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Evidence from Rb–Sr mineral ages for multiple orogenic events in the Caledonides of Shetland, Scotland

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Abstract: Shetland occupies a unique central location within the North Atlantic Caledonides. Thirty-three new high-precision Rb–Sr mineral ages indicate a polyorogenic history. Ages of 723–702 Ma obtained from the vicinity of the Wester Keolka Shear Zone indicate a Neoproterozoic (Knoydartian) age and preclude its correlation with the Silurian Moine Thrust. Ordovician ages of *c*. 480–443 Ma obtained from the Yell Sound Group and the East Mainland Succession constrain deformation fabrics and metamorphic assemblages to have formed during Grampian accretionary orogenic events, broadly contemporaneously with orogenesis of the Dalradian Supergroup in Ireland and mainland Scotland. The relative paucity of Silurian ages is attributed to a likely location at a high structural level in the Scandian nappe pile relative to mainland Scotland. Ages of *c*. 416 and c. 411 Ma for the Uyea Shear Zone suggest a late orogenic evolution that has more in common with East Greenland and Norway than with northern mainland Scotland.

Supplementary materials: Detailed appraisal of biotite petrography is available at http://www.geolsoc.org.uk/SUP18887.

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The Caledonides of the North Atlantic region are the result of a series of orogenic events spanning the early Palaeozoic, culminating in the sinistrally oblique collision of three major continental blocks, Laurentia, Baltica and Avalonia, as the Iapetus Ocean closed (Pickering *et al.* 1988; Soper *et al.* 1992; Dewey & Strachan 2003; Bird *et al.* 2013). The timing of tectonothermal events in such collisional orogens can be constrained by the isotopic dating of metamorphic mineral assemblages and igneous intrusions of known structural age. This may allow the identification of discrete zones within an orogen that are dominated by structures and metamorphic assemblages of a certain age, which relate to a particular accretionary or collisional event, provided isotopic systems have not been reset. Within various sectors of the North Atlantic Caledonides it has therefore been possible to differentiate deformation fabrics and mineral assemblages formed during early phases of Ordovician arc–continent collision from those formed during Silurian continental collision (e.g. Kinny *et al*. 1999, 2003; Roberts 2003; Kocks *et al*. 2006; Bird *et al*. 2013).

Caledonian orogenic activity in the North Atlantic region commenced with the development of east-dipping (present reference frame) subduction zones in the Iapetus Ocean during the late Cambrian to early Ordovician, followed by accretion of ophiolites and magmatic arcs to the margin of Laurentia. Accretionary-related orogenic events include the 480–460 Ma Grampian event of Scotland and Ireland (Lambert & McKerrow 1976; Oliver *et al.* 2000; Chew *et al*. 2010; Tanner 2014; Fig. 1), and the Finnmarkian event within Laurentian-derived allochthons of Norway (Roberts 2003; Fig. 1). Following a flip in subduction polarity, renewed deformation and metamorphism at *c*. 450 Ma along sectors of the Laurentian margin may correspond to terrane accretion (Bird *et al*. 2013) and/or flat-slab subduction (Dewey *et al*. 2015). The culminating sinistrally oblique continental collision of Baltica and Laurentia during the Silurian and early Devonian formed the Himalayan-scale Scandian orogen (Gee 1975). The orogen has bivergent geometry with regional thrust belts developed both in the pro-wedge (Norway) and retro-wedge (East Greenland) (Streule *et al.* 2010). In both Norway and East Greenland there is evidence for metamorphism up to eclogite facies and examples of hinterland-directed synconvergent extensional shear zones, perhaps indicative of 'channel flow' (e.g. Hartz *et al.* 2001; Andresen *et al*. 2007; Grimmer *et al.* 2015). In mainland Scotland, the Northern Highland Terrane (Fig. 1) represents the southernmost part of Laurentia to be affected by the Scandian collision, and was juxtaposed with the Grampian Terrane to the SE in Early–Middle Devonian times during sinistral displacement along the Great Glen Fault (Coward 1990; Dallmeyer *et al.* 2001; Dewey & Strachan 2003). Scandian orogenesis in the Northern Highland Terrane was complete by *c*. 430 Ma (Goodenough *et al.* 2011); metamorphic grade was no higher than mid-amphibolite facies and no examples of syn- or late-convergent extensional shear zones have been identified, all features consistent with its location on the periphery of the main, longer-lived continental collision to the north. The Scandian collision was followed at *c*. 400 Ma by sinistrally oblique plate divergence associated with displacements along extensional and strike-slip shear zones and faults, exhumation of the ultrahigh-pressure rocks of SW Norway, and development of late- to post-orogenic 'Old Red Sandstone' sedimentary basins in East Greenland, Svalbard, Scotland and Norway (Seranne 1992; Krabbendam & Dewey 1998; Dewey & Strachan 2003; Fossen 2010).

Shetland formed part of the Laurentia palaeo-continent and occupies a key location within the North Atlantic Caledonides owing to its pre-Mesozoic proximity to the East Greenland, Scottish and Norwegian sectors of the Caledonian belt (Fig. 1). Despite this location it remains poorly understood, as relatively few modern, systematic geochronological studies have been carried out in conjunction with detailed structural and metamorphic analysis. Here we present 33 new Rb–Sr white mica and biotite mineral ages, obtained from various deformed and metamorphosed lithologies across a wide geographical area of Shetland. Using a combination of isotope dilution thermal ionization mass spectrometry (ID-TIMS) for Sr and Zr-normalization for Rb by multicollector inductively coupled plasma mass spectrometry (MC-ICP-MS) we achieve Rb/Sr ratio reproducibility better than 0.4%, yielding more precise ages than

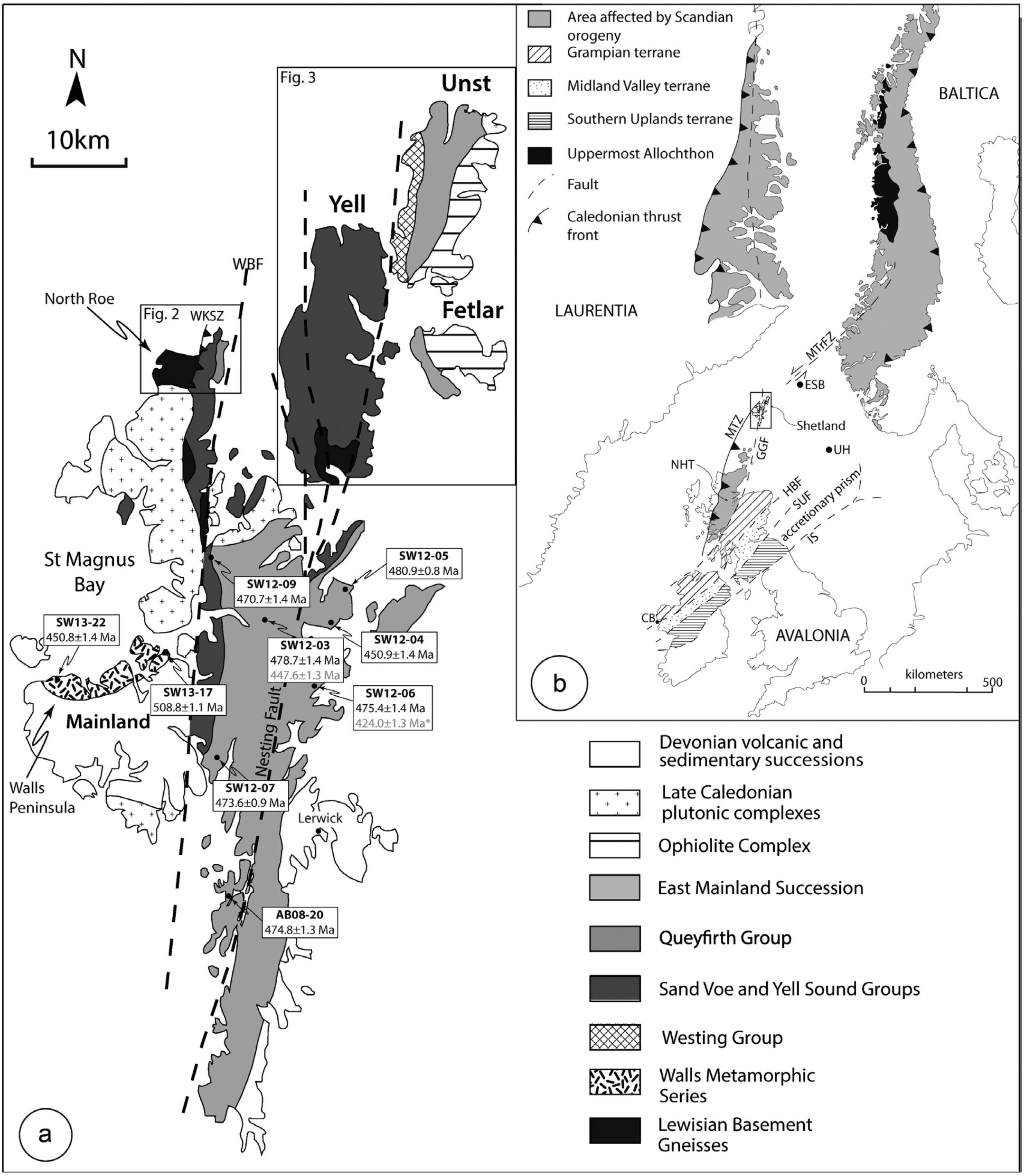

Fig. 1. (**a**) Simplified geological map of Shetland including sample sites on Mainland. (**b**) Regional context of Shetland in its pre-Mesozoic rifting setting (modified from Bird *et al.* 2013). Ages shown in grey are biotite–feldspar ages; all others are white mica–feldspar. WBF, Walls Boundary Fault; WKSZ, Wester Keolka Shear Zone; IS, Iapetus Suture; SUF, Southern Uplands Fault; HBF, Highland Boundary Fault; GGF, Great Glen Fault; MTZ, Moine Thrust Zone; NHT, Northern Highland Terrane; MTrFZ, Møre–Trøndelag Fault Zone; ESB, East Shetland Basin; UH, Utsira High; CB, Clew Bay. Asterisk indicates ages that are not robust.

previous regional Rb–Sr studies in the Caledonides. Rb–Sr mica geochronology is well suited to regional geochronological studies as micas are common within metasedimentary and meta-igneous rocks, often defining fabrics that allow for the linkage of a radiometric age with a particular phase of deformation, as well as providing the analytical advantage of high parent–daughter isotope ratios. This study aims to (1) place constraints on the ages of structures and regional metamorphic events within Shetland, and (2) propose correlations with orogenic events recorded in other parts of the Caledonides.

Regional geological framework of Shetland

The pre-Devonian geology of Shetland includes metamorphic rock units that have been correlated with various components of the

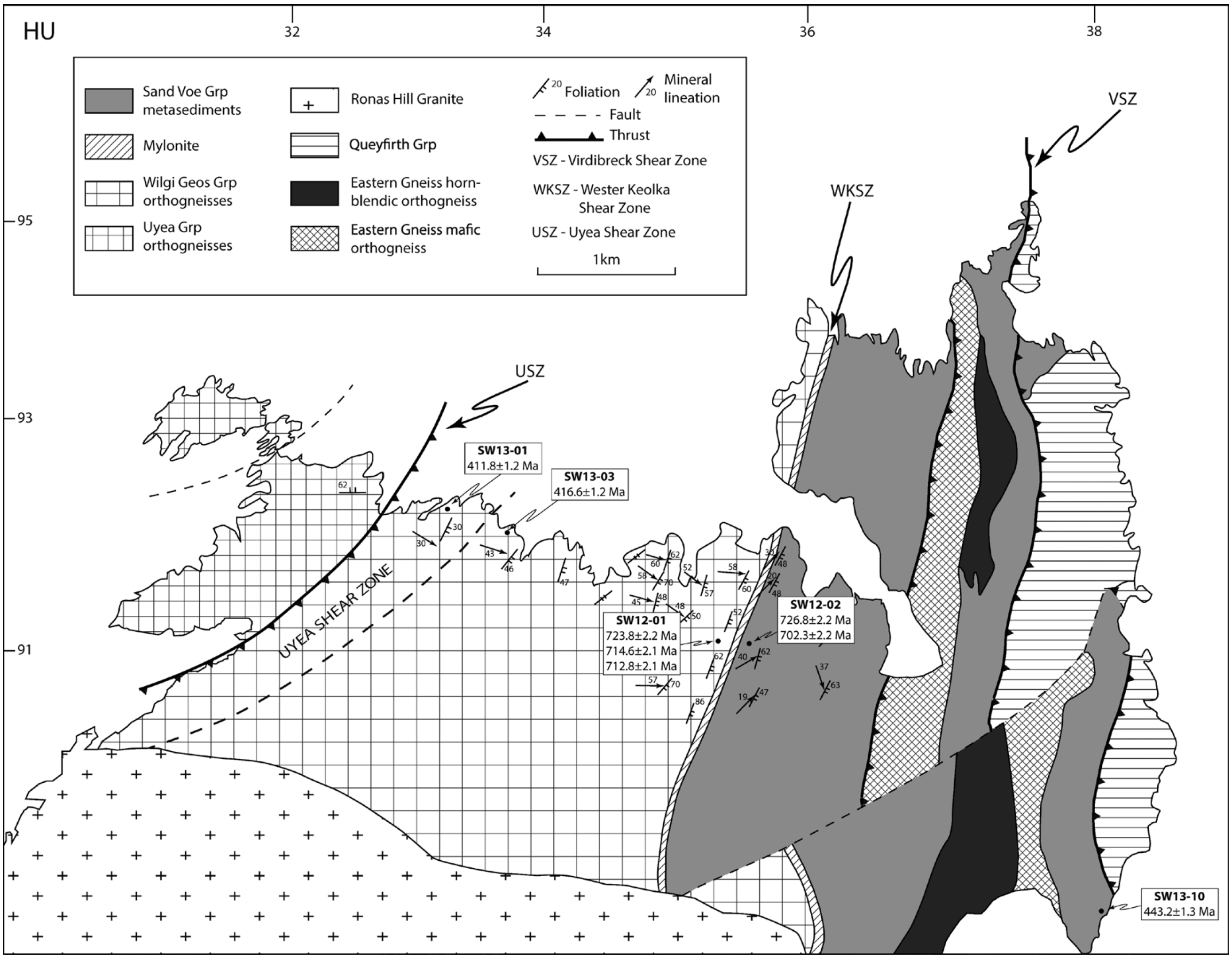

Fig. 2. Geology of the North Roe region of northern Mainland Shetland, including sample sites and age determinations.

geology of mainland Scotland on the basis of lithological comparisons and/or limited geochronological datasets (Miller & Flinn 1966; Flinn *et al.* 1972, 1979; Flinn 1985, 1988). The Wester Keolka Shear Zone and the Walls Boundary Fault (Fig. 1) have been equated respectively with the Moine Thrust and the Great Glen Fault (Flinn 1961, 1977, 1993; Pringle 1970; Flinn *et al.* 1979), resulting in the northward extension of the Hebridean, Northern Highland and Grampian Terranes from mainland Scotland to Shetland (Bluck *et al.* 1992). The Unst ophiolite in NE Shetland (Garson & Plant, 1973; Flinn *et al.* 1979; Flinn 1985; Prichard 1985) has been linked with other ophiolitic units that crop out along the Highland Boundary Fault and its extension into Ireland (e.g. Chew *et al.* 2010). Flinn (1977) proposed sinistral strike-slip displacement of at least 200 km along the Walls Boundary Fault. If it is the continuation of the Great Glen Fault as commonly supposed, displacements may be significantly greater, perhaps 500–700 km (Dewey & Strachan 2003). Further, but more generalized, correlations can also be made along-strike to the north with the East Greenland Caledonides and the Laurentian-derived allochthons of western Norway (Fig. 1, inset) and are alluded to below as appropriate.

West of the Walls Boundary Fault

Late Caledonian plutonic complexes, and Devonian volcanic and sedimentary successions dominate the region west of the Walls Boundary Fault. Pre-Devonian basement crops out in the North Roe area of NW Mainland Shetland, and in an east–west-striking strip along the northern margin of the Walls Peninsula (Flinn *et al.* 1979; Fig. 1).

In North Roe (Fig. 2), Pringle (1970) identified the Uyea orthogneisses, which are largely felsic orthogneisses with subordinate metagabbros. K–Ar and $^{40}Ar/^{39}Ar$ ages of *c.* 2900–2500 Ma obtained from the Uyea orthogneisses led to their correlation with the Archaean Lewisian Gneiss Complex that underlies the foreland to the Caledonian orogen (= Hebridean Terrane) in mainland Scotland (Fig. 1; Flinn *et al.* 1979; Robinson 1983). The Wilgi Geos orthogneisses to the east are interpreted as the reworked equivalents of the Uyea orthogneisses, separated from them by the Uyea Shear Zone (Fig. 2; Pringle 1970). At a higher structural level to the east, the Wester Keolka Shear Zone separates the Wilgi Geos orthogneisses from the overlying Sand Voe Group psammites (Fig. 2; Pringle 1970). The latter have been compared lithologically with the early Neoproterozoic Moine Supergroup of the Northern Highland Terrane in mainland Scotland (Flinn 1985, 1988). It logically follows that the Wester Keolka Shear Zone could therefore be correlated with the Moine Thrust, which defines the western limit of the Caledonides in mainland Scotland, separating the foreland Lewisian Gneiss Complex from the Moine Supergroup (Andrews 1985; Ritchie *et al*. 1987; Flinn 1992, 1993; McBride & England 1994). However, two lines of field evidence suggest that this correlation needs to be treated with caution. First, the lowermost parts of the Sand Voe Group contain what were interpreted by Pringle (1970) as deformed pebbles derived from the underlying Wilgi Geos orthogneisses, implying that the Wester Keolka Shear Zone is localized along a basement–cover unconformity and is therefore unlikely to be associated with any significant displacement. Second, although the Wilgi Geos orthogneisses are associated with an east-plunging mineral lineation and sparse top-to-the-west kinematic indicators, the dominant linear fabrics within the Wester Keolka Shear Zone and the Sand Voe Group are obliquely to gently plunging, consistent with transpression or transtension. The age of the Wester Keolka Shear Zone has been constrained only by a single $^{40}Ar/^{39}Ar$ muscovite age of 466 ± 6 Ma obtained from the mylonitic Wilgi Geos orthogneisses, suggesting that the Wester Keolka Shear Zone was active either at or before this date (Flinn 2009).

Further east, the Sand Voe Group is interleaved with infolds or tectonic slices of hornblendic gneisses (Fig. 2). These have yielded hornblende K–Ar and $^{40}Ar/^{39}Ar$ ages of *c*. 2300–1000 Ma and are thought to represent inliers of Lewisian-type basement (Flinn *et al.* 1979; Robinson 1983). The steeply dipping Virdibreck Shear Zone (Fig. 2) separates the Sand Voe Group from the metasedimentary and metavolcanic rocks of the Queyfirth Group, which has been correlated with the Neoproterozoic to Cambrian Dalradian Supergroup, which underlies large tracts of the Grampian Terrane in mainland Scotland (Fig. 1; Flinn 1988).

Further south, on the northern margin of the Walls Peninsula (Fig. 1), the east–west-striking Walls Metamorphic Series comprising quartzo-feldspathic gneisses, amphibolites, limestones and calc-silicates crops out. Mykura (1976) proposed these lithologies to be broadly equivalent to the Sand Voe Group on the basis of lithological and deformational similarities. However, the Walls Metamorphic Series subsequently yielded K–Ar hornblende ages of *c*. 863–366 Ma and was assigned to an older 'Grenvillian' basement (Flinn *et al.* 1979).

East of the Walls Boundary Fault

The Yell Sound Group of Yell and Mainland Shetland (Figs 1 and 3) comprises gneissic psammites and pelites that have been correlated with the Moine Supergroup (Flinn 1988). On Unst, the pelites and marbles of the Westing Group (Fig. 3) may form part of essentially the same sedimentary package. Both successions record evidence for amphibolite-facies metamorphism at *c*. 930–920 Ma (Cutts *et al.* 2009, 2011) and incorporate strips of mafic and felsic orthogneisses that have been interpreted as inliers of the Lewisian Gneiss Complex (Flinn & Roddam 1994; Flinn 2014). The Yell Sound Group and the Westing Group are succeeded eastwards by the *c*. 14 km thick East Mainland Succession consisting of psammites, pelites and marbles with minor volcanic horizons (Flinn 1967), although the presumed intervening unconformity is obscured by high tectonic strain (Flinn 1988). The East Mainland Succession is partly time-equivalent to the Dalradian Supergroup (Prave *et al*. 2009; Strachan *et al.* 2013), and hence probably accumulated on the passive margin of Laurentia during continental break-up and development of the Iapetus Ocean (Anderton 1985; Strachan *et al*. 2002). The Eleonore Bay Supergroup of East Greenland is broadly time-correlative with the Dalradian and East Mainland successions (Leslie *et al*. 2008).

The East Mainland Succession is overlain by the Unst ophiolite, which is disposed in two thrust sheets and is thought to have been emplaced during the early Ordovician Grampian orogenic event that resulted from the collision of an oceanic island arc with the Laurentian margin (e.g. Dewey & Ryan 1990; Fig. 3). Ophiolitic fragments of similar age occur in mainland Scotland along the Highland Boundary Fault and its extension into Ireland as far west as Clew Bay (Chew *et al*. 2010), and to the north within the Laurentian-derived allochthons of western Norway (Roberts 2003). The coeval island arc(s) may also be traced discontinuously along the length of the Caledonides from west Ireland (Lough Nafooey Group), through the Midland Valley of Scotland (albeit buried beneath younger cover), into the North Sea area (Utsira High, East Shetland Basin, Fig. 1 inset, Lundmark *et al*. 2014) and onshore in the Laurentian-derived allochthons as far north as northern Norway.

The formation of the Unst ophiolite is constrained by a U–Pb zircon age of 492 ± 3 Ma obtained from a plagiogranite (Spray & Dunning 1991), and obduction is bracketed by a U–Pb zircon age of 484 ± 4 Ma and K–Ar ages of *c*. 465–479 Ma obtained from its metamorphic sole (Spray 1988; Crowley & Strachan 2015). Crustal thickening and metamorphism of the footwall successions followed obduction. Pelites on NW Unst and Yell yield U–Pb monazite ages of *c*. 451–462 Ma with *P*–*T* conditions varying from *c*. 7.5 kbar and 550°C directly below the ophiolite to *c*. 10 kbar and 775°C at structurally deeper levels (Cutts *et al.* 2011). The gently dipping foliations, east–west-trending mineral lineations and prograde kyanite–staurolite assemblages preserved in NW Unst are plausibly related to obduction and nappe stacking (Cannat 1989). However, the metamorphic contrast between the low-grade rocks associated with the ophiolite and regional *P*–*T* conditions in its footwall indicate that its present basal contact is a younger tectonic break (Cutts *et al.* 2011). A gently dipping, retrogressive greenschist-facies shear zone underlies the lower ophiolite sheet (Read 1934; Cannat 1989; Flinn 2014), but whether final ophiolite emplacement resulted from orogen-parallel shear (Cannat 1989) or orthogonal, NW-directed thrusting (Flinn & Oglethorpe 2005) is uncertain. Evidence for Silurian greenschist-facies metamorphism in NE Unst is provided by $^{40}Ar/^{39}Ar$ muscovite and K-feldspar ages of *c*. 420–430 Ma (Flinn & Oglethorpe 2005). In contrast to Unst and Fetlar, the dominant foliation within the Yell Sound Group and the East Mainland Succession in Mainland Shetland is steep to vertical and associated with gently plunging to horizontal mineral lineations (Flinn 1967, 1994, 2007). This foliation overprints staurolite and kyanite in the East Mainland Succession (May 1970), and was probably superimposed on fabrics related to earlier nappe stacking. The only constraint on the age of syn- to post-tectonic migmatization within the 'central steep belt' (Flinn 1967; May 1970) is an Rb–Sr whole-rock isochron of 530 ± 25 Ma obtained from migmatitic gneisses (Flinn & Pringle 1976), which is unlikely to have geological significance. The age of the 'central steep belt' is therefore uncertain in the context of recent Caledonian tectonic models (e.g. Bird *et al.* 2013).

Sampling strategy

Samples for Rb–Sr analysis were collected with the aim of providing a systematic regional dataset and to place constraints on the age(s) of the major structures, structural domains and/or metamorphic events that were poorly constrained on the basis of previous geochronological studies, in particular the following: (1) deformation fabrics within the Wilgi Geos orthogneisses, the Uyea Shear Zone, the Wester Keolka Shear Zone and the Sand Voe Group; (2) metamorphism of the Walls Metamorphic Series; (3) the 'central steep belt' of Yell and Mainland Shetland; (4) the retrogressive shear zone beneath the Unst ophiolite. The locations of samples, together with brief descriptions of lithologies, mineral assemblages and structural setting, are presented in Table 1.

Analytical techniques

After crushing in a steel jaw-crusher to chips of *c*. 1 cm^3, 50 g of each sample was powdered in a tungsten carbide Tema mill prior to preparation for whole-rock X-ray fluorescence (XRF) analysis, which was used only to estimate the amount of mixed $^{87}Rb/^{84}Sr$ spike to add to mineral separates. The remaining material was sieved into different grain size fractions, and fresh white micas,

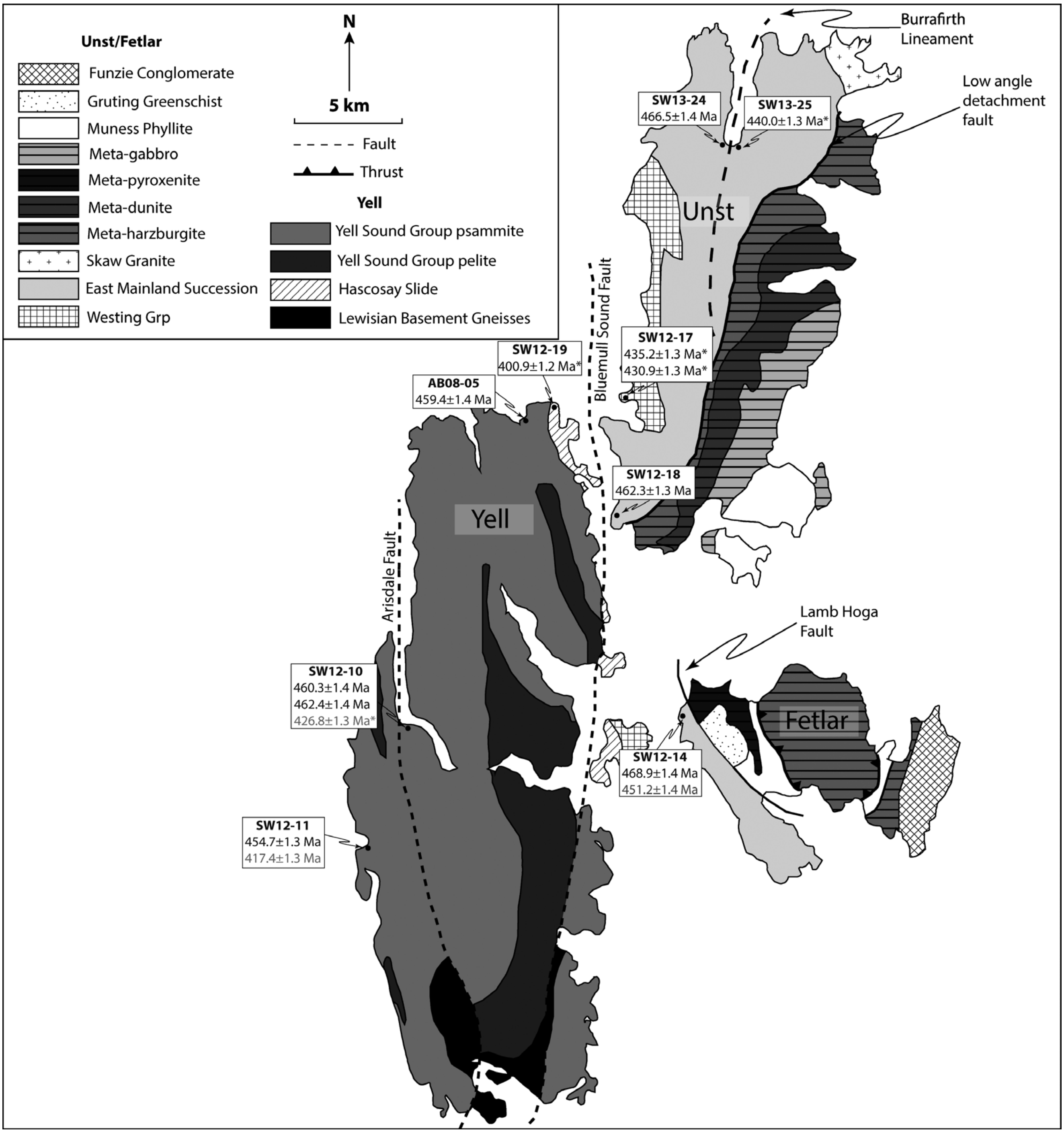

Fig. 3. Geology of the islands of Yell, Unst and Fetlar in Shetland, including sample sites and age determinations. Ages shown in grey are biotite–feldspar ages; all others are of white mica. Asterisk indicates ages that are not robust.

biotites and feldspars were picked by hand under a binocular microscope. Mica fractions were then ground in an agate pestle and mortar under methanol, washed in MQ water, and further sieved between 200 and 75 µm to remove non-mica impurities. Mineral separates then underwent HF–HNO_3 dissolution prior to chemical separation. Sr was separated using Eichrom Sr-spec resin, and Rb was separated from K using 0.5M HNO_3 on Bio-rad AG50W-X8 cation exchange resin.

Twenty-four mineral separates were analysed for Sr isotopes by TIMS on a VG354 system, with 36 later analyses undertaken on an Isotopx Phoenix system. Isotope ratios and concentrations were determined using a multidynamic method modified from Thirlwall (1991). The accuracy and reproducibility of Sr isotope data were monitored using the external standard SRM987. During the course of this study, $^{87}Sr/^{86}Sr$ of SRM987 was 0.710256 ± 19 2SD, n = 20 (VG354), and 0.710238 ± 8 2SD, n = 59 (Phoenix). Total procedural blanks for Sr were typically less than 0.2% (0.5 ng) of the analyte mass, and hence a blank correction has no significant effect on ages presented.

Rb analyses were undertaken on the GV IsoProbe MC-ICP-MS system at Royal Holloway University of London (RHUL). The technique allows for the correction of the mass fractionation of Rb using Zr, leading to higher precision compared with conventional TIMS analysis, where mass fractionation correction possibilities are limited (Halliday & Lee 1998; Waight *et al.* 2002). Uncertainties on Rb/Sr ratios contribute the largest source of analytical uncertainty on any of these ages. These uncertainties are monitored and minimized using a method modified from Waight

Table 1. *Locations, lithology, structural significance and mineral assemblages of dated samples*

Sample	Location	Grid reference	Lithology	Structural significance	Mineral assemblage
West of the WBF					
SW12-1	North Roe	HU 3519 9149	WG felsic orthogneiss	Mylonitized basement immediately below WKSZ	Qtz + Pl + Ms + Ep + Chl + Opaq
SW12-2	North Roe	HU 3555 9140	SVG mylonite	Moine-correlative above WKSZ	Qtz + Kfs + Pl + Ms + Chl + Bt + Ep
SW13-1	North Roe	HU 3339 9219	WG felsic orthogneiss	Mylonitized basement east of USZ	Qtz + Kfs + Ms + Kfs + Ep + Opaq
SW13-3	North Roe	HU 3367 9196	WG felsic orthogneiss	Deformed basement east of USZ	Qtz + Pl + Ms + Ep + Chl + Rt + Opaq
SW13-10	Burra Voe	HU 3747 8924	SVG psammite	SW foliation west of VSZ	Qtz + Ms + Pl + Kfs + Chl + Opaq
SW13-17	West Walls	HU 3163 6060	WMS pelite	Main S-dipping foliation in eastern WMS	Qtz + Ms + Bt + Pl + Spn + Opaq
SW13-22	Norby Beach	HU 1971 5802	WMS semi-pelite	Steep SE-dipping foliation in western WMS	Qtz + Pl + Ms + Chl + Bt + Ep
East of the WBF					
Mainland					
SW12-3	Between Voe and Laxo	HU 4204 6284	EMS foliated granitoid	Steep ESE-dipping gneissic foliation	Qtz + Kfs + Mc + Pl + Ms + Bt + Zrn
SW12-4	Levaneap	HU 4867 6303	EMS foliated granitoid	Steep NW-dipping gneissic foliation	Qtz + Pl + Kfs + Ms + Chl
SW12-5	Lunning	HU 4966 6613	EMS pelite	Steep NW-dipping schistose foliation	Qtz + Pl + Ms + Chl + Grt + Chd + Rt
SW12-6	South Nesting	HU 4746 5645	EMS semi-pelite	Steep NW-dipping foliation east of NF	Qtz + Ms + Bt + Pl + St + Chd + Zrn
SW12-7	Wiesdale	HU 3695 5080	EMS semi-pelitic gneiss	Steep NW-dipping mylonitic fabric W of BZ	Qtz + Ms + Pl
SW12-9	Valayre Quarry	HU 3683 6957	YSG retrogressed granite–gneiss	Main steep fabric W of BZ and E of WBF	Qtz + Pl + Ms + Chl + Cal
AB08-20	Meal Beach	HU 3750 3523	EMS foliated granitoid	Shallow NW-dipping foliation	Qtz + Kfs + Ms + Chl + Grt + Zrn + Rt
Yell					
SW12-10	Grimister	HU 4665 9336	YSG foliated micaceous gneiss	Moderate WSW-dipping foliation in W Yell	Qtz + Pl + Bt + Ms + Chl + Zrn
SW12-11	West Sandwick	HU 4456 8893	YSG migmatitic gneiss	Steep WSW-dipping foliation in W Yell	Qtz + Pl + Bt + Ms + Zrn
SW12-19	North Brough	HP 5373 0521	Lineated felsic sheet intruded into YSG	Moderate NW-plunging lineations in N Yell	Qtz + Ms + Pl + Bt + Chl + Opaq
AB08-5	Sands of Breckon	HP 5275 0534	Folded syntectonic pegmatite intruded into YSG	Moderate W-dipping foliation in N Yell	Qtz + Kfs + Ms + Grt
Fetlar					
SW12-14	Hamars Ness	HU 5789 9287	EMS migmatitic gneiss	Shallow NW foliation	Qtz + Bt + Ms + Pl + Grt + Chl + Opaq
Unst					
SW12-17	Houllnan Ness	HP 5657 0520	Lineated pegmatite within WGr schists	Pronounced SW lineations	Pl + Qtz + Ms + Grt
SW12-18	Belmont	HP 5569 0074	EMS migmatitic gneiss	SW-trending lineations and sinistral shear	Qtz + Ms + Pl + Bt + Chl + Grt + Chd + Ky + Ep
SW13-24	Burrafirth	HP 6104 1422	EMS semi-pelitic schist	Higher grade metamorphism W of BFL	Qtz + Pl + Ms + Kfs
SW13-25	Burrafirth	HP 6131 1400	EMS pelitic schist	Lower grade metamorphism E of BFL	Ms + Qtz + Kfs + Chl + Bt + Grt + Opaq

Mineral name abbreviations taken from Kretz (1983). WG, Western Gneisses; SVG; Sand Voe Group; WMS, Walls Metamorphic Succession; EMS, East Mainland Succession; YSG, Yell Sound Group; WGr, Westing Group; WKSZ, Wester Keolka Shear Zone; USZ, Uyea Shear Zone; VSZ, Virdibreck Shear Zone; NF, Nesting Fault; BZ, Boundary Zone; WBF, Walls Boundary Fault; BFL, Burrafirth Lineament.

et al. (2002), where the normalizing Zr ratios (^{92}Zr/^{90}Zr and ^{91}Zr/^{90}Zr) used to correct for Rb mass fractionation are determined daily using the Sr standard SRM987 admixed with Zr (see Charlier *et al.* 2006). The Rb standard SRM984 was analysed at least every four samples during analytical sessions ($n = 31$ for the duration of this study), to test the accuracy and precision of this technique. Unspiked geological material (mostly micas, but also two basalts) were analysed to test for potential matrix effects of samples v. standards, which could affect the accuracy of the mass fractionation correction. During and immediately preceding the course of this study, unspiked materials fall within error of the long-term mean of SRM984 ^{87}Rb/^{85}Rb 0.38645±33 2SD (0.09%, $n = 86$, with three earlier analyses, during procedural set-up, falling significantly below this value). Therefore 0.09% is the lowest possible per cent error on the ^{87}Rb/^{86}Sr, but the feldspar standard SRM607 over the period of the study gave reproducibility of 0.5% 2RSD, which in part probably is an effect of the documented heterogeneity of this standard (Nebel & Mezger 2006). However, analyses of identical separates in different analytical sessions yielded ^{87}Rb/^{86}Sr reproducibility of <0.2% (2σ). The ^{87}Rb/^{86}Sr uncertainty used in age calculations was therefore taken as 0.3% (2σ), although this is likely to be an overestimate. Ages and uncertainties were calculated in Isoplot version 4 (Ludwig, 2003), using the decay constant for ^{87}Rb recommended by Villa *et al.* (2015). Using this decay

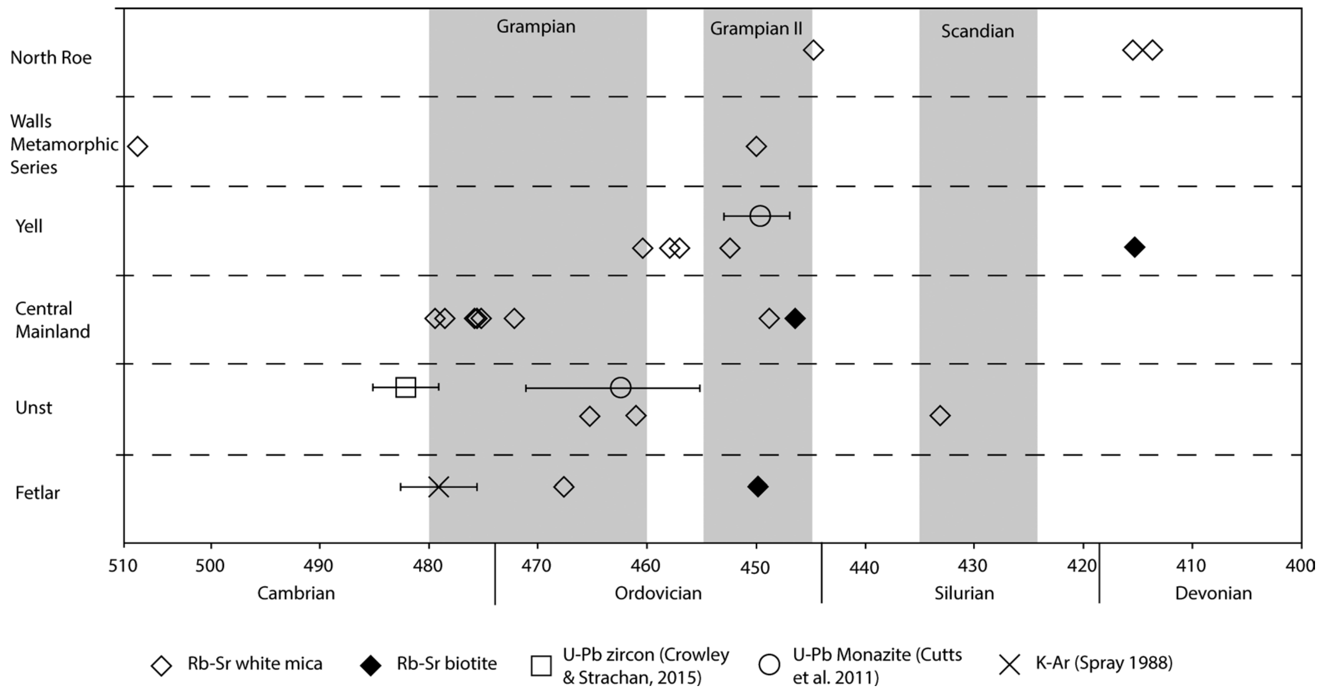

Fig. 4. Graphical representation of Caledonian ages in Shetland, including data from this study and other modern geochronological work. For ages where no error bars are shown, uncertainties are smaller than the marker symbol.

constant, ages are 1.6% older than Rb–Sr ages calculated using the decay constant recommended by Steiger & Jäger (1977), which has been pervasive throughout the last 40 years.

Results

The new Rb–Sr mineral ages reported here are depicted in Figure 4, together with published mineral ages obtained by other workers. The Rb–Sr system in micas has been shown to be robust to temperatures greater than 600°C over orogenic timescales (>15 Ma), provided the rock is free of fluids (e.g. Glodny *et al*. 2008). We therefore consider it unlikely that white mica ages relate to cooling through a specific closure temperature, as isotopic equilibrium is more likely to be achieved by fluid-induced recrystallization than by temperature-driven diffusional processes. However, in cases where biotite ages are observed to be younger than white mica ages, with no evidence of biotite defining a distinct younger fabric, then cooling or thermal resetting at lower temperatures may be invoked. An Rb–Sr date recorded in a single sample may therefore represent any of the following processes.

(1) Growth or partial or complete recrystallization of mica (Willigers *et al*. 2004; Glodny *et al*. 2008; Villa 2010). Of the samples presented in this study, all micas and feldspars show evidence of dynamic recrystallization, and are therefore interpreted as recording metamorphic or deformational ages unless otherwise stated.

(2) Alteration of Rb- or Sr-rich minerals used for age determination, or of the rock as a whole, during later introduction of fluids resulting in metasomatic changes to the Rb/Sr system.

(3) Mixing between ages of micas of different sizes in polymetamorphic rocks, where Rb/Sr has not fully re-equilibrated. Mica and feldspar separates for all samples were picked from comparable size fractions, typically 500–250 µm, and analysed samples show no evidence of multiple mica populations unless stated otherwise.

Careful consideration of the mineralogical, structural, petrographic and chemical evidence is therefore required before assigning geological significance to a single age, or series of ages. All samples were scrutinized closely for evidence of alteration within the mica and feldspar phases, which could lead to erroneous age determinations. Petrographically, all samples appear fresh and unaltered unless specified otherwise. Owing to the lack of calcite in all but one sample (SW12-09), the majority of the Sr budget for the rock is presumed to be contained within feldspar. Provided there is no textural evidence for the incorporation of later fluid, feldspar can be assumed to represent the initial Sr isotopic composition of the reservoir from which the micas crystallized, when corrected for radiogenic growth.

Biotite can be affected by chloritization, which may render a biotite age meaningless. To evaluate this issue, detailed petrography was undertaken on the samples where biotite Rb–Sr ages have been determined.

The Rb–Sr results are summarized in Table 2.

The significance of two-point ages

Multi-point isochron ages are statistically more robust than two-point ages as they allow for the derivation of an MSWD, a test of the goodness of fit of data to the isochron line. This work, however, utilizes mostly two-point ages for the following reasons.

(1) The use of two-point ages rather than multi-point isochrons allows for a larger number of samples to be analysed, hence permitting a larger geographical spread in available ages for regional interpretation.

(2) Repeat analysis, where new mica separates were prepared and analysed from the initial crushing stage, showed that the ages are reproducible within error. Some multi-point isochron ages (Fig. 5) have been included to test the robustness of the technique and dataset.

(3) The 33 ages determined fall into four distinct groups and were obtained from a lithologically and texturally diverse set of samples. It is argued that a large number of similar ages, recorded in varied lithologies across a wide geographical spread, is more geologically meaningful than a small number of internally consistent multi-point isochron ages.

Neoproterozoic (726–702 Ma) white mica ages

In the North Roe area of northern Mainland Shetland (Fig. 2), the Wilgi Geos felsic orthogneiss (SW12-01) has yielded three ages

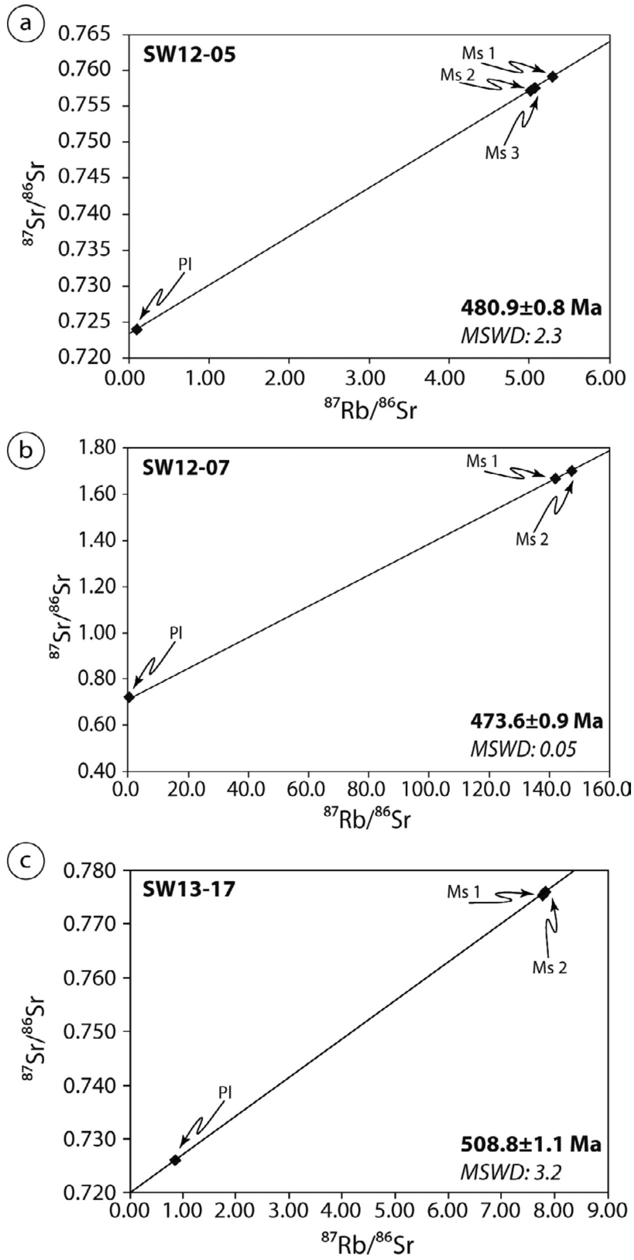

Fig. 5. Rb–Sr isochron diagrams for samples where multiple mica separates were analysed. Pl, plagioclase fraction; Ms, white mica, with fraction indicated numerically. Error bars are smaller than symbols.

between 723.8 ± 2.2 and 712.8 ± 2.1 Ma, and the overlying Sand Voe Group psammite (SW12-02) yielded ages of 702.3 ± 2.1 and 726.8 ± 2.2 Ma. This variability is probably due to compositional variation within the mica population, given that other samples from different white mica separates usually yielded ages within uncertainty. However, the relative consistency of these ages strongly suggests that they have geological significance. The samples carry apparently the same east-dipping foliation and were collected in close proximity (*c.* 300 m of vertical separation), but are separated by the Wester Keolka Shear Zone (Fig. 2). Metamorphic grade is within the amphibolite facies (>500°C) as shown by stable hornblende–plagioclase assemblages of metabasic sheets contained within the Wilgi Geos orthogneisses. The ages for the two samples have been determined on white mica grains that define the main blastomylonitic fabric, with no evidence of alteration. We therefore suggest that the samples are recording a deformational age.

Cambrian (c. 500 Ma) white mica age

Sample SW13-17 from the eastern margin of the Walls Metamorphic Series (Fig. 1) yielded a three-point isochron age of 508.8 ± 1.1 Ma (MSWD 3.2, Fig. 5). This is significantly different from other ages presented within this study, and hence only limited conclusions may be drawn. In thin section, the mica-bearing schistosity wraps zoned garnet porphyroblasts (Fig. 6). Metamorphic grade is within the amphibolite facies (>500°C) as shown by stable hornblende–garnet–plagioclase assemblages within metabasic sheets contained within the eastern Walls Metamorphic Series. It is therefore likely that the white mica age relates to the timing of formation of the pervasive mica-bearing schistosity.

Early and Middle-Ordovician (c. 480–461 Ma) white mica ages

A migmatitic gneiss from the East Mainland Succession in north-western Fetlar (Fig. 3; SW12-14) yielded a white mica age of 468.9 ± 1.4 Ma. The mica-bearing foliation wraps plagioclase porphyroblasts and small (*c.* 1 mm) euhedral garnets (Fig. 6). A similar white mica age of 466.5 ± 1.4 Ma was obtained from a migmatitic gneiss (SW13-24) sampled at a similar structural level in NW Unst (Fig. 3). These kyanite–garnet–staurolite-bearing lithologies have yielded peak *P*–*T* estimates of 7.5 kbar and 630°C (Cutts *et al.* 2011). The ages of these samples are therefore interpreted to represent the timing of formation of the mica-bearing schistosity.

Of seven samples from central Mainland Shetland, six yielded white mica ages that lie within the 480.9–470.7 Ma age bracket (Figs 1 and 4). The samples represent a variety of East Mainland Succession lithologies, including micaceous psammites, pelites, gneisses and foliated granitoids (Table 1). Two of the ages have proven to be reproducible within error when new mica separates were analysed (Table 2, Fig. 5). The $^{87}Rb/^{86}Sr$ ratios of the white micas range from very high (147) to moderate (5.0). There are no recent estimates on *P*–*T* conditions in this part of Shetland. However, the occurrence of staurolite, chloritoid and garnet places these rocks in the low to lower-middle amphibolite facies, as the transition from low- to middle-amphibolite in pelites is marked by the disappearance of chloritoid from the system at *c.* 600°C (Bucher & Grapes 2011). The white mica ages are interpreted to record close to peak metamorphic conditions of these samples.

Three samples from Yell and Unst yielded a slightly younger cluster of ages between 462.4 and 459.4 Ma (Fig. 4). A pelite from SW Unst (SW12-18, Fig. 3) yielded a white mica age of 462.7 ± 1.4 Ma. The sample was obtained from the retrogressive greenschist-facies shear zone that underlies the lower ophiolite sheet (Fig. 3). A relict gneissic fabric is preserved within the pelite, but the dominant micaceous shear band fabric is the result of a lower-grade, greenschist-facies overprint. Although precise *P*–*T* estimates are not available, it seems unlikely that temperatures exceeded *c.* 500°C (Cannat 1989; Flinn 2014). Accordingly, the white mica age is interpreted to be closely dating deformation within the retrogressive shear zone underneath the lower ophiolite sheet.

A micaceous gneiss from western Yell (SW12-10, Fig. 3) yielded white mica ages of 462.4 ± 1.4 Ma. AB08-05, a foliated syntectonic pegmatite from northern Yell, has yielded a similar age of 459.4 ± 1.4 Ma. Cutts *et al.* (2011) reported peak *P*–*T* conditions of 9 kbar and 650°C and a U–Pb monazite age of 451 ± 4 Ma from the Yell Sound Group on Yell.

Late Ordovician (454–443 Ma) ages

White mica ages between 454.0 ± 1.4 and 450.9 ± 1.3 Ma were obtained from samples spread over a geographically wide area. In west Yell, a micaceous gneiss yielded an age of 454.0 ± 1.4 Ma

Table 2. *Rb–Sr ages for Shetland Caledonides*

Sample fraction	Rb (ppm)	Sr (ppm)	$^{87}Sr/^{86}Sr$	2SE	$^{87}Rb/^{86}Sr$	2SE	$^{87}Sr/^{86}Sr_{init}$	Age (Ma)
West of the Walls Boundary Fault								
SW12-01 Pl	11.16	210.7	0.709788	0.000011	0.1528	0.0004		
SW12-01 Ms 1	189.9	44.81	0.833987	0.000012	12.372	0.035	0.708234	723.8 ± 2.2
SW12-01 Ms 2	194.9	44.84	0.835556	0.000011	12.686	0.037	0.708244	714.6 ± 2.1
SW12-01 Ms 3	185.8	43.72	0.832417	0.000008	12.405	0.037	0.708258	712.8 ± 2.1
SW12-02 Pl	10.47	107.4	0.722483	0.000018	0.2816	0.0008		
SW12-02 Ms 1	165.3	117.1	0.761373	0.000011	4.092	0.012	0.719611	726.8 ± 2.2
SW12-02 Ms 2	159.4	110.20	0.761050	0.000012	4.193	0.013	0.719706	702.3 ± 2.2
SW13-01 Pl	10.46	177.8	0.709926	0.000007	0.1697	0.0005		
SW13-01 Ms	147.4	56.47	0.752567	0.000019	7.560	0.023	0.708947	411.8 ± 1.2
SW13-03 Pl	9.201	225.4	0.708696	0.000012	0.1177	0.0003		
SW13-03 Ms	271.4	169.8	0.734981	0.000017	4.620	0.013	0.708009	416.6 ± 1.2
SW13-10 Pl	13.84	43.95	0.727437	0.000009	0.9093	0.0025		
SW13-10 Ms	325.9	110.2	0.775138	0.000009	8.588	0.024	0.721788	443.2 ± 1.3
SW13-17 Pl	70.21	236.2	0.726032	0.000008	0.8586	0.0024		
SW13-17 Ms 1	302.6	112.8	0.775466	0.000011	7.788	0.022		
SW13-17 Ms 2	302.6	112.3	0.775918	0.000011	7.820	0.022	0.719895	508.8 ± 1.1
							MSWD	3.2
SW13-22 Pl	67.11	421.1	0.718716	0.000007	0.4600	0.0013		
SW13-22 Ms	274.6	29.38	0.889064	0.000029	27.421	0.077	0.715810	450.8 ± 1.4
East of the Walls Boundary Fault								
Mainland								
SW12-03 Pl	367.4	233.4	0.748864	0.000009	4.5574	0.0128		
SW12-03 Ms	491.1	24.99	1.113617	0.000018	58.91	0.17	0.718276	478.7 ± 1.4
SW12-03 Bt	771.3	8.557	2.662386	0.000028	309.6	0.87	0.72027	447.6 ± 1.4
SW12-04 Pl	5.752	747.7	0.724212	0.000010	0.0221	0.0001		
SW12-04 Ms	211.1	73.72	0.776912	0.000014	8.360	0.0251	0.7240716	450.9 ± 1.4
SW12-05 Pl	24.34	736.1	0.724033	0.000014	0.0954	0.0003		
SW12-05 Ms 1	194.3	106.49	0.759141	0.000011	5.286	0.015		
SW12-05 Ms 2	204.9	118.28	0.757184	0.000010	5.018	0.015		
SW12-05 Ms 3	196.2	112.32	0.757511	0.000011	5.061	0.015	0.723389	480.9 ± 0.8
							MSWD	2.3
SW12-06 Pl	216.6	515.6	0.731926	0.000011	1.21624	0.0034		
SW12-06 Ms	308.2	34.05	0.900985	0.000013	26.585	0.074	0.724105	475.4 ± 1.4
SW12-06 Bt	434.9	40.24	0.913525	0.000012	31.78	0.089	0.724701	424.0 ± 1.3*
SW12-07 Pl	12.69	166.2	0.723487	0.000012	0.22046	0.0006		
SW12-07 Ms 1	571.8	12.69	1.666280	0.000020	142.05	0.39		
SW12-07 Ms 2	563.3	12.09	1.700337	0.000049	147.37	0.41	0.722023	473.6 ± 0.9
							MSWD	0.05
SW12-09 Pl	257.3	244.9	0.774629	0.000014	3.0486	0.0085		
SW12-09 Ms	361.5	23.04	1.06342	0.00011	46.82	0.13	0.754607	470.7 ± 1.4
AB08-20 Pl	237.7	209.7	0.744600	0.000006	3.2782	0.0092		
AB08-20 Ms	528.8	18.24	1.311965	0.000031	88.52	0.25	0.722847	474.8 ± 1.4
Yell								
SW12-10 Pl	13.03	908.9	0.716395	0.000001	0.0413	0.0001		
SW12-10 Ms	257.7	70.41	0.785055	0.000011	10.634	0.029	0.716127	462.4 ± 1.4
SW12-10 Ms 2	262.4	68.55	0.787888	0.000009	11.121	0.0033	0.716128	460.3 ± 1.4
SW12-10 Bt	404.0	5.57	2.142894	0.000033	238.54	0.67	0.719375	426.8 ± 1.3*
SW12-11 Pl	37.74	279.9	0.732745	0.000015	0.389	0.097		
SW12-11 Ms	260.6	21.84	0.954260	0.000061	35.201	0.011	0.730264	454.0 ± 1.4
SW12-11 Bt	384.8	11.94	1.305162	0.000017	98.34	0.28	0.730467	417.0 ± 1.3
SW12-19 Pl	25.752	312.0	0.730488	0.000011	0.2384	0.0007		
SW12-19 Ms	200.2	147.0	0.751298	0.000011	3.943	0.011	0.729174	400.9 ± 1.2*
AB08-05 Pl	71.86	262.1	0.721808	0.000006	0.7917	0.0022		
AB08-05 Ms	513.8	22.54	1.158625	0.000017	68.62	0.19	0.716750	459.4 ± 1.4
Fetlar								
SW12-14 Pl	18.19	650.3	0.723970	0.000011	0.0336	0.0001		
SW12-14 Ms	189.6	108.0	0.757171	0.000012	5.085	0.014	0.723776	468.9 ± 1.4
SW12-14 Bt	345.5	10.37	1.370556	0.000017	102.27	0.29	0.723779	451.2 ± 1.4
Unst								
SW12-17 Pl	13.26	1117	0.716285	0.000001	0.0342	0.0001		
SW12-17 Ms 1	197.9	198.1	0.733695	0.000013	2.8884	0.0081	0.716087	435.2 ± 1.3*
SW12-17 Ms 2	178.7	226.1	0.729868	0.000011	2.2837	0.0069	0.716082	430.9 ± 1.3*
SW12-18 Pl	11.31	575.9	0.722462	0.000011	0.0567	0.0002		
SW12-18 Ms	214.4	79.11	0.773094	0.000015	7.863	0.022	0.722126	462.7 ± 1.4
SW13-24 Pl	164.1	404.6	0.733803	0.000006	1.1725	0.0033		
SW13-24 Ms	272.1	23.46	0.950007	0.000016	34.236	0.096	0.726136	466.5 ± 1.4
SW13-25 Pl	28.56	308.0	0.726164	0.000007	0.2678	0.0007		
SW13-25 Ms	253.6	231.5	0.744054	0.000006	3.1688	0.0089	0.724512	444.0 ± 1.3*

*Ages regarded as not meaningful owing to either the unradiogenic nature of the mica separate or chloritization of the biotite separate.
All age uncertainties are stated to 2σ. Ms, white mica fraction; Bt, biotite fraction; Pl, plagioclase fraction.

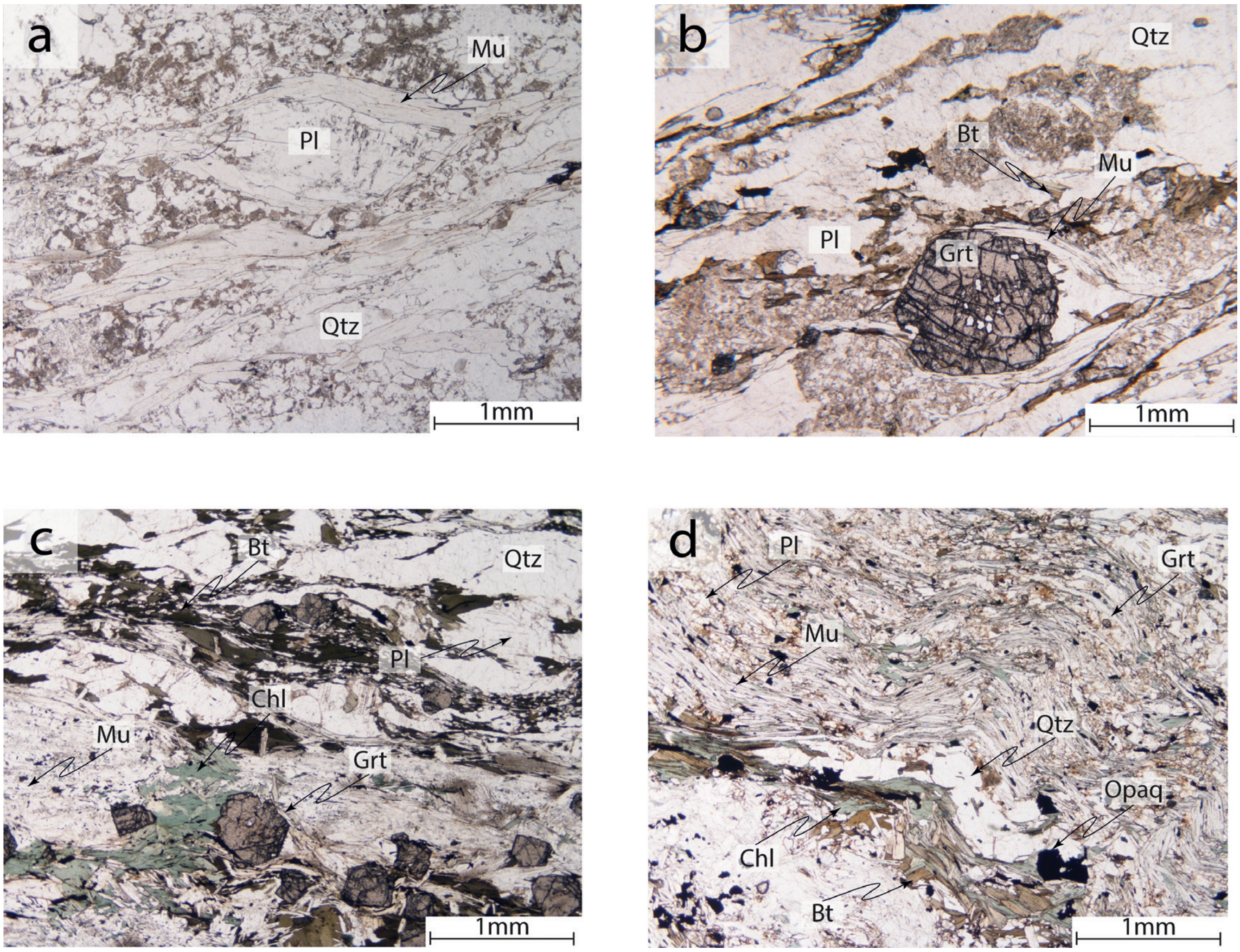

Fig. 6. Representative thin section photomicrographs in plane-polarized light: (**a**) SW12-07; (**b**) SW13-17; (**c**) SW12-14; (**d**) SW13-25. Mineral name abbreviations taken from Kretz (1983).

(Fig. 3), and an East Mainland Succession foliated granite–gneiss from the eastern part of Mainland (SW12-04, Fig. 1) yielded a white mica age of 450.9 ± 1.4 Ma. The significance of this age is difficult to assess given that the sample site is located approximately equidistant from three other samples (SW12-03, SW12-05 and SW12-06) that yielded significantly older Ordovician ages (see above), even though all samples apparently carry the same steep foliation. The coarse-grained gneissose nature of sample SW12-04 (mica up to 1.5 cm and feldspar up to 3 cm) may suggest that it reached a higher metamorphic grade than surrounding lithologies, hence taking longer to reach isotopic equilibrium. Alternatively, the regional, steep foliation is composite, and the age relates to a younger tectonothermal event.

A semi-pelite from the west of the Walls Metamorphic Series (SW13-22, Fig. 1) yielded a white mica age of 450.8 ± 1.4 Ma. In the absence of any detailed information on *P–T* conditions for the western part of the Walls Metamorphic Series, and in view of a lack of metamorphic indicator minerals within the sample, this age is interpreted as a deformational age, similar to those obtained from the Yell Sound Group in Yell.

In the far east of North Roe, a psammite sampled from the Sand Voe Group immediately to the west of the Virdibreck Shear Zone (SW13-10; Fig. 2) yielded an age of 443.2 ± 1.3 Ma. The sample carries a strong, locally mylonitic schistosity defined by muscovite and chlorite. These characteristics are consistent with broadly greenschist-facies temperatures, suggesting that the white mica age is dating deformation.

Two Silurian white mica ages were obtained, both from Unst, but their significance is difficult to assess. A sample of the Saxa Vord Schist collected east of the Burrafirth lineament (SW13-25, Fig. 3) yielded an age of 440.0 ± 1.3 Ma, but the low $^{87}Rb/^{86}Sr$ in the white mica suggests that the age may not be robust. A deformed pegmatite within the Westing Group in western Unst (SW12-17, Fig. 3) has yielded ages of 435.2 ± 1.3 and 430.9 ± 1.3 Ma. The sample has a rather small difference of $^{87}Sr/^{86}Sr$ between the white mica and feldspar phases, and repeat analyses provided significantly different ages, suggesting that the age determination is not meaningful.

Devonian (c. 410 Ma) white mica ages

In western North Roe, samples of mylonitic Wilgi Geos orthogneiss were collected within the Uyea Shear Zone. Sample SW13-01 collected from within the shear zone yielded a white mica Rb–Sr age of 411.8 ± 1.2 Ma (Fig. 2). Sample SW13-03 was collected *c.* 400 m to the east and yielded an age of 416.6 ± 1.2 Ma (Fig. 2). Both carry apparently the same east-dipping mylonitic schistosity, which is defined by trails of aligned mica, and elongate aggregates of recrystallized quartz and feldspar (Fig. 7). Syndeformational temperatures must have exceeded 450–500°C as indicated by the ductile recrystallization of feldspar, but are otherwise difficult to evaluate in the dominantly quartzo-feldspathic lithology. Accordingly, the interpretation is that the white mica ages record the time of deformation.

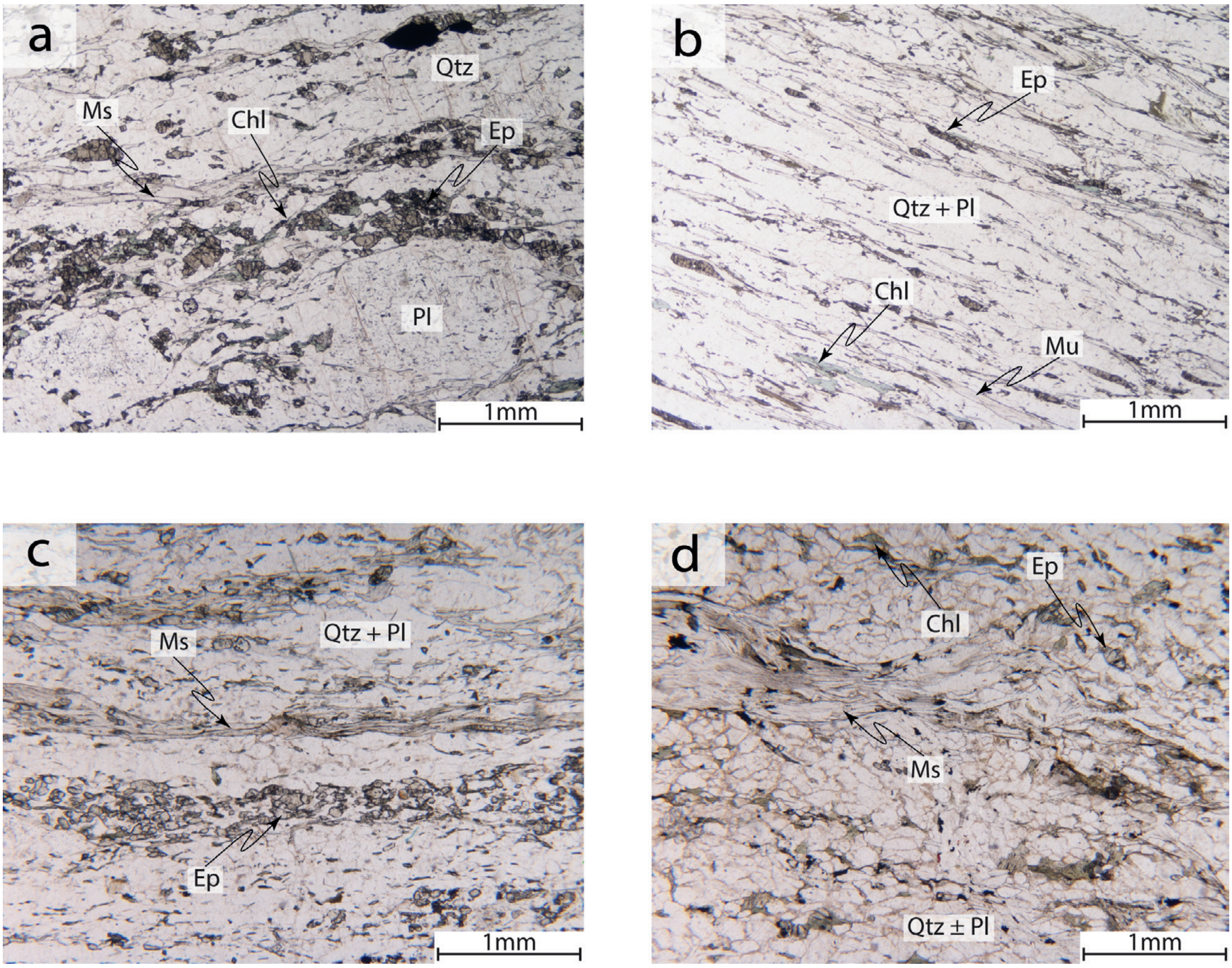

Fig. 7. Thin section photomicrographs in plane-polarized light from North Roe: (**a**) SW12-01; (**b**) SW12-02; (**c**) SW13-01; (**d**) SW13-03. Mineral name abbreviations taken from Kretz (1983).

A synkinematic felsic sheet within the Yell Sound Group in north Yell (SW12-19, Fig. 3) yielded a white mica age of 400.9 ± 1.2 Ma, the youngest of this study. Although the white mica appears fresh and unaltered, it has an unusually low $^{87}Rb/^{86}Sr$ of 3.9. Furthermore, plagioclase has undergone intense sericitization, a process that has the potential to lead to metasomatic changes to the Rb/Sr system during fluid flux. The age is therefore not considered to be geologically meaningful.

Late Ordovician–Devonian (451–417 Ma) biotite ages

Five biotite ages have been obtained from samples that also yielded white mica ages reported above. The biotite ages fall into two groups. The older group is represented by samples SW12-03 from central Mainland (Fig. 1) and SW12-14 from Fetlar (Fig. 3), which yielded ages of 447.6 ± 1.4 Ma and 451.2 ± 1.4 Ma, respectively. The younger group is represented by samples SW12-10 and SW12-11 from west Yell (Fig. 3), which yielded, respectively, ages of 426.8 ± 1.3 Ma and 417.0 ± 1.3 Ma, and SW12-06 from eastern Mainland (Fig. 3), which provided an age of 424.0 ± 1.3 Ma. Of this younger group, only one of the ages is likely to be robust (SW12-11: 417.0 ± 1.3 Ma), as chloritization is observed within the other two samples. There is no evidence that chloritization has affected the other biotite ages reported here.

Discussion

The Rb–Sr ages reported here provide new constraints on the ages of deformation fabrics and mineral assemblages within major lithological units in Shetland. Furthermore, comparison of these with the growing database of mineral ages obtained from the Caledonides of mainland Scotland, East Greenland and Scandinavia allows conclusions to be drawn concerning the regional correlations of orogenic events.

Evidence for Knoydartian deformation and metamorphism in North Roe

The white mica ages of *c*. 727–702 Ma obtained from the vicinity of the Wester Keolka Shear Zone indicate that the dominant foliation here is Neoproterozoic in age. It probably relates in a general way to slightly older Knoydartian orogenic events dated between 820 and 735 Ma in the Moine Supergroup of mainland Scotland (Rogers *et al*. 1998; Vance *et al*. 1998; Cutts *et al*. 2010; Cawood *et al*. 2015) and the Laurentian-derived Sørøy Succession of northern Norway (Kirkland *et al*. 2006, 2008). The overall tectonic significance of these orogenic events has been much debated, the most recent syntheses suggesting that they correspond to accretionary events along a proximal active margin of the Rodinia supercontinent (Cawood *et al*. 2010, 2015; Kirkland *et al*. 2011). Although there is evidence of Neoproterozoic metamorphism within the Westing Group in western Unst at *c.* 930 Ma (Cutts *et al.* 2009), younger Cryogenian Knoydartian orogenesis has hitherto been unreported in Shetland. This is important for regional tectonic models, as Knoydartian events are now shown to extend significantly northwards from northern mainland Scotland to Shetland. This sector of North Roe is of particular importance, as it appears to be the only area in the Scottish Caledonides where the dominant metamorphic fabrics are Knoydartian, and do not appear to have been extensively reworked during subsequent Caledonian events. However, some very localized Caledonian reworking may be indicated by the Ordovician (466 ± 6 Ma) $^{40}Ar/^{39}Ar$ muscovite age reported by Flinn (2009). The new data reported here therefore indicate that the Wester Keolka Shear Zone cannot be correlated with the Silurian (*c.* 430 Ma) Moine Thrust Zone in mainland Scotland (see Andrews 1985; Ritchie *et al.* 1987; Flinn 1992, 1993; McBride & England 1994). No evidence currently precludes the suggestion that the Wester Keolka Shear Zone is essentially a highly tectonized basement–cover unconformity (Pringle 1970), and therefore not a significant regional structure.

Timing of metamorphism and age of the Walls Metamorphic Series

The white mica ages of *c.* 509 and *c.* 451 Ma obtained from, respectively, the eastern and western sectors of the Walls Metamorphic Series are clearly consistent with Caledonian metamorphism, and most probably record more than one thermal event. The *c.* 509 Ma age is rather older than most published ages that have been related to the Grampian orogenic event. However, broadly similar ages have been recorded in western Ireland and the southwestern part of the Grampian Highlands of Scotland and interpreted to represent the onset of deformation and metamorphism (Chew *et al.* 2010). However, with a lack of similar (*c.* 500 Ma) ages from other dated samples in Shetland, the significance of this age is difficult to assess.

The lack of any evidence from the present study for Neoproterozoic metamorphism in the Walls Peninsula means that the interpretation of Flinn *et al*. (1979) that the Walls Metamorphic Series represents a *c.* 1.0 Ga 'Grenvillian' metamorphic complex must be called into question.

Extent and nature of Grampian orogenesis in Shetland

The ages reported here, in combination with published isotopic data (Cutts *et al*. 2011; Crowley & Strachan 2015), constrain the main deformation fabrics and metamorphic assemblages within the East Mainland Succession and the Yell Sound Group to have formed during the 480–460 Ma Grampian orogenic event. Formation of the gently dipping (thrust-related?) foliations on Unst and Fetlar, the late retrogressive shear zone that underlies the Unst Ophiolite, and the 'central steep belt' on Mainland are therefore bracketed between the *c.* 484 Ma U–Pb zircon age obtained from the metamorphic sole of the lower ophiolite sheet in Unst (Crowley & Strachan 2015) and the *c.* 460 Ma ages reported above from Unst and Yell. The Grampian structure of Shetland is dominated by the steep, possibly transpressive fabrics of the 'central steep belt', in marked contrast to the Grampian Highlands of Scotland, which are characterized by large, Alpine-scale recumbent folds (e.g. Bailey 1922; Roberts & Treagus 1977; Thomas 1979; Krabbendam *et al*. 1997). However, the 'central steep belt' in Shetland could be analogous to, and a larger-scale example of, belts of steep high strain in the Grampian Highlands such as the Geal Charn–Ossian Steep Belt, which resulted from late-stage upright reworking of early flat-lying foliations and fold nappes (Thomas 1979; Robertson & Smith 1999).

The significantly younger Late Ordovician white mica and biotite ages are difficult to evaluate in the absence of additional data from different chronometers and mineral phases. The central issue is whether or not Shetland was affected by younger orogenic events, the *c.* 450–445 Ma 'Grampian II' accretionary event recognized in northern mainland Scotland (Bird *et al.* 2013; Cawood *et al.* 2015) and the *c.* 435–425 Ma Scandian event. Although the U–Pb monazite ages obtained by Cutts *et al*. (2011) from eastern Yell (451 ± 4 Ma) and western Unst (462 ± 10 Ma) overlap within error, the high uncertainty of the latter age does not allow for correlation with either the *c.* 450 Ma Grampian II or the *c.* 480–460 Ma Grampian event. However, the *c.* 462–451 Ma white mica ages reported here from Yell and Mainland Shetland are interpreted as dating deformation, and are essentially identical to the U–Pb monazite age determinations of Cutts *et al*. (2011) for Yell and Unst. Hence these ages may be recording the Late Ordovician Grampian II orogenesis. The 451–447 Ma biotite ages may relate to cooling, as there is no evidence of a biotite-bearing fabric overprinting an older muscovite-bearing fabric in any of the samples.

The comparison of white mica and biotite Rb–Sr ages (468.9 ± 1.4 Ma and 451.2 ± 1.4 Ma respectively) from a migmatitic pelite from the footwall of the ophiolite on Fetlar (SW12-14) shows a difference between white mica and biotite ages of 17 myr, which suggests that biotite may have been isotopically disturbed during a later event. It is important to note that these conclusions are based on a limited dataset of biotite ages in the immediate footwall of the ophiolite, and that further work is needed to constrain differences in the biotite and white mica Rb–Sr ages in Shetland.

The white mica age of *c.* 443 Ma obtained from a strongly deformed Sand Voe Group psammite immediately to the west of the Virdibreck Shear Zone is thought to be dating deformation. The 450.8 ± 1.4 Ma white mica age obtained from the western Walls Metamorphic Series (see above) suggests that the area west of the Walls Boundary Fault may have been affected by the Late Ordovician Grampian II orogenic event. Further detailed work is necessary to establish the kinematic significance of the dated fabrics.

The lack of Silurian Scandian ages in Shetland is attributed to a likely location at a high structural level in the Scandian nappe pile relative to the Northern Highland Terrane of mainland Scotland where Silurian reheating was pervasive (Dallmeyer *et al.* 2001).

Significance of Devonian ages in North Roe

The ages of *c.* 416 and c. 411 Ma obtained from the Uyea Shear Zone are consistent with an early Devonian age for this structure. This is entirely feasible in the context of published data that indicate diachronous, northward-younging evolution of the marginal thrust belt that defines the western margin of the Laurentian Caledonides. In Scotland, development of the Moine Thrust Zone is known to have been essentially complete by *c.* 430 Ma (Freeman *et al*. 1998; Dallmeyer *et al*. 2001; Goodenough *et al*. 2011). In contrast, marginal thrusting in East Greenland continued until at 400–380 Ma (Dallmeyer *et al*. 1994), a necessary requirement to accommodate early Devonian (*c.* 400 Ma) high-pressure metamorphism within the internal sector of the orogen (Gilotti *et al*. 2004). This difference indicates the long-lived nature of the collision between Baltica and the East Greenland sector of Laurentia. Marginal thrusting on the Baltica side of the orogeny in west Norway also continued into the early Devonian (Fossen & Dunlap 1998).

In light of the above considerations, could the Uyea Shear Zone be structurally analogous to the Moine Thrust, and the Uyea Group orthogneisses therefore represent the Caledonian foreland? The Uyea Group and Wilgi Geos Group orthogneisses have similar protolith ages and chemical compositions (S. Walker, unpublished data), and it could be argued that these features are consistent with relatively limited displacement across the shear zone, although they are not definitive. An alternative solution is that the western margin of the Caledonides in NW Shetland is located some distance offshore of North Roe. However, we acknowledge that we cannot preclude significant extensional displacement(s) across the Uyea Shear Zone, and note the close correspondence in age to extensional detachments in East Greenland and Scandinavia (Krabbendam & Dewey 1998; Hartz *et al*. 2001; Fossen 2010). The tectonic significance of the Uyea Shear Zone is therefore uncertain at present.

Conclusions

(1) White mica ages of 723–702 Ma obtained from the vicinity of the Wester Keolka Shear Zone in the North Roe area indicate that the dominant foliation here is Neoproterozoic in age, and probably relates to Knoydartian orogenic events dated in mainland Scotland. This is the only area in the Scottish Caledonides where the dominant metamorphic fabrics are Knoydartian, and do not appear to have been extensively reworked during Caledonian events. The Wester Keolka Shear Zone cannot therefore be correlated with the Silurian Moine Thrust Zone in mainland Scotland and it may simply represent a highly tectonized basement–cover unconformity (see Pringle 1970).

(2) The oldest white mica age obtained from the Walls Metamorphic Series is *c*. 509 Ma. Although this age is difficult to interpret given the absence of similar ages within the Caledonides of Shetland, no evidence supports the view that the Walls Metamorphic Series represents a *c*. 1.0 Ga 'Grenvillian' metamorphic complex (see Flinn *et al.* 1979)

(3) White mica ages of *c*. 481–459 Ma obtained from the East Mainland Succession and Yell Sound Group, in combination with published isotopic data, constrain the main deformation fabrics and metamorphic assemblages to have formed during the *c*. 480–460 Ma Grampian orogenic event, approximately contemporaneous with peak Grampian orogenesis in the Moine and Dalradian supergroups of mainland Scotland.

(4) Significantly younger white mica ages of *c*. 454–443 Ma on Yell and Mainland Shetland, and biotite ages of *c*. 444 Ma, are interpreted as most probably recording fabric development during the *c*. 450 Ma 'Grampian II' event identified in the Moine Nappe of the Northern Highland Terrane.

(5) Ages of *c*. 416 and *c*. 411 Ma from within the Uyea Shear Zone are consistent with an early Devonian or slightly older age for this structure, consistent with published data that indicate diachronous, northward-younging evolution of the marginal thrust belt that defines the western margin of the Laurentian Caledonides. Whether the Uyea Shear Zone is structurally analogous to the Moine Thrust, or the western margin of the Caledonides in NW Shetland is located some distance offshore is uncertain. The paucity of ages that relate to the Silurian Scandian (*sensu stricto*) event in Shetland is attributed to a likely location at a high structural level in the Scandian nappe pile relative to the Northern Highland Terrane, where Silurian reheating was pervasive.

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