U–Pb zircon geochronology and geodynamic significance of ‘Newer Granite’ plutons in Shetland, northernmost Scottish Caledonides

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Abstract

U–Pb zircon ages obtained from the late- to post-tectonic ‘Newer Granite’ suite in Shetland, northernmost Scottish Caledonides, indicate a significantly more protracted intrusion history than was inferred previously from K–Ar data. Emplacement of the Brae Complex (c. 465 Ma), Graven Complex (c. 440 Ma) and the Muckle Roe Granophyre (c. 438 Ma) followed regional deformation and metamorphism of metasedimentary successions during the Grampian orogenic event, and is attributed to NW-directed subduction beneath Laurentia. The almost complete absence of plutons of this age along strike in mainland Scotland suggests a change in subduction angle and/or the distance between the subduction zone and the Laurentian margin. Intrusion of the Ronas Hill Granite (c. 427 Ma) was approximately coeval with displacement on the Moine Thrust in mainland Scotland, and so was likely emplaced during Baltica-Laurentia collision. A gap of c. 35 myr followed before emplacement of the Mangaster Voe intrusion and Eastern Granophyre (c. 390 Ma), and a further gap of c. 20 myr before emplacement of the Sandsting Complex (c. 370 Ma). Both periods of magmatism are attributed to pulses of localised lithospheric melting in the

vicinity of the Walls Boundary Fault during Devonian sinistral relative displacements between Laurentia and Baltica.

[End of abstract]

The Caledonian orogenic belt of Britain and Ireland (Fig. 1a) is classic ground for the study of the emplacement and petrogenesis of granitic (*sensu lato*) plutons (e.g. Read 1961; Pitcher & Berger 1972; Hutton 1982; Stephens & Halliday 1984; Thompson & Fowler 1986; Thirlwall 1988; Jacques & Reavy 1994; Atherton & Ghani 2002; Fowler *et al.* 2008; Neilson *et al.* 2009; Miles *et al.* 2016). Orogenesis resulted from the closure of the Iapetus Ocean in the Ordovician–Silurian, culminating in the sinistrally oblique collision of three continental blocks: Laurentia, Baltica, and Avalonia (Fig. 1b; Pickering *et al.* 1988; Soper *et al.* 1992). Final stages of the orogeny were associated with emplacement of the Silurian–Devonian ‘Newer Granites’ suite (Read 1961). It is dominated by calc-alkaline, I-type (*sensu lato*) granodioritic intrusions, with a trend towards syenitic and alkaline compositions in northwesternmost Scotland (Atherton & Ghani 2002; Fowler *et al.* 2008). Coeval high-level dyke swarms and volcanic rocks are well developed in SW Scotland (e.g. Anderson 1937; Bailey 1960; Kokelaar & Moore 2006). Some of the earliest members of the suite were emplaced at *c.* 435–425 Ma during regional thrusting in NW Scotland (Kocks *et al.* 2006; Goodenough *et al.* 2011). However, the major plutons mostly post-date regional ductile deformation, were often emplaced at high crustal levels along steep strike-slip faults, and are hence generally regarded as ‘late-’ or ‘post-’ orogenic (Jacques & Reavy 1994; Stewart *et al.* 2001; Kocks *et al.* 2014). Although the term ‘Newer Granites’ has generally been restricted in its use to the Siluro–Devonian plutons of the Scottish and Irish Caledonides, lithologically and geochemically similar plutons of this age also occur along strike further north in East Greenland, and within the Laurentian-derived allochthons of Scandinavia (Fig. 1).

Models for the Laurentian Caledonides of Scotland and Ireland envisage initiation of southeast-dipping (present reference frame) subduction zones in the Iapetus Ocean in the late Cambrian to early Ordovician. Collision of an oceanic magmatic arc with the Laurentian passive margin was associated with obduction of fore-arc ophiolites (Ryan & Dewey 1991) and regional ‘Grampian’ deformation and metamorphism of Dalradian and Moine successions of the Grampian and Northern Highland terranes (Lambert & McKerrow 1976;

66 Oliver *et al.* 2000; Chew *et al.* 2010). In Scotland, the magmatic arc is thought to be buried
67 beneath the Devonian and younger cover successions of the Midland Valley Terrane (Bluck
68 2002 and references therein). The Grampian orogenic event in Scotland and Ireland is
69 analogous to the approximately coeval Finnmarkian event in the Laurentian-derived
70 Uppermost Allochthon of Scandinavia (Fig. 1b; Roberts 2003). Following a change in
71 subduction to northwest-directed and initiation of an accretionary prism in the Southern
72 Uplands Terrane, renewed 'Grampian II' deformation and metamorphism at c. 445–450 Ma
73 has been attributed to terrane accretion (Bird *et al.* 2013) and flat-slab subduction (Dewey
74 *et al.* 2015) in different places. The late Silurian sinistrally oblique collision of Baltica and
75 Laurentia at c. 430–425 Ma formed the Himalayan-scale Scandian orogen (Gee 1975). In
76 contrast, the coeval Avalonia-Laurentia collision was relatively soft and did not result in
77 major crustal thickening (Soper & Woodcock 1990).

78 Much of the 'Newer Granite' suite cannot be associated directly with subduction as
79 it postdates continental collision by up to 20–25 myr, and has therefore been attributed to
80 asthenospheric and crustal melting following slab break-off (Atherton & Ghani 2002; Neilson
81 *et al.* 2009). Pluton emplacement was facilitated by development of a major orogen-parallel,
82 sinistrally transcurrent fault system in the c. 425–410 Ma interval (Jacques & Reavy 1994;
83 Dewey & Strachan 2003). This was followed by a transition to a sinistrally transtensive
84 deformation regime from c. 415 to 395 Ma during which many Old Red Sandstone basins
85 developed in Scotland, East Greenland, Scandinavia and Svalbard (Dewey & Strachan 2003;
86 Soper & Woodcock 2003). Early-Middle Devonian sinistral displacement of at least 700 km
87 along the Great Glen Fault juxtaposed the Northern Highland Terrane (Fig. 1; the only part
88 of Scotland affected by the Scandian collision) with the Grampian Terrane (Coward 1990;
89 Dallmeyer *et al.* 2001; Dewey & Strachan 2003).

90 Shetland formed part of the Laurentia palaeocontinent and occupies a unique
91 location within the North Atlantic Caledonides due to its pre-Mesozoic proximity to the East
92 Greenland, Scottish, and Norwegian sectors of the orogen (Fig. 1b). The northernmost
93 examples of plutons assigned to the 'Newer Granite' suite are exposed on Shetland (Fig. 2),
94 but are the most poorly documented of all in terms of their age, chemistry and
95 petrogenesis. Three granites yielded K–Ar mineral ages of between 405–397 Ma (Miller &
96 Flinn 1966) and this led to the perception that these plutons are mainly Devonian in age.
97 The Sandsting Complex (Fig. 2) intrudes Middle Devonian sedimentary rocks and is possibly

the youngest member of the 'Newer Granite' suite. This study: 1) provides new U–Pb zircon ages for the crystallisation of six major plutons in Shetland, 2) uses these ages to place constraints on the ages of structures and regional metamorphic events within Shetland, and 3) discusses the geodynamic significance of these plutons in the context of regional tectonic models.

Regional geology of Shetland

Many of the 'Newer Granite' plutons of Shetland intrude strongly-deformed amphibolite to greenschist facies metasedimentary successions that originated as part of the Laurentia palaeocontinent and have been correlated with various components of the geology of mainland Scotland to the south and East Greenland and Scandinavia to the north (Flinn *et al.* 1972, 1979; Flinn 1985, 1988; Prave *et al.* 2009). The sub-vertical Walls Boundary Fault divides Shetland into two tectonic blocks (Fig. 2). Flinn (1977) proposed sinistral strike-slip displacement of at least 200 km, but if it is the continuation of the Great Glen Fault, as commonly supposed (Fig 1; Flinn 1961, 1977, 1993; Watts *et al.* 2007), displacements may be at least 700 km (Dewey & Strachan 2003).

West of the Walls Boundary Fault, the oldest lithologies are the Archaean orthogneisses of the Uyea Group exposed north of the Ronas Hill Granite (Fig. 2; Flinn 1985). These are succeeded to the east by the metasedimentary Sand Voe Group, which has been correlated with the Neoproterozoic Moine Supergroup of NW Scotland (Pringle 1970; Flinn 1988). The intervening east-dipping Wester Keolka Shear Zone has been correlated with the Silurian Moine Thrust, which defines the western margin of the Caledonides on mainland Scotland (Andrews 1985; Ritchie *et al.* 1987; Flinn 1992, 1993; McBride & England 1994). However, Walker *et al.* (2016) have shown that the Wester Keolka Shear Zone is a Neoproterozoic structure and the western front of the Caledonides in Shetland may alternatively be defined by the early Devonian Uyea Shear Zone a few kilometres to the west or located some distance offshore. East of the Sand Voe Group, the mainly metasedimentary Queyfirth Group may correlate with the Neoproterozoic to Cambrian Dalradian Supergroup that underlies large tracts of the Grampian Terrane in mainland Scotland (Flinn 1988). Further south, on the northern margin of the Walls Peninsula, the

orthogneisses and metasedimentary rocks of the Walls Metamorphic Series are of uncertain protolith age, but speculatively assigned to the Archaean in Figure 2.

East of the Walls Boundary Fault, the metasedimentary Yell Sound Group and the Westing Group (Fig. 2) were metamorphosed at *c.* 930 Ma (Cutts *et al.* 2009, 2011). Both successions are thought to be time-equivalent to older parts of the Moine Supergroup (Flinn 1988) and include inliers of Lewisian-type basement (Flinn 1994, 2014). They are succeeded eastwards by the metasedimentary East Mainland Succession, although the presumed intervening unconformity is obscured by high tectonic strain (Flinn 1988). The East Mainland Succession is partly time-equivalent with the Dalradian Supergroup, and hence probably accumulated on the passive margin of Laurentia during continental breakup and development of the Iapetus Ocean (Anderton 1985; Prave *et al.* 2009; Strachan *et al.* 2013).

The earliest phase of the Caledonian orogeny in Shetland corresponds to the obduction of the Unst ophiolite during the early Ordovician Grampian orogenic event (Fig. 2; Spray 1988; Crowley & Strachan 2015). This resulted from collision of the Laurentian passive margin with an intra-oceanic magmatic arc (Ryan & Dewey 1991). In mainland Scotland and Ireland, the Grampian orogenic event resulted in large-scale recumbent folding of the Dalradian Supergroup to form structures such as the Tay Nappe (e.g. Shackleton 1958; Tanner 2014). In Shetland by contrast, early recumbent folding was followed by formation of the regional 'steep belt' that dominates the structure of Yell and Mainland Shetland east of the Walls Boundary Fault. Rb–Sr mineral ages indicate that this was formed by *c.* 480–470 Ma (Walker *et al.* 2016). Localised ductile deformation at amphibolite facies at *c.* 450 Ma (Walker *et al.* 2016), may represent the younger 'Grampian II' accretionary event identified in mainland northern Scotland (Bird *et al.* 2013). The dominant ductile fabrics and metamorphic assemblages in Shetland therefore appear to have formed during the Ordovician, with evidence of only localised deformation at greenschist facies during the Silurian Scandian orogenic event. This suggests that Shetland occupied a relatively high structural level in the regional nappe pile during the final Baltica-Laurentia collision.

The final stages of the Caledonian orogeny in Shetland were followed by accumulation of Devonian terrestrial sedimentary and volcanic successions (Fig. 2; Mykura 1976; Mykura & Phemister 1976; Stephenson 1999; Marshall 2000). The oldest Melby Formation outcrops west of the Melby Fault (Fig. 2) and is Eifelian in age (Marshall 2000). On the Walls Peninsula (Fig. 2), the younger Walls Group is Givetian in age (Marshall 2000),

and contains evidence for two phases of folding accompanied by low-grade metamorphism (Mykura & Phemister 1976). The Walls Group is interpreted to have been deposited and progressively deformed in a sinistral pull-apart basin between the Melby and Walls Boundary faults (Seranne 1992; Dewey & Strachan 2003).

‘Newer Granite’ plutons of central and northwest Shetland

The metasedimentary successions of Shetland contain numerous pre- to syn-orogenic mafic and felsic igneous rocks that share the metamorphic and structural history of their country rocks (e.g. Mykura 1976; Flinn 1985, 1988). The focus of this paper is instead the largely post-orogenic ‘Newer Granite’ plutons of central and northwest Shetland (Fig. 2). These have been relatively poorly studied, the only descriptions provided by Phemister *et al.* (1950), Mykura (1976) and Mykura and Phemister (1976). These intrusions were divided into two groups by Mykura (1976), east and west of the Walls Boundary Fault.

Eastern complexes

The two intrusions that are included in the present study are the Brae and Graven complexes (Fig. 2). The *Brae Complex* is a composite, steep-sided intrusion dominated by a two-pyroxene diorite with subordinate masses of peridotite, pyroxenite and dunite (Mykura 1976). It cuts across the steeply-dipping tectonic boundary between the Yell Sound Group and the East Mainland Succession (Fig. 2). The main outcrop of the *Graven Complex* occupies a similar structural setting a few kilometres to the north-northeast (Fig. 2), and was described by Mykura (1976) as comprising two superimposed vein complexes. Metre- to decametre-scale metasedimentary inclusions are abundant, and their foliation trends are parallel to those of the country rocks, suggesting they have not been disorientated significantly from each other. The oldest intrusive phase is represented by veins, pods and dykes of granite and pegmatite, and slightly younger lamprophyre and porphyrite dykes. The youngest phase comprises a network of intrusive sheets of diorite, monzonite, granodiorite and granite with mafic enclaves of hornblendite (Mykura 1976).

Western complexes

193

194 These comprise two main composite bodies, the *Northmaven* and *Sandsting* complexes (Fig.
195 2). The Northmaven Complex includes various types of granite, granophyre, diorite and
196 gabbro with minor occurrences of ultrabasic rock. The complex can be divided into three
197 major bodies: the Ronas Hill Granite, the Mangaster Voe Intrusion and closely associated
198 Eastern Granophyre, and the Muckle Roe Granophyre (Fig. 2; Mykura & Phemister 1976;
199 British Geological Survey 2004). A wide range of dykes and other minor intrusions is also
200 present. The Ronas Hill Granite is a red, leucocratic granophyre with two large, sheet-like
201 bodies of hornblende gabbro and diorite. The Mangaster Voe Intrusion is dominated by
202 diorite and gabbro which are strongly net-veined by granophyre and show complex magma
203 mingling relationships along the contact with the Eastern Granophyre. Exposed intrusive
204 contacts with the Ronas Hill Granite and between the Mangaster Voe Intrusion and the
205 Eastern Granophyre are generally steep to sub-vertical. The Muckle Roe Granophyre was
206 regarded by Mykura and Phemister (1976) as the youngest component of the Northmaven
207 Complex. However, our reinvestigation of the field relationships of this intrusion fails to
208 substantiate their conclusion since much of its northeastern contact is faulted (Fig. 2). What
209 appears to be a steep primary igneous contact with the composite Mangaster Voe
210 Intrusion/Eastern Granophyre pluton is exposed on the southeast coast of Muckle Roe but
211 there is no field evidence to indicate which is the older intrusion. We therefore conclude
212 that the age of the Muckle Roe Granophyre in relation to other components of the
213 Northmaven Complex is unknown.

214 The Sandsting Complex is dominated by granite with subordinate granodiorite,
215 porphyritic microgranite and porphyritic microadamellite. The oldest components of the
216 complex are composed of diorite but magma mingling textures developed along the
217 contacts between diorite and adjacent granitic rocks indicate that mafic and felsic magmas
218 were emplaced more or less contemporaneously (Mykura & Phemister 1976). The Devonian
219 country rocks are strongly hornfelsed around the northern margin of the complex, but there
220 is no evidence within the aureole of the large-scale folds and associated cleavage which are
221 distinctive features of the Devonian rocks farther away from the aureole (Mykura &
222 Phemister 1976). This has led to the conclusion that folding and low-grade metamorphism
223 of the Devonian rocks occurred *after* the complex was intruded (Mykura & Phemister 1976).

224

Previous geochronology

Miller and Flinn (1966) obtained K–Ar biotite and muscovite ages for the Ronas Hill Granite (358 ± 8 Ma), various components of the Graven Complex (397 ± 5 Ma, 398 ± 5 Ma, 405 ± 14 Ma), and the Brae Complex (385 ± 6 Ma). The data led them to conclude that these intrusions were emplaced at c. 400 Ma. A significantly younger K–Ar age obtained by them for the Sandsting Complex (334 ± 13 Ma) is consistent with its intrusion into Middle Devonian sedimentary rocks. Mykura and Phemister (1976) quoted slightly older K–Ar mica ages of 360 ± 11 Ma and 369 ± 10 Ma obtained from the Sandsting Complex.

U–Pb zircon dating

U–Pb zircon dating was undertaken in order to place constraints on the crystallisation ages of the Brae and Graven complexes east of the Walls Boundary Fault, and various components of the Northmaven and Sandsting complexes west of the fault.

Analytical techniques

Zircons were separated from 3–4 kg samples using standard techniques, mounted, polished, and then examined in cathodoluminescence (CL) imaging to determine any growth zoning, structural defects and inclusions. U–Pb analyses were carried out by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) at the University of Portsmouth, UK. Full details are presented in the Supplementary material. Representative CL images with analytical spots are provided in Figure 3.

New U–Pb zircon ages

Sample sites are located with eight-figure grid references to the Ordnance Survey National Grid 100 km square HU. In all cases, the new U–Pb zircon ages are interpreted to correspond to the crystallisation ages of the dated intrusions as they were measured in the final growth zone of typically euhedral grains. The absence of further overgrowths, habit alteration and recrystallization of metamict zones suggests that crystallisation and

257 emplacement were penecontemporaneous within analytical precision. Concordia diagrams
258 are presented in Figure 4.

259
260 *Brae Complex.* Sample 11BC01 is an enstatite gabbro collected at Hevden Ness (HU 3566
261 6561). It is fine- to medium-grained and comprises enstatite, augite, plagioclase and minor
262 interstitial biotite. The alignment of plagioclase grains defines a linear fabric thought to have
263 formed during emplacement. Zircons are either euhedral with no obvious zoning in CL, or
264 rounded with either sector zoning or 2–3 layers with a mixture of sector and oscillatory
265 zoning (Fig. 3a). Seven grains yielded a Concordia age of 464.6 ± 4.6 Ma (Fig. 4a), with
266 inherited grains reporting mostly Proterozoic ages (one reported 2650 Ma). The Concordia
267 age was derived entirely from analyses of unzoned grains with very high U concentrations
268 (over 1000ppm), which would normally raise suspicions of Pb loss. However, since the
269 calculated age is older than any of the other samples in this study, we interpret it as a
270 minimum age of crystallisation and/or emplacement.

271
272 *Graven Complex.* Sample 11GC01 is a granodiorite collected from Muckle Head (HU 4799
273 6063). It is fine- to medium-grained, comprising quartz, plagioclase, subordinate perthitic
274 orthoclase and microcline with green hornblende, greenish-brown biotite and accessory
275 titanite, zircon, apatite and allanite. Zircons are chiefly euhedral, with oscillatory rims and
276 sector-zoned or oscillatory cores (Fig. 3b). Thirteen rims yielded a Concordia age of $439.8 \pm$
277 3.1 Ma (Fig. 4b). Comparatively little inheritance is observed, with most cores recording
278 similar ages, although four have Proterozoic or Archaean ages (the oldest at 2660 Ma).

279
280 *Northmaven Complex.* Five samples were collected to represent the main constituent
281 plutons. The *Muckle Roe Granophyre* is represented by sample 08MR02, a granite from
282 Little Ness of Ayre (HU 3222 6270). It is fine- to medium-grained, mainly comprising quartz,
283 orthoclase and plagioclase feldspar, and accessory zircon and an opaque phase. Zircons are
284 typically euhedral with oscillatory rims and homogeneous or sector-zoned cores (Fig. 3c).
285 Very few grains resulted in concordant ages, and evidence of common Pb was apparent in
286 all growth zones. Three oscillatory rims yielded a Concordia age of 438.0 ± 7.6 Ma (Fig. 4c),
287 consistent with the common Pb regression intercept age of 433.8 ± 4.0 Ma.

The *Ronas Hill Granite* is represented by sample 08BH02, a granite collected between North Roe and Ronas Hill (HU 3614 8562). It is fine- to medium-grained, comprising quartz, perthitic orthoclase, plagioclase, quartz-orthoclase granophyric intergrowths, minor muscovite an accessory opaque phase, and secondary epidote and calcite. Zircons are typically euhedral, show faint oscillatory zoning in mantle and rims, and display homogeneous or sector-zoned cores (Fig. 3d). Six oscillatory rims and a whole sector-zoned grain yielded a Concordia age of 427.5 ± 5.1 Ma (Fig. 4d). Despite the apparent preservation of primary zoning patterns, nearly all analyses show evidence of Pb loss (see Supplementary material).

Two samples of diorite were collected from the *Mangaster Voe Intrusion*. Sample 11MGQ03 was collected from an abandoned quarry at Mavis Grind (HU 3395 6875). It is fine- to coarse-grained, comprising plagioclase, quartz, clinopyroxene, biotite and hornblende with accessory apatite and allanite and secondary epidote. Zircons are strongly tabular with only weak formation of angled terminations, and typically have large, sector zoned cores surrounded by thin oscillatory rims (Fig. 3e). Whole grains are either sector zoned or stripy. Areas of apparent structural damage to the cores replaced with material of a lower average atomic mass are common, particularly in larger grains. Eight rims and whole grains yielded a Concordia age of 389.3 ± 1.8 Ma (Fig. 4e), while four whole grains form an older cluster of concordant ages at c. 450 Ma.

A second diorite sample 11H01 was collected from the *Mangaster Voe Intrusion* near Hamar (HU 3126 7599). It is fine- to medium-grained, comprising plagioclase, hornblende, orthoclase, quartz and biotite, with accessory apatite, zircon and interstitial titanite. Zircon habits are more frequently euhedral than those in the Mavis Grind sample (11MGQ03), although many display the same patchy replacement texture in their cores. Grains are either sector zoned with oscillatory rims or whole grains with stripy zoning (Fig. 3f). Five oscillatory rims and whole grains yielded a Concordia age of 389.3 ± 2.6 Ma (Fig. 4f), identical to the diorite from Mavis Grind. Similarly, a small subset of rims records a cluster of c. 450 Ma ages.

The *Eastern Granophyre* is represented by sample 08MG06, a red granophyre from Mavis Grind (HU 3378 7049). It is fine- to coarse-grained, comprising quartz, orthoclase, plagioclase, biotite, hornblende, accessory zircon, and secondary epidote and sericite. Zircons are generally tabular with partial formation of dipyramidal terminations, and have

dark, weakly oscillatory cores surrounded by brighter oscillatory rims (Fig. 3g). Three oscillatory rims yielded a Concordia age of 396.2 ± 3.8 Ma (Fig. 4g), with only one discordant rim analysis older than 425 Ma.

Sandsting Complex. Three samples were collected from the diorite plutons that dominate the southern part of the complex and all yielded a similar age of c. 371 Ma within analytical uncertainty. Sample 08HS01 (HU 2898 4566) is fine- to medium-grained diorite comprising plagioclase, perthitic microcline, hornblende, biotite and quartz with accessory titanite, apatite, and zircon and secondary epidote. The alignment of plagioclase grains defines a linear fabric thought to have formed during emplacement. Zircon grains are typically euhedral, with bright unzoned or incoherent zoning in the cores and oscillatory zoning in the rims (Fig. 3h). Two oscillatory rims and a stripy whole grain yielded a Concordia age of 371.4 ± 3.2 Ma (Fig. 4h), while the majority of other grains displayed signs of Pb loss until c. 350 Ma. Unzoned cores gave a slightly older age of c. 375 Ma, but also showed signs of later Pb loss.

Samples 10CU10 (HU 272 443) and 10CU11 (HU 270 443) were collected in close proximity and are similar in mineralogy and texture. Both are fine- to medium-grained, comprising plagioclase, perthitic orthoclase and microcline, amphibole, biotite, and notably more quartz than 08HS01. Accessories include apatite, titanite and zircon. Zircons in sample 10CU10 are generally euhedral, with dark, altered cores and weakly oscillatory rims (Fig. 3i). Whole stripy grains form a substantial subpopulation. Six oscillatory rims and two stripy whole grains yielded a Concordia age of 371.4 ± 2.6 Ma (Fig. 4i). Cores show a minor population at c. 420 Ma in addition to ages within uncertainty of 371 Ma. All zones showed evidence for contamination by common Pb, but not in any coherent pattern through which an array could be calculated. Zircons in sample 10CU11 are generally euhedral, with dark unzoned or weakly stripy cores surrounded weak oscillatory zoned rims, or tabular with stripy zoning (Fig 3j). Thirteen rims and whole grains yielded a Concordia age of 371.6 ± 1.6 Ma (Fig. 4j). One whole grain gave a much older age of 441 Ma, but the vast majority of analyses in all zones are concordant and fall between 390 and 360 Ma.

Discussion and conclusions

352 The new U–Pb zircon data reported here indicate a far more protracted intrusion history for
 353 the ‘Newer Granite’ plutons in Shetland than was previously supposed based on limited K–
 354 Ar data (Fig. 5). There is a c. 75 myr difference in ages between the Brae Complex (c. 465
 355 Ma) and the youngest components of the Northmaven Complex (c. 390 Ma), contrasting
 356 strongly with earlier interpretations that these plutons were all intruded at c. 400 Ma (Miller
 357 & Flinn 1966). The undeformed and unmetamorphosed nature of the Brae Complex
 358 provides an upper age limit on the formation of the regionally steep, amphibolite facies
 359 fabrics within host Yell Sound Group and East Mainland Succession rocks. This is consistent
 360 with Rb–Sr mineral ages of c. 470–480 Ma obtained from the Yell Sound Group and the East
 361 Mainland Succession on Mainland Shetland, indicating that formation of the ‘regional steep
 362 belt’ occurred during the early Ordovician Grampian orogenic event (Walker *et al.* 2016).
 363 This is reinforced by the U–Pb zircon ages of c. 440–438 Ma for the Graven Complex and the
 364 Muckle Roe Granophyre, neither of which show any evidence for subsequent structural or
 365 metamorphic overprint. This further suggests that this part of Shetland occupied either a
 366 relatively high structural level in the late Silurian Baltica-Laurentia collision zone (see also
 367 Walker *et al.* 2016) or perhaps a recess in the collision zone.

368 The new U–Pb zircon data obtained from different components of the Northmaven
 369 Complex indicate that it is composite, assembled over c. 37 myr (Fig. 5). The Ronas Hill
 370 Granite cuts the east-dipping Uyea Shear Zone within basement rocks on its northern
 371 margin (Fig 2; Pringle 1970; British Geological Survey 2004), implying a pre-427 Ma age for
 372 the structure. Walker *et al.* (2016) obtained Rb–Sr white mica ages of c. 411 and c. 416 Ma
 373 from the shear zone which were interpreted as dating deformation. An alternative
 374 explanation prompted by the c. 10 myr older zircon age for the Ronas Hill Granite is that the
 375 Rb–Sr ages represent the timing of isotopic closure through a blocking temperature of c.
 376 500°C. The new U–Pb zircon data are relatively consistent for the Mangaster Voe Intrusion
 377 and associated Eastern Granophyre which were intruded at c. 390 Ma and represent an
 378 entirely younger intrusive complex.

379 The U–Pb zircon age of c. 371 Ma reported here for the Sandsting Complex provides
 380 a lower limit on the timing of folding and low-grade metamorphism of the Walls Formation.
 381 However, folding and cleavage were imposed on rocks that were not completely lithified

(Mykura & Phemister 1976) and thus deposition, pluton intrusion, and deformation and low-grade metamorphism must have occurred in a relatively short time period between 380 and 370 Ma. Given that formation of the Walls Formation basin and its subsequent deformation are thought to have been related to sinistral displacement along the Walls Boundary Fault (Seranne 1992; Dewey & Strachan 2003), it is tempting to suggest that the fault acted as a steep conduit that facilitated emplacement of the Sandsting Complex. The pluton is an important marker in the geological history of the Walls Boundary Fault as it contains xenoliths of blastomylonites formed during early sinistral displacements, but itself is only affected by cataclasites and gouges associated with dextral, post-Devonian reactivation of the fault (Watts *et al.* 2007).

Geodynamic significance of Ordovician to Silurian plutonism: along-strike variations in the convergent Laurentian margin

The new data from Shetland cast light on the period between the end of the Grampian orogeny in the middle Ordovician and the onset of Scandian collision in the late Silurian. The Grampian orogenic event was followed by reversal of subduction polarity and development of an accretionary prism in the Southern Uplands Terrane above a northwesterly-dipping subduction zone (Ryan & Dewey 1991). A puzzling aspect of Scottish geology has hitherto been the lack of evidence of subduction-related plutonism between c. 448 and 430 Ma within the Grampian and Northern Highland terranes of mainland Scotland (Fig. 5), despite evidence from the Southern Uplands Terrane of an active accretionary prism. In contrast, the data reported here from the likely equivalent Laurentian terranes along strike in Shetland indicate that the 'I-type' Brae and Graven complexes and the Muckle Roe Granophyre were all intruded during the supposed 'magmatic gap' between these two orogenic events (Fig. 5). A growing dataset also indicates a record of calc-alkaline, 'I-type' magmatism between 455 Ma and 430 Ma in East Milne Land and Liverpool Land in the Laurentian Caledonides of East Greenland (Fig 1b; Kalsbeek *et al.* 2008; Rehnström 2010; Corfu & Hartz 2011; Augland *et al.* 2012) and within the Laurentian-derived allochthons of Scandinavia (Bingen & Solli 2009; Slagstad *et al.* 2011).

The lack of plutonism between 448 and 430 Ma in mainland Scotland north of the Highland Boundary Fault has been suggested by Oliver *et al.* (2008) and Miles *et al.* (2016) to

reflect flat-slab subduction, a scenario also invoked by Dewey *et al.* (2015) to account for localised c. 450–445 Ma deformation and metamorphism within the Grampian Terrane. Oliver *et al.* (2008) also suggested that highly oblique plate convergence could have resulted in a transcurrent plate boundary and consequent lack of subduction-related magmatism. Another way of accounting for the apparent 448–430 Ma ‘magmatic gap’ is to invoke extensive erosion north of the Highland Boundary Fault (Miles *et al.* 2016), although it might be argued that the intrusive remnants of any putative arc would still be preserved at the present erosion level as steep, dyke-like feeders. However, Silurian sedimentary rocks in the Midland Valley Terrane do contain evidence for locally-derived calc-alkaline igneous detritus and detrital zircons as young as 430 Ma (Phillips *et al.* 2009), suggestive of a contemporaneous magmatic arc in this area. The lack of obvious arc-derived detritus in the Southern Uplands accretionary prism in Scotland might argue against the existence of a contemporaneous magmatic arc to the north, but arc-derived detritus could have been trapped in an intervening fore-arc basin (Miles *et al.* 2016). The balance of evidence is perhaps still consistent with the existence of an active magmatic arc located in the Midland Valley Terrane during late Ordovician to Silurian times. However, the arc may have been located significantly outboard of the edge of Laurentia (the Highland Boundary Fault) prior to end-Caledonian orogen-normal shortening and strike-slip displacements, thus accounting for the ‘magmatic gap’ further north.

By implication, the presence of 455–430 Ma plutons in the Laurentian Caledonides of Shetland, East Greenland and Scandinavia suggests an along-strike change in the angle of subduction and/or a significant narrowing of the distance between the subduction zone and the Laurentian margin. Such along strike changes in the architecture of modern convergent margins are commonly accommodated by oceanic transform faults or fracture zones (e.g. Pilger 1981) which may in turn have originated during continental rifting (e.g. Lister *et al.* 1991; Miller *et al.* 2002). The proposed along-strike change in the nature of the convergent margin must have occurred within the relatively short distance (c. 150 km) between the north coast of mainland Scotland and Shetland. The most prominent transverse structure so far identified in this region is the North Coast Transfer Zone (Fig 1a), and documented Devonian and Permian displacements (Wilson *et al.* 2010; Dichiarante *et al.* 2016) may therefore have resulted from reactivation of an older structure.

The Ronas Hill pluton is believed to be located close to the basal thrust of the Caledonides in Shetland, and is of similar age to the c. 430 Ma alkaline intrusions that were emplaced within and proximal to the Moine Thrust Zone in the Assynt area of NW Scotland (Goodenough *et al.* 2011). In that context, it could have resulted from lithospheric melting induced by the early stages of slab break-off following Laurentia-Baltica collision (Atherton & Ghani 2002; Neilson *et al.* 2009; Miles *et al.* 2016).

Geodynamic significance of Devonian plutonism: the result of lithospheric melting during sinistral transtension and plate divergence?

Assuming that end-Caledonian collision occurred at c. 430 Ma, there is then a gap of c. 40 myr before emplacement of the Mangaster Voe intrusion and Eastern Granophyre (c. 390 Ma), and a further gap of c. 20 myr before emplacement of the Sandsting Complex (c. 370 Ma) (Fig. 5). The explanation favoured here is that both periods of magmatism resulted from pulses of renewed localised lithospheric melting that accompanied Devonian sinistral relative displacements between Laurentia and Baltica (Dewey & Strachan 2003). U–Pb dating of syn-tectonic intrusions emplaced either proximal to or along the Great Glen Fault indicate that sinistral displacements commenced at c. 427 Ma (Stewart *et al.* 2001) and continued until at least c. 399–393 Ma (Mendum & Noble 2010). The youngest phases of faulting might be in part far-field effects of the coeval Acadian Orogeny (Fig 5). Various studies in Tertiary to Recent tectonic settings elsewhere have shown that magmatism may be triggered by local decompression effects related to lithospheric-scale transtensive fault systems (e.g. Beccaluva *et al.* 1998; Till *et al.* 2007; Riley *et al.* 2012). This is the mode of origin proposed for the Mangaster Voe intrusion and Eastern Granophyre which lie close to the Walls Boundary Fault. It is envisaged that pulses of melt generation during transtension may have alternated with periods of localised transpression along the fault zone which resulted in the vertical transport of magma (e.g. D’Lemos *et al.* 1992). The spatial and temporal links with a transtensional tectonic setting are clearer between the younger Sandsting Complex and the development of a sinistral pull-apart basin adjacent to the Walls Boundary Fault. However, in this case there is no correlative magmatism and basin development elsewhere in northern Scotland, although transtensional deformation

persisted through the Devonian and into the Early Carboniferous along strike to the north in the North-Central Norwegian Caledonides (Osmundsen et al. 2003).

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Figure captions:

Fig. 1. (a) The 'Newer Granites' of Scotland and Ireland (black) (modified from Neilson et al. 2009). NHT, Northern Highland Terrane; MVT, Midland Valley Terrane; SUT, Southern Uplands Terrane; NCTZ, North Coast Transfer Zone. Arrows adjacent to the dashed line delimiting the NCTZ indicate the Devonian and/or Permian transtensional displacement(s) across this structure (Wilson et al. 2010). The intrusions in the Southern Uplands Terrane are slightly younger than, and petrogenetically unrelated to, the 'Newer Granites' further north. (b) Relative positions of sectors of the North Atlantic Caledonides prior to late Mesozoic rifting. NHT, Northern Highland Terrane; MTZ, Moine Thrust Zone; GGF, Great Glen Fault; HBF, Highland Boundary Fault; SUF, Southern Uplands Fault; IS, Iapetus Suture; LL, Liverpool Land; EML, East Milne Land; CB, Clew Bay.

Fig. 2. Simplified geology map of Shetland with locations of samples. USZ, Uyea Shear Zone; WKSZ, Wester Keolka Shear Zone.

Fig.3. Typical cathodoluminescence images of zircons from this study and locations of laser spots; all scale bars 50 microns. U-Pb analyses indicated by solid shapes. Data presented as grain number (with mount if needed), U-Pb age $\pm$ 2 sigma Ma or % discordance. Where multiple analyses were made in the same grain, these are designated core (c), mantle (m) or rim (r) as applicable.

Fig. 4. Terra-Wasserburg Concordia plots for all samples (left-hand column; all error ellipses shown at 2σ and analyses coded by growth zone) together with corresponding Concordia ages (right-hand column).

759 Fig. 5. Summary of the new U-Pb data reported here for the 'Newer Granite' suite in
760 Shetland in the context of Ordovician to Devonian magmatic and tectonic events
761 (horizontal shaded segments) in northern Britain.

762

763

764

Figure 1

Figure 2

g) 08MG06

h) 08HS01

i) 10CU10

j) 10CU11

Figure 5

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