/⁸⁶Sr and ⁸⁷Rb/⁸⁶Sr ratios were drift-corrected and calibrated against NIST SRM 610 (⁸⁷Sr/⁸⁶Sr = 0.709699 ± 0.000018, ⁸⁷Rb/⁸⁶Sr = 2.389 ± 0.005; Woodhead and Hergt 2001). Unknowns were bracketed with LaPosta and Mount Dromedary biotite (Rösel and Zack 2022), with the latter being used as a matrix-matching reference material to account for matrix effects using the isochronous approach (cf., Giuliani *et al.* 2024). The matrix-corrected LaPosta yield a combined isochron age across two analytical sessions of 93.1 ± 1.8 Ma (MSWD = 0.7, *n* = 44), overlapping with the expected age (Rösel and Zack 2022). Isochrons, ages and respective uncertainties were calculated using IsoplotR (Vermeesch 2018), and presented at 2-standard error level of confidence. The external uncertainties of the secondary reference materials were propagated following the approach of Rösel and Zack (2022).

In situ apatite U–Pb geochronology

In-situ U–Pb isotopic analyses were performed using an ASI RESOLUTION 193 nm ArF excimer laser coupled to an Agilent 8900 ICP-MS triple quadrupole at the University of Portsmouth. The laser was operated at a fluence of 3.5 J cm^{−2}, a frequency of 3 Hz

and a spot size of 24 μm throughout all analytical runs. For U–Th–Pb geochronology, ^{204}Pb , ^{206}Pb , ^{207}Pb , ^{208}Pb , ^{232}Th , ^{235}U , and ^{238}U were measured. ^{202}Hg was also measured to correct for ^{204}Pb – ^{204}Hg mass interference. MAD apatite (weighted average $^{206}\text{Pb}/^{238}\text{U}$ age of 474.2 ± 0.4 Ma, Thomson *et al.* 2012) was used as the primary reference material to correct for mass bias, instrument drift, and laser-induced elemental fractionation. McClure Mountain (weighted mean $^{207}\text{Pb}/^{235}\text{U}$ age of 523.51 ± 1.47 Ma, Schoene and Bowring 2006), Durango ($^{40}\text{Ar}/^{39}\text{Ar}$ age of 31.44 ± 0.18 Ma, McDowell *et al.* 2005) and Xuxa apatites (573 ± 0.8 Ma, Schuch 2018) were used as secondary reference materials. Discordia lower-intercept ages on Tera–Wasserburg plots obtained for the McClure and Xuxa secondary reference materials are within uncertainty of their respective reference ages, whilst Durango is apparently younger than its $^{40}\text{Ar}/^{39}\text{Ar}$ age (McClure: 524.9 ± 5.1 Ma; (2σ , $n = 38$, MSWD = 1.8, anchored to $^{207}\text{Pb}/^{206}\text{Pb}$ of 0.874 ± 0.010 , Krestianinov *et al.* 2021); Durango: 27.80 ± 0.80 Ma (2σ , $n = 22$, MSWD = 1.5, anchored to $^{207}\text{Pb}/^{206}\text{Pb}$ of 0.838 ± 0.012 , Paul *et al.* 2021); Xuxa: 580 ± 18 (2σ , $n = 38$, MSWD = 2.9)). U–Pb data reduction was performed using the ‘VisualAge_UcompBine’ data reduction scheme in Iolite 4 (Paton *et al.* 2011; Chew *et al.* 2014), applying a curve fit to correct for downhole U–Pb fractionation, and a ^{207}Pb based common-Pb correction scheme to the primary reference material (MAD apatite). Presented errors on ratios and ages include internal and external sources of uncertainty. $^{238}\text{U}/^{206}\text{Pb}$ and $^{207}\text{Pb}/^{206}\text{Pb}$ isotopic ratios are uncorrected for common-Pb and plotted on Tera–Wasserburg concordia diagrams using IsoplotR (Vermeesch 2018).

Results

Micro-textural analysis of white mica and apatite

White mica

The abundance and variety of phyllosilicates within the phyllonite belts varies greatly along strike of the OHFZ. At Rubha Bollum and Rubha Rossul on South Uist, the phyllonites were likely derived from the mafic Corodale Gneiss (Fig. 1b) and hence are often dominated by chlorite, actinolite and epidote group phases rather than white mica. Where present, white mica is mostly aggregated with chlorite and sometimes epidote along thinly laminated bands or as pseudomorphs of retrogressed amphibole. In contrast, the phyllonite precursors on North Uist and Scalpay are mainly quartzofeldspathic thrust-related cataclases and mylonites, respectively. Complete sericitization of abundant K-bearing phases (orthoclase, microcline) within the phyllonite protoliths on North Uist and Scalpay has allowed white mica to develop during fluid-assisted neocrystallization, to form shear-parallel, very-fine (<50 μm) grained laths. In the strike-slip-related samples JM-21-02 and JM-21-04, the network of white mica shear bands anastomoses between discontinuous quartz ribbons and wrap albite and apatite porphyroclasts (Fig. 7a–c). Occasionally, the mica aggregates develop c'-type shear fabrics consistent with a sinistral shear sense (Fig. 6a, b). In sample SP11 from Eigneag Bheag on North Uist, the extension-related ESE-verging folds are also apparent in thin section at the μm -scale. The folds are defined by continuous laminations of white mica laths and cogenetic chlorite, which interlayer flattened ribbons of partially recrystallized quartz and albite (Figs 6c and 7d–g). Between their laminations, the white mica needles bend sigmoidally to form c'-type shear fabrics axial planar to the ESE-verging folds (Fig. 7e, f). Pre-kinematic phases such as apatite are commonly wrapped and sometimes crosscut by the white mica–chlorite aggregates (Fig. 7e–g), demonstrating clearly that the white mica grew during the main phases of strike-slip and/or extensional shearing.

Apatite

Apatite grains show marked differences in their crystal shape and internal structure both between different phyllonite domains along the OHFZ and within samples. Within the sinistral strike-slip phyllonites on Scalpay, monocrystalline grains prevail, showing characteristic equant to tabular form up to 500 μm in diameter (Fig. 7a–c). Such apatites are preferentially aligned within the shear fabric and sometimes display quartz–albite strain shadows. White mica laths occasionally latch onto these coarser apatites to form δ - or σ -type shear tails, indicating that the apatites have been rotated to some degree during sinistral shearing (Fig. 7a–c). Internally, the coarser apatites are invariably fractured but appear to lack internal strain under BSE-SEM imaging. Structurally complex grains with irregular forms are less common, but where present tend to be associated with trails of very fine (<50 μm) apatite and titanite strongly aligned within the shear fabric. Mosaic fracture patterns in some of the apatites may represent sub-granular triple junctions or more likely brecciation.

On North Uist, the extension-related phyllonites from Eigneag Bheag (SP11 and SP12) mostly host trails of interspersed coarse apatites (up to 500 μm), which are aligned and oriented parallel to the top-to-the-ESE extension-related fold axial surfaces. Such apatites often occur in groups of two or three grains and appear to have been pulled apart (Fig. 7d). Recrystallized albite commonly occupies the intervening spaces, sometimes forming top-to-the-ESE, δ -type shear tails bound by white mica bands (Fig. 7e). Internally, apatites from SP11 and SP12 resemble those from Scalpay. Most are lacking internal strain, but occasionally exhibit dissolved rims and chlorite-infilled fracture patterns (Fig. 7f, g). A lesser population has a polycrystalline or brecciated appearance. The cataclastic or sometimes resorbed form of these apatites suggest they have been dissolved and crushed during shearing. At Eigneag Mhor (EM10 and EM13), apatite is less frequent and occurs predominantly as dispersed fine-grained (<100 μm) clusters. Coarser-grained (100–300 μm) apatites show examples of chlorite-infilled pull-apart shears, brecciation, and dissolution or alteration (Fig. 7h).

The phyllonites from South Uist host strongly shear-aligned apatites which comprise stretched out and broken-up ribbons aggregated with chlorite, epidote, and white mica (Fig. 7i). At Rubha Bollum (JM-21-13, -14 and -15), apatite shows signs of retrogression often through epidote coronae rimmed by very fine ilmenite (<50 μm) (Fig. 7j–m). The epidote/ilmenite rims assist in reconstructing the original form of the apatites, showing that apatite has been significantly resorbed and replaced by chlorite and quartz (e.g. Fig. 7k). Networks of phyllosilicates criss-cross the ribboned apatite trails, probably utilizing pre-existing fracture patterns (Fig. 7i). Internally, many grains are intensely fractured and brecciated, generally more so towards grain rims, giving the appearance that the apatites have been crushed during shear-induced flattening (Fig. 7k–m). On Stuley Island (STU1) and Rubha Rossul (RR7), metasomatized apatites have sometimes irregular grain edges, resulting in very fine (<10 μm) residual apatite, epidote, and titanite forming elongate trails or clusters (Fig. 7n). At Rubha Rossul (RR7), coarser (up to 250 μm) rounded grains also occur and are frequently mantled by σ -type chlorite tails consistent with a sinistral (top-to-the-NE) shear sense (Fig. 7n). Many have also been torn apart along fractures oriented normal to the shear fabric, with shear-oriented chlorite laths infilling the cracks (Fig. 7o). Such features are also common within albitized feldspar and titanite porphyroclasts.

Summary

The contrast in textural characteristics of white mica and apatite outlined above indicate that they represent syn-kinematic neoblasts and pre-kinematic porphyroclasts, respectively. Shear-parallel white

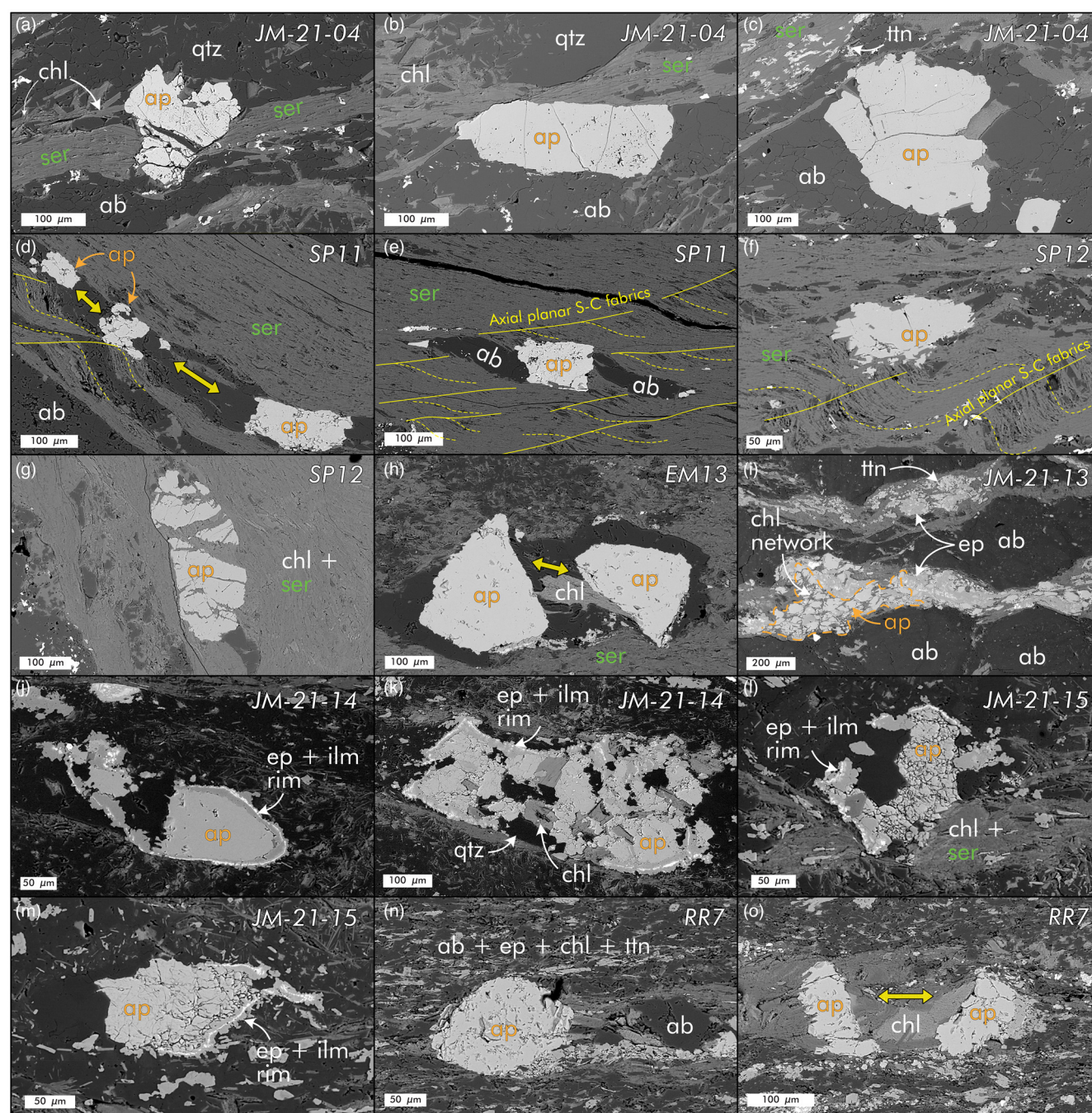


Fig. 7. SEM-BSE images of apatite and white mica microstructures. (a–c) coarse (250–500 μm), igneous-like apatite wrapped by tails of sericite laths. Shear sense is top-to-the-left (JM-21-04). (d–g) well-foliated bands of sericite (white mica) and chlorite laths wrapping partially dissolved, cataclastic and pulled-apart apatite porphyroclasts. Sericite bands often exhibit c'-type S-C fabrics which are axial planar to the extensional folds and have clearly grown during deformation. Shear sense is top-to-the-left (SP11, SP12). (h) igneous-like apatite which has been pulled-apart and since infilled by new fibrous chlorite. Shear sense is top-to-the-right (EM13). (i) elongate trail of strung-out apatite–epidote–chlorite aggregates. Relic apatite has been replaced by epidote and new very fine titanite (<50 μm) towards the outer zone, and internally by a braided chloritic network. Shear sense is top-to-the-left (JM-21-13). (j–m) Partially dissolved and/or brecciated apatite replaced by quartz and chlorite, and very-thin rims of epidote and ilmenite. Shear sense is top-to-the-left (JM-21-14, JM-21-15). (n) Rounded apatite porphyroclast surrounded by a matrix of very fine (<50 μm) albite, epidote, chlorite and titanite. Shear sense is top-to-the-right (RR7). (o) Partially dissolved/cataclastic apatite which has been pulled apart during shearing and since infilled by new fibrous chlorite. Shear sense is top-to-the-right. (RR7). Abbreviations: ab, albite; ap, apatite; chl, chlorite; ep, epidote; ilm, ilmenite; qtz, quartz; ser, sericite; ttn, titanite.

mica laths wrap relict phases (e.g. feldspar, apatite, titanite) from the gneissic protolith and have grown at the expense of feldspar during strike-slip and extensional shear. In contrast, the variably dissolved and cataclastic nature of apatite grains shows that these grains were likely inherited from the previous stable parageneses belonging to the 'mashed' gneisses affected by brittle thrusting or the greenschist-facies mylonites formed during early ductile thrusting. The bimodal *Type-1* and *Type-2* varieties described for the early thrust-

related mylonites (Metcalfe *et al.* 2024) can plausibly explain the heterogeneity in apatite microtextures within the phyllonites. Potentially, the mechanically weaker, recrystallized *Type-2* varieties were more prone to brittle deformation and dissolution along grain rims and sub-grain boundaries during phyllonitization, whilst the idiomorphic and structurally preserved *Type-1* apatite remained largely intact. Rb–Sr and U–Pb geochronology was carried out to test the results of our microtextural analysis.

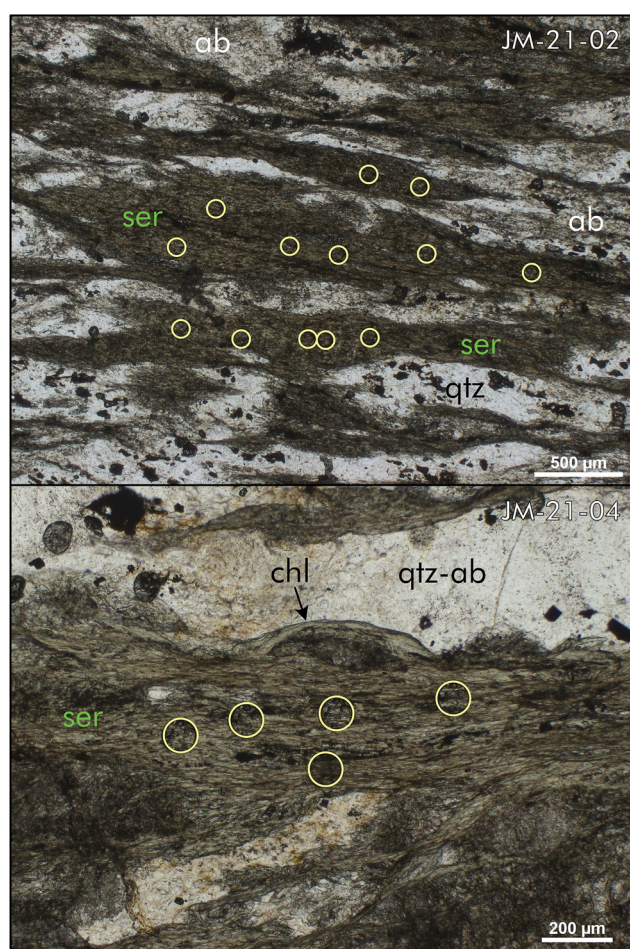


Fig. 8. Plane-polarized light photomicrographs of JM-21-02 (top) and JM-21-04 (bottom). Yellow circles indicate 64 μm analytical spots across clusters of intergrown white mica domains. All samples were cut parallel to the mineral lineation and indicate a sinistral sense of shear. Mineral abbreviations: ab, albite; chl, chlorite; ser, sericite; qtz, quartz.

***In situ* white-mica Rb–Sr geochronology: results and interpretation**

White-mica fabrics were dated from two phyllonite samples from Scalpay (see analytical spot positions in Fig. 8), and one from Eigneag Bheag. Samples JM-21-02 and JM-21-04 from Scalpay yield isochron ages of 407.6 ± 2.5 Ma ($n = 64$, MSWD = 0.4) and 395.9 ± 2.7 Ma ($n = 59$, MSWD = 0.7) with initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of 0.7179 ± 0.0024 and 0.7165 ± 0.0026 , respectively (Fig. 9a, b).

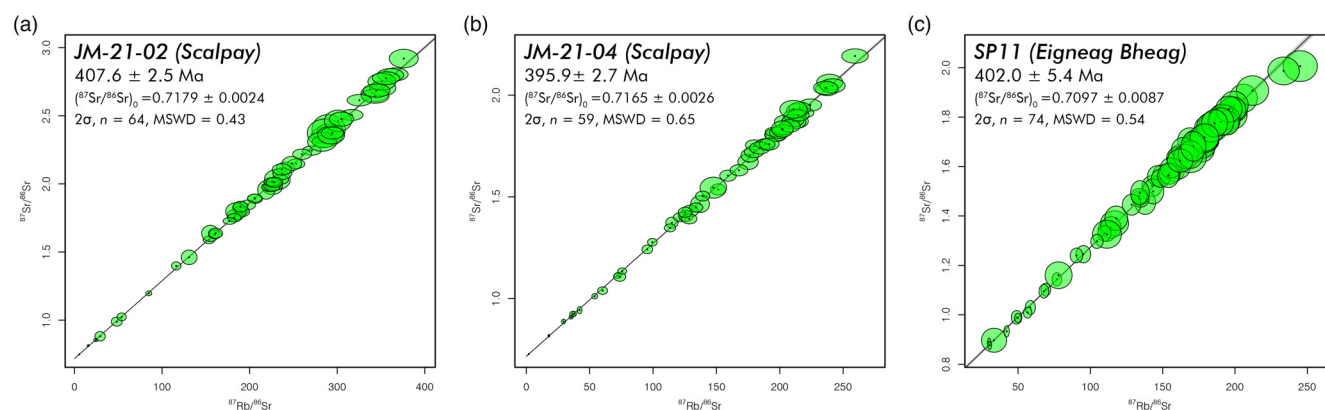


Fig. 9. Rb–Sr white mica isochrons for samples (a) JM-21-02 (Scalpay – strike-slip), (b) JM-21-04 (Scalpay – strike-slip), (c) SP11 (Eigneag Bheag – down-dip).

White-mica fabrics from sample SP11 (Eigneag Bheag) yield an isochron age of 402.0 ± 5.4 Ma ($n = 74$, MSWD = 0.5) with an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7097 ± 0.0087 , similar to the Scalpay samples (Fig. 9c). Because the white mica in all samples formed at temperatures significantly lower ($150\text{--}370^\circ\text{C}$; Szulc *et al.* 2008) than the probable closure temperature for Rb–Sr in fine-grained white mica ($400\text{--}500^\circ\text{C}$; Ribeiro *et al.* 2023a, b), we interpret these ages as closely dating recrystallization during deformation rather than cooling.

Apatite U–Pb geochronology: results and interpretation

Scalpay (JM-21-02 and JM-21-04)

Thirty spot analyses targeted across 22 separate apatite grains were undertaken for JM-21-02, with six analyses discarded due to ablation across cracked or inclusion-rich domains. JM-21-02 produces a discordia lower-intercept age of 949 ± 62 Ma (2σ , $n = 24$, MSWD = 1.1) with a Y-axis intersection implying a $^{207}\text{Pb}/^{206}\text{Pb}$ isotopic ratio of 1.058 ± 0.023 (Fig. 10a). For JM-21-04, twenty-five analyses were performed across sixteen separate apatites, producing a slightly older discordia lower-intercept age of 996 ± 32 Ma (2σ , $n = 17$, MSWD = 1.2) with an ordinate intercept indicating a $^{207}\text{Pb}/^{206}\text{Pb}$ isotopic ratio of 1.035 ± 0.018 (Fig. 10b). Seven of the eight analyses excluded from the isochron regression have low U content ($^{238}\text{U}/^{206}\text{Pb} < 0.1$), with the remaining analysis discarded due to ablation across an inclusion-rich domain.

Rubha Bollum (JM-21-13, JM-21-14, JM-21-15)

Apatite from JM-21-13 yielded consistently low U concentrations between 0 and 0.54 ppm, likely a result of extensive fluid-related alteration during phyllonitization as indicated by typical epidote coronae. Twelve out of thirty spot analyses returned $^{238}\text{U}/^{206}\text{Pb} < 0.1$ and have been excluded from isochron regression calculations. The remaining eighteen analyses were obtained from 12 apatite grains and yield a poorly constrained discordia lower-intercept age of 988 ± 771 Ma (2σ , $n = 18$, MSWD = 1.8) and an upper intercept $^{207}\text{Pb}/^{206}\text{Pb}$ isotopic ratio of 1.026 ± 0.040 (Fig. 10c). Despite the very large uncertainty, this age is consistent with samples JM-21-14 and JM-21-15 and therefore may be geologically meaningful. Thirty spot analyses targeted across 22 apatites were conducted for JM-21-14. Excluding two analyses which have erratic $^{238}\text{U}/^{206}\text{Pb}$ and $^{207}\text{Pb}/^{206}\text{Pb}$ values, JM-21-14 returns a discordia lower-intercept age of 988 ± 40 Ma (2σ , $n = 28$, MSWD = 1.1) and an upper intercept $^{207}\text{Pb}/^{206}\text{Pb}$ isotopic ratio of 1.039 ± 0.013 (Fig. 10d). Thirty spot analyses were performed each across separate apatite grains for JM-21-15. Discarding two analyses

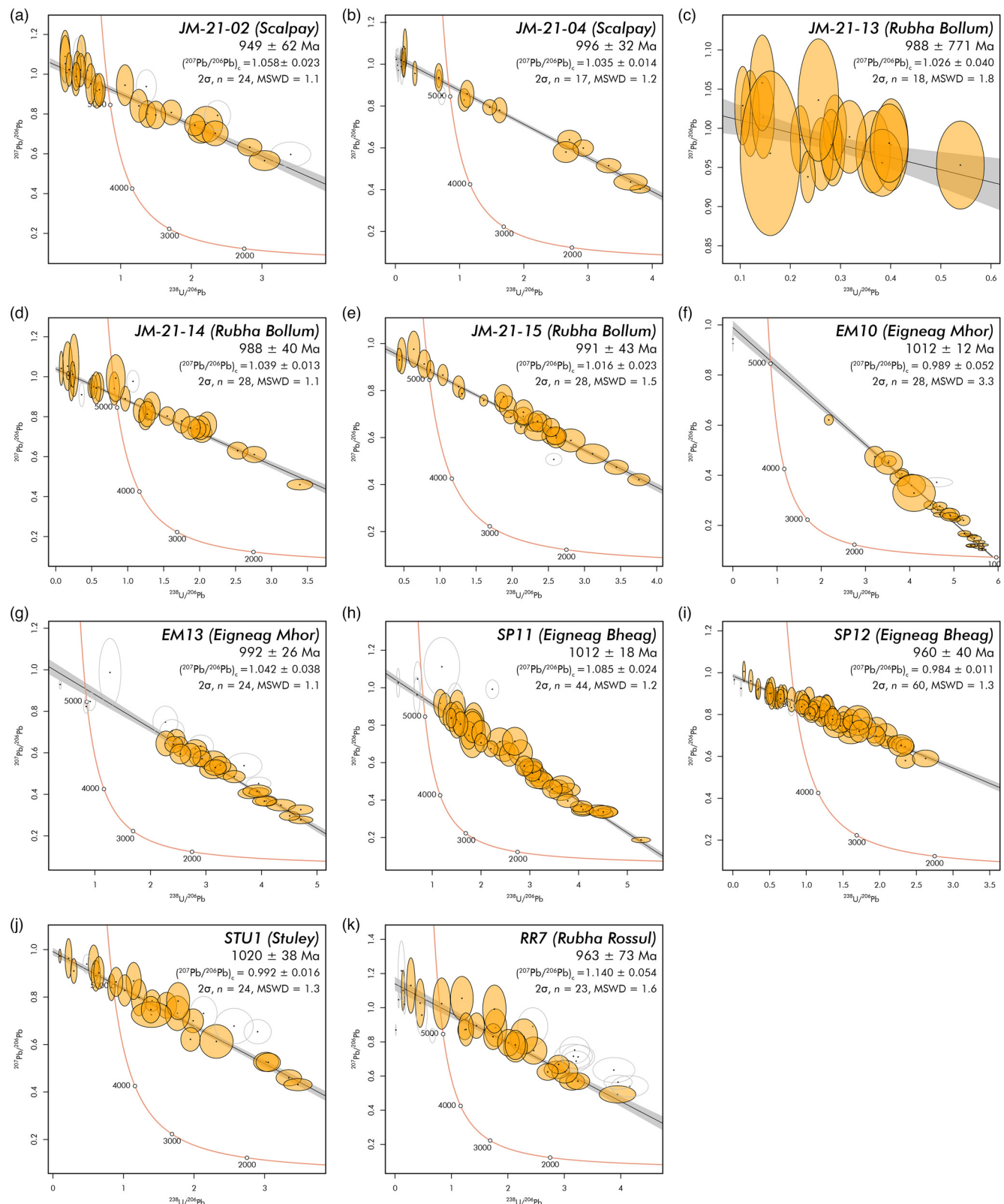


Fig. 10. U–Pb apatite Tera–Wasserburg plots for samples (a) JM-21-02 (Scalpay; strike-slip), (b) JM-21-04 (Scalpay; strike-slip), (c) JM-21-13 (Rubha Bollum; downdip), (d) JM-21-14 (Rubha Bollum; downdip), (e) JM-21-15 (Rubha Bollum; strike-slip), (f) EM10 (Eigneag Mhor; downdip), (g) EM13 (Eigneag Mhor; strike-slip), (h) SP11 (Eigneag Bheag; downdip), (i) SP12 (Eigneag Bheag; downdip), (j) STU1 (Stuley; downdip), (k) RR7 (Rubha Rossul; strike-slip). Greyed out (unfilled) ellipses refer to analyses excluded from the discordia intercept age calculation.

because of extremely low U content (<0.01 ppm) or skewed U–Pb ratios, JM-21-15 produces a near indistinguishable discordia lower-intercept age of 991 ± 43 Ma ($2\sigma, n = 28$, MSWD = 1.5) and an upper intercept $^{207}\text{Pb}/^{206}\text{Pb}$ isotopic ratio of 1.016 ± 0.023 (Fig. 10e).

Eigneag Mhor (EM10 and EM13)

Thirty-one analyses targeted across 26 apatite grains were obtained for EM10. With the exception of two analyses which yielded no U content, the data display a wide spread of U/Pb isotopic ratios in Tera–

Wasserburg space, resulting in a well-constrained discordia lower-intercept age of 1012 ± 12 Ma (2σ , $n = 28$, MSWD = 3.3) and an upper intercept $^{207}\text{Pb}/^{206}\text{Pb}$ isotopic ratio of 0.989 ± 0.052 (Fig. 10f). Thirty-three analyses across 14 apatites were undertaken for EM13. Rejecting nine analyses due to spot positioning over grain boundaries or ablation of inclusion-rich domains, EM13 yields a discordia lower-intercept age of 992 ± 26 Ma (2σ , $n = 24$, MSWD = 1.1) and an upper intercept $^{207}\text{Pb}/^{206}\text{Pb}$ isotopic ratio of 1.042 ± 0.038 (Fig. 10g).

Eigneag Bheag (SP11 and SP12)

Fifty spot analyses targeted across 31 apatite grains were obtained for SP11, with six rejected either due to low U (<0.1 ppm) or skewed $^{238}\text{U}/^{206}\text{Pb}$ and $^{207}\text{Pb}/^{206}\text{Pb}$ values. The remaining data from SP11 form a very well defined isochron regression with a discordia lower-intercept age of 1012 ± 18 Ma (2σ , $n = 44$, MSWD = 1.2) and an upper intercept $^{207}\text{Pb}/^{206}\text{Pb}$ isotopic ratio of 1.085 ± 0.024 (Fig. 10h). Sixty-six analyses were undertaken for SP12 and targeted across 40 apatite grains. Three analyses with $^{238}\text{U}/^{206}\text{Pb}$ of <0.1 and three analyses ablated across a grain boundary were rejected from age calculations. The remaining data from SP12 are generally skewed towards common-Pb compositions but show sufficient spread to produce a discordia lower-intercept age 960 ± 40 Ma (2σ , $n = 60$, MSWD = 1.3) and an upper intercept $^{207}\text{Pb}/^{206}\text{Pb}$ isotopic ratio of 0.984 ± 0.011 (Fig. 10i).

Stuley (STU1)

Twenty-nine spot analyses targeted across 18 apatite grains were obtained for STU1. Four analyses were rejected from age calculations due to ablations crossing-over grain boundaries or sampling of inclusion-rich domains. STU1 forms a well spread isochron regression with a discordia lower-intercept age of 1020 ± 38 Ma (2σ , $n = 24$, MSWD = 1.3) and an upper intercept $^{207}\text{Pb}/^{206}\text{Pb}$ isotopic ratio of 0.992 ± 0.016 (Fig. 10j).

Rubha Rossul (RR7)

Thirty-seven spot analyses targeted across 28 apatite grains were obtained for RR7. Fourteen analyses were rejected from age calculations either due to cross ablation within inclusion-rich domains, low $^{238}\text{U}/^{206}\text{Pb}$ (<0.1) or skewed U/Pb ratios which lay off discordia. The remaining data form a poorly constrained discordia lower-intercept age of 963 ± 73 Ma (2σ , $n = 23$, MSWD = 1.6) and an upper intercept $^{207}\text{Pb}/^{206}\text{Pb}$ isotopic ratio of 1.140 ± 0.054 (Fig. 10k).

The U–Pb apatite ages range between *c.* 1020 and 950 Ma and are significantly older than the timing of deformation within the phyllonites as determined by the Rb–Sr white mica ages. We therefore interpret the U–Pb ages as representing the timing of recrystallization or isotopic resetting of porphyroclastic apatite inherited from the gneissic protolith of the phyllonites. Furthermore, the elevated initial $^{207}\text{Pb}/^{206}\text{Pb}$ ratios of 0.99–1.14 implied by the apatite regressions corresponds to Pb evolution in a broadly Paleoproterozoic to Archean crust under the Stacey and Kramers (1975) model and overlap the 3100–1650 Ma protolith and metamorphic history of the Lewisian Gneiss Complex (Corfu *et al.* 1994; Friend and Kinny 1995, 2001; Whitehouse *et al.* 1996; Kinny and Friend 1997; Zhu *et al.* 1997; Love *et al.* 2004; Mason and Brewer 2004; Mason *et al.* 2004; Mason 2012, 2016; Crowley *et al.* 2015).

Discussion

The importance of microstructural characterization of mineral phases before isotopic analysis

The geochronological results from the phyllonites confirm the results of our microtextural analysis which interpreted white mica to

have crystallized syn-kinematically during strike-slip and extensional deformation (Fig. 7), whereas apatite grains appear to be porphyroclasts and therefore older. The white mica ages spanning 408–396 Ma indicate that phyllonitization occurred during the early Devonian, later than the main (Ordovician and Silurian) contractional stages of the Caledonian orogeny in NW Scotland. In contrast, the apatite ages ranging between *c.* 1020 and 950 Ma overlap with those attributed to Grenville thrusting in the Northern Segment of the OHFZ (Metcalfe *et al.* 2024).

Our study shows that the microstructural characterization of mineral phases prior to isotopic dating is pivotal in the study of low-temperature deformation fabrics such as those recorded in phyllonites. The metamorphic conditions in which phyllonites develop are often below the closure temperature (in the sense of Dodson 1973) for most conventional U–Pb chronometers, posing limitations in determining the timing of low-temperature deformation. Although most phyllonites might retrogress to chlorite-bearing mineral assemblages, some might preserve white mica textures that can yield robust and reliable Rb–Sr isochron dates. This approach not only expands the chronological toolbox for dating low-temperature deformation with textural context but also enhances the tectonic understanding of complex deformed terranes.

Regional tectonic significance of the early Devonian Rb–Sr white mica ages

The ages of 407.6 ± 2.5 and 395.9 ± 2.7 Ma obtained from sinistral strike-slip related phyllonites on Scalpay lie outside of analytical uncertainty despite having been collected within a few metres of each other (Figs 2 and 9a, b). Whether this reflects two episodes of strike-slip deformation or fluid-related alteration that resulted in the younger of the two ages is uncertain. The age of 402.0 ± 5.4 Ma obtained from extension-related phyllonites at Eigneag Bheag (Fig. 9c) overlaps both white mica ages obtained from the Scalpay sinistral shear belt. The similar ages, mineralogy and metamorphic grade of the sinistral strike-slip and extensional phyllonites are consistent with broadly contemporaneous development. This in turn implies an overall sinistral transtensional deformation regime. In the absence of any evidence for early Devonian deformation elsewhere in the Outer Hebrides, the possible wider significance of the phyllonite belts can only be assessed by comparison with potentially related geological structures from the Scottish mainland. We draw attention to the overlap in timing between early Devonian phyllonitization in the Outer Hebrides and the development of ‘Old Red Sandstone’ (ORS) sedimentary basins from *c.* 400 Ma onwards in NE mainland Scotland (Orcadian basin) and in the Grampian terrane east of the Great Glen Fault Zone (e.g. Moray Firth basin) (Marshall 2024 and references therein). Dewey and Strachan (2003) invoked a transition during the early Devonian from sinistrally oblique end-Caledonian collision to sinistral transtension to explain the development of these basins (Fig. 11).

The Great Glen Fault Zone (GGFZ; Fig. 11) in Scotland is a key component of the regional Devonian sinistrally transtensive network of faults and shear zones (Wilson *et al.* 2010; Dichiarante *et al.* 2020; Utley *et al.* 2023). Early (425–410 Ma) sinistral displacement at the end of Caledonian convergence was coeval with pluton emplacement along and either side of the GGFZ and its extension in Ireland, the Leannan Fault (e.g. Hutton and McErlean 1991; Rogers and Dunning 1991; Jacques and Reavy 1994; Stewart *et al.* 2001; Dewey and Strachan 2003; Kirkland *et al.* 2008; Holdsworth *et al.* 2015). Later sinistral displacement is constrained at *c.* 400 Ma on the basis of U–Pb isotopic and microstructural data from syn-kinematic granites and their reworked host rocks within the Rosemarkie basement inlier in the NE of the GGFZ (Fig. 11; Mendum and Noble 2010; Law *et al.* 2025). Early Devonian phyllonitization in the Outer Hebrides thus overlaps with

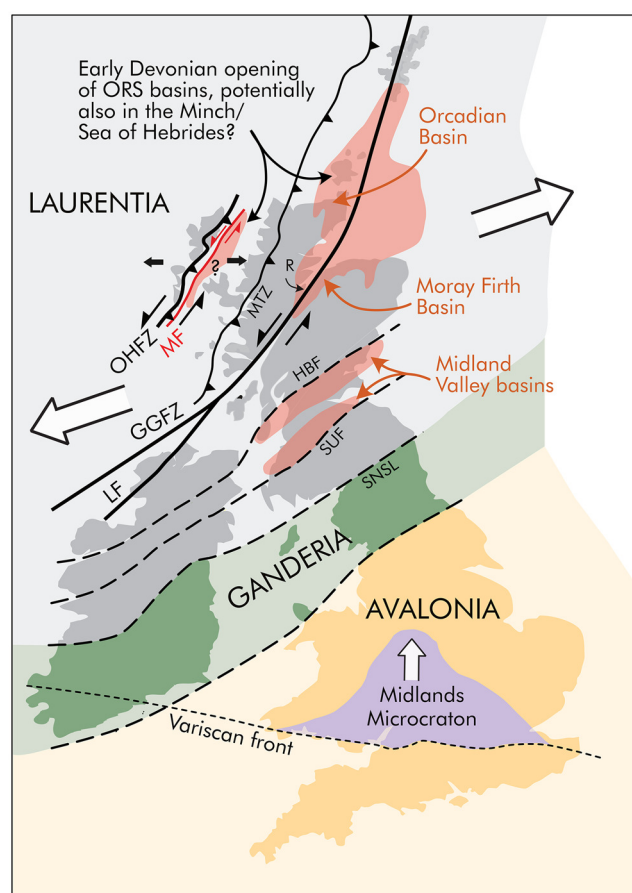


Fig. 11. Cartoon reconstruction model for regional tectonics in Britain and Ireland during the early Devonian (c. 400 Ma). In Scotland, north of the Southern Uplands Fault (SUF), the dominant tectonic regime is sinistral transtension (large white arrows), associated with the development of the Orcadian, Moray Firth and Midland Valley ‘Old Red Sandstone’ basins, coeval with displacement along the Great Glen Fault Zone (see text for discussion). In the Outer Hebrides, the OHFZ is reactivated by top-to-the-NE sinistral strike-slip and top-to-the-east extensional displacements. The Devonian basin to the east of the Minch Fault (MF, red line) is speculative as indicated by the question mark. To the south, the dominant tectonic regime across Ganderia and Avalonia is sinistral transpression associated with the northern impingement of the Midlands Microcraton (Soper *et al.* 1987). Abbreviations: GGF, Great Glen Fault; HBF, Highland Boundary Fault; LF, Leannan Fault; MF, Minch Fault; MTZ, Moine Thrust Zone; OHFZ, Outer Hebrides Fault Zone; ORS, Old Red Sandstone; R, Rosemarkie basement inlier; SNSL, Solway-Navan-Silvermines line; SUF, Southern Uplands Fault.

the timing of the youngest phase of sinistral strike-slip faulting identified along the GGFZ. We note that (Piper 1992) and Lisle (1993) suggested that the Minch Fault east of the Outer Hebrides (Fig. 11) may have originated as a sinistral strike-slip fault with an estimated displacement of 84–95 km, and an early Devonian age now seems likely given the isotopic data reported in the present study. Early Devonian sinistral strike-slip faulting and transtensional basin development in Scotland overlapped Acadian deformation in England, Wales and southern Scotland that resulted from the accretion of Avalonia (Fig. 11; Waldron *et al.* 2025) but we see no evidence of kinematic linkage between the two deformation regimes.

There are no known Devonian sedimentary rocks exposed onshore in the Outer Hebrides, although Stein (1988) suggested that they may be present offshore within the Minch Basin. The clear association in the Orcadian and Moray Firth basins between their transtensional development and sinistral shear along the GGFZ

lends some weight to this suggestion given the early Devonian age that we have demonstrated for sinistral strike-slip and extension related phyllonites in the Outer Hebrides (Fig. 11). Within the MINCH-1 BP exploration well midway between the northern Outer Hebrides and the Scottish mainland, sub-Triassic strata comprised undated purple-grey sandstones, siltstones and mudstones that were attributed to the Proterozoic ‘Torridonian’ (Fig. 1a; Fyfe *et al.* 2021). However, in the absence of any direct constraints on their age the possibility exists that these sedimentary rocks could be part of a Devonian basin.

Evidence for Grenville ductile thrusting along the Southern Segment of the OHFZ

Prior to this study, evidence that the OHFZ was initiated during the Grenville orogeny has only been forthcoming from the Northern Segment (Metcalfe *et al.* 2024). Petrological study of samples obtained from footwall orthogneisses, and the thrust-related mylonite belt established two texturally different types of apatite grains that can also be differentiated using geochemical and isotopic criteria. Type-1 apatite is most abundant within the footwall orthogneisses and shows no signs of recrystallization or plastic deformation. Type-2 apatite is best developed within the mylonite belt and displays textures indicating plastic deformation, sub-grain rotation, and/or fluid-assisted recrystallization (Metcalfe *et al.* 2024). Type-1 grains produce variably older U–Pb ages than Type-2 grains, although remain within uncertainty. The Type-1 grains are interpreted as relicts of the gneissic protolith, preserved as porphyroclasts that were thermally reset during initial overthrusting at 1100–1000 Ma. Type-1 grains were variably preserved as strain intensified to develop the mylonite belt within which syn-kinematic recrystallization of Type-2 apatite occurred between c. 1030 Ma and possibly as young as c. 900 Ma (Metcalfe *et al.* 2024).

In the Southern Segment of the OHFZ there is extensive evidence for top-to-the-NW brittle thrusting (Table 1) but only very local field evidence for ductile thrusting (e.g. Butler 1995; MacInnes *et al.* 2000; Osinski *et al.* 2001). Cliff and Rex (1989) demonstrated a transition in Rb–Sr biotite ages across the dextrally oblique Langavat Shear Zone in South Harris (LaSZ, Fig. 1b). Contrasting age groupings of >1300 and c. 1100 Ma were obtained from, respectively, orthogneisses to the south and north of the LaSZ. Cliff and Rex (1989) attributed this age distribution to cooling following kilometre-scale north-side-up movement across the LaSZ at c. 1100 Ma during the Grenville orogeny. In this context, the Northern and Southern segments might therefore represent different crustal levels, potentially accounting for the lack of extensive mylonites in the latter. Imber *et al.* (2002) explored two further solutions to explain the distribution of mylonites. First, both segments were affected by ductile thrusting, and the southern part of the mylonite was then displaced dextrally across the LaSZ so that it is presently located offshore to the NW of the Southern Segment. Alternatively, early Grenville thrusting along the OHFZ in the Northern Segment was followed by displacement along the LaSZ and accretion of a Southern Segment orthogneiss terrane that had not been affected by ductile thrusting.

The suggestion of significant Grenville displacements along the LaSZ was not, however, substantiated by Mason and Brewer (2005) who proposed only minor reactivation of the shear zone post c. 1675 Ma, not its initiation which must be older. The cause of the contrasting Rb–Sr biotite age groupings across the LaSZ is still to be determined. However, given that the LaSZ is older than c. 1675 Ma, this rules out the alternative solutions proposed by Imber *et al.* (2002). We suggest that the most likely scenario is that the ductile thrust of the Northern Segment of the OHFZ continues southwards and is located just offshore to the east of the Southern Segment (Fig. 12). In this context, the 1020–960 Ma U–Pb ages obtained

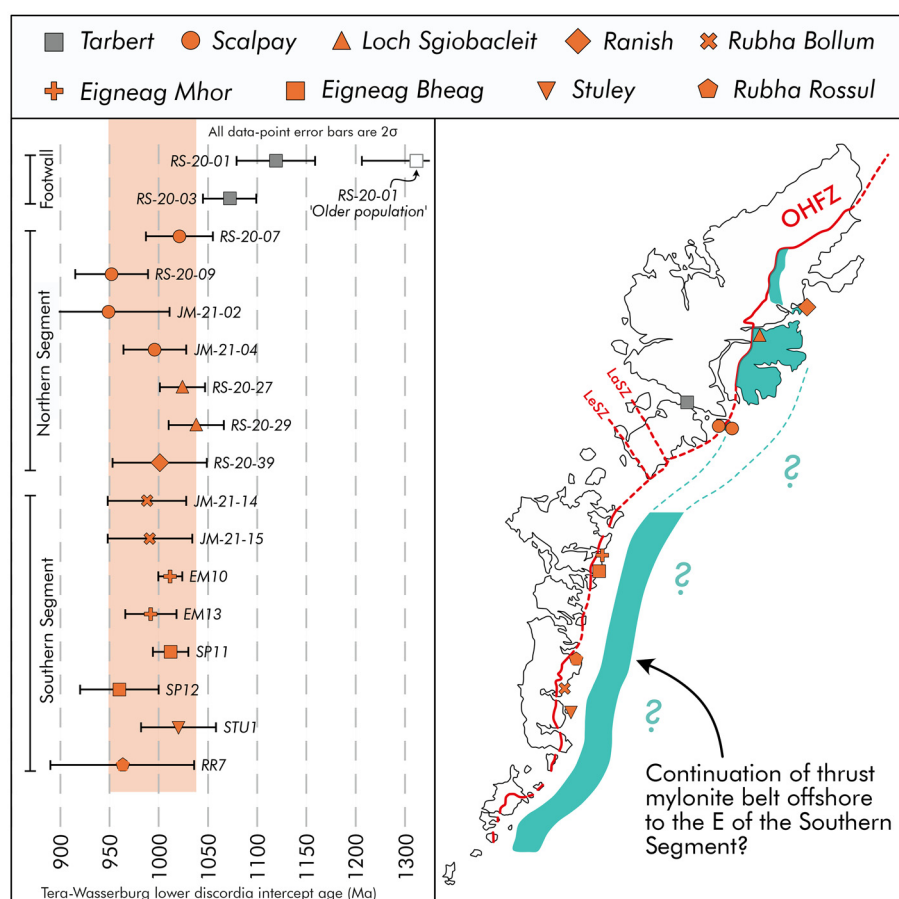


Fig. 12. U-Pb apatite ages and associated error (2σ) across all samples within this study and Metcalfe *et al.* (2024) (RS-samples). Samples belonging to the OHFZ footwall, Northern Segment, and Southern Segment are indicated. The shaded region marks the range in ages from within the fault zone reported, excluding JM-21-13 (this study) and RS-20-40 (Metcalfe *et al.* 2024) due to high error and/or low U. The cartoon map proposes a southern continuation of the Grenville-age thrust mylonite belt offshore to the east of the Southern Segment. LaSZ, Langavat Shear Zone; LeSZ, Leverburgh Shear Zone; OHFZ, Outer Hebrides Fault Zone.

from the apatite porphyroclasts within phyllonites along the eastern margin of the Southern Segment represent the result of thermal resetting of older apatite grains in the footwall of the Grenville thrust zone (Fig. 12). It is noteworthy that the great majority of dated apatite grains are Type-1 which in the Northern Segment are most abundant within the footwall orthogneisses. Very few Type-2 apatite grains appear to be preserved as porphyroclasts and so the ductile thrust zone probably lies offshore to the east.

Conclusions

- (1) This work emphasizes the importance of microstructural characterization before isotopic analysis. Phyllonite belts within reactivated segments of the crustal-scale Outer Hebrides Fault Zone (OHFZ), NW Scotland, contain syn-kinematic white mica grains that formed during successive and likely overlapping sinistral strike-slip and extensional ('transtensional') deformation events within the lower greenschist facies. In contrast, apatite grains within the phyllonites show evidence of brittle deformation and replacement and are interpreted as porphyroclasts.
- (2) The new Rb-Sr white mica ages of 408–396 Ma reported here from sinistral strike-slip and extension related phyllonites show that their development was coeval with sinistral strike-slip faulting along the Great Glen Fault Zone and transtensional development of the early Devonian Orcadian and Moray Firth 'Old Red Sandstone' basins on and adjacent to the Scottish mainland. The Outer Hebrides phyllonite belts are therefore interpreted as the uniquely preserved ductile expression within the foreland crystalline basement of end- to post-Caledonian Old Red Sandstone sedimentary basin development.
- (3) Apatite porphyroclasts within phyllonites scattered along the eastern margin of the Southern Segment of the OHFZ

yield U-Pb ages of 1020–960 Ma. These ages are interpreted as the result of thermal resetting of older apatite grains in the footwall of the Grenville ductile thrust zone which is located offshore to the east of the Southern Segment. The ductile thrust zone thus extends along the greater part of the length of the Outer Hebrides and is not restricted to the Northern Segment as thought previously.

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Data availability All data generated or analysed during this study are included in this published article (and its supplementary material files).

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