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

Penelope J. Lancaster[1], Rob A. Strachan*[1], Dean Bullen[1], Mike Fowler[1], Mariana Jaramillo[1,2] and Ana M. Saldarriaga[1,2]

[1]School of Earth & Environmental Sciences, University of Portsmouth, Portsmouth, UK
[2]Departamento de Ciencias de la Tierra, Universidad EAFIT, Medellín, Colombia

*Corresponding author: (e-mail: rob.strachan@port.ac.uk)

Running title: 'Newer Granite' plutons in Shetland

Keywords: U–Pb zircon, LA-ICP-MS, Newer Granites, Shetland, Caledonides

Supplementary material: Petrological details, full analytical methods and data tables are available at www.geolsoc.org.uk/SUP00000.

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 (*senso 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 (*senso 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;

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

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

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

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

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

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

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

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

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

Constraints on the timing of Caledonian deformation and metamorphism in Shetland

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

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

The U–Pb zircon age of *c*. 371 Ma reported here for the Sandsting Complex provides a lower limit on the timing of folding and low-grade metamorphism of the Walls Formation. 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).

Acknowledgements We thank Andrew Miles and an anonymous reviewer for their comments which improved the manuscript.

References

Anderson, J.G.C. 1937. The Etive Granite Complex. *Quarterly Journal of the Geological Society of London*, **93**, 487-533.

Anderton, R. 1985. Sedimentation and tectonics in the Scottish Dalradian. *Scottish Journal of Geology*, **21**, 407-436.

Andrews, I.J. 1985. The deep structure of the Moine Thrust, southwest of Shetland. *Scottish Journal of Geology*, **21**, 213-217.

Atherton, M.P. & Ghani, A.A. 2002. Slab breakoff: a model for Caledonian, Late Granite syn-collisional magmatism in the orthotectonic (metamorphic) zone of Scotland and Donegal, Ireland. *Lithos*, **62**, 65-85.

Augland, L.E., Andresen, A., Corfu, F. & Daviknes, H.K. 2012. Late Ordovician to Silurian ensialic magmatism in Liverpool Land, East Greenland: New evidence extending the northeastern branch of the continental Laurentian magmatic arc. *Geological Magazine*, **149**, 561-577.

Bailey, E.B. 1960. The Geology of Ben Nevis and Glen Coe and the Surrounding Country: (Explanation Sheet 53) **53**, HM Stationery Office.

Beccaluva, L., Siena, F., Coltorti, M., Di Grande, A., Lo Giudice, A., Macciotta, G., Tassinari, R. & Vaccaro, C. 1998. Nephelinitic to Tholeiitic Magma Generation in a Transtensional Tectonic Setting:an Integrated Model for the Iblean Volcanism, Sicily. *Journal of Petrology*, **39**, 1547-1576.

Bingen, B. & Solli, A. 2009. Geochronology of magmatism in the Caledonian and Sveconorwegian belts of Baltica: Synopsis for detrital zircon provenance studies. *Norwegian Journal of Geology*, **89**, 267-290.

Bird, A.F., Thirlwall, M.F., Strachan, R.A. & Manning, C.J. 2013. Lu–Hf and Sm–Nd dating of metamorphic garnet: Evidence for multiple accretion events during the Caledonian orogeny in Scotland. *Journal of the Geological Society*, *London,* **170**, 301-317.

Bluck, B.J. 2002. The Midland Valley terrane. *In:* Trewin, N.W. (ed) *The Geology of Scotland*, Geological Society of London, 149-166.

British Geological Survey 2004. Northmaven. Scotland Sheet 129. Bedrock., *1:50,000 Geology Series*, Keyworth, Nottingham.

Chew, D.M., Daly, J.S., Magna, T., Page, L.M., Kirkland, C.L., Whitehouse, M.J. & Lam, R. 2010. Timing of ophiolite obduction in the Grampian orogen. *Geological Society of America Bulletin*, **122**, 1787-1799.

Corfu, F. & Hartz, E.H. 2011. U–Pb geochronology in Liverpool Land and Canning Land, East Greenland — the complex record of a polyphase Caledonian orogeny. *Canadian Journal of Earth Sciences*, **48**, 473-494.

Coward, M.P. 1990. The Precambrian, Caledonian and Variscan framework to NW Europe. *In*: Hardman, R.F.P. & Brooks, J. (eds) *Tectonic Events Responsible for Britain's Oil and Gas Reserves*. Geological Society, London, Special Publications, **55,** 1-34.

Crowley, Q.G. & Strachan, R.A. 2015. U–Pb zircon constraints on obduction initiation of the Unst Ophiolite: an oceanic core complex in the Scottish Caledonides? *Journal of the Geological Society*, *London,* **172**, 279-282.

Cutts, K.A., Hand, M., Kelsey, D.E., Wade, B., Strachan, R.A., Clark, C. & Netting, A. 2009. Evidence for 930 Ma metamorphism in the Shetland Islands, Scottish Caledonides: implications for Neoproterozoic tectonics in the the Laurentia-Baltica sector of Rodinia. *Journal of the Geological Society*, *London,* **166**, 1033-1048.

Cutts, K.A., Hand, M., Kelsey, D.E. & Strachan, R.A. 2011. P–T constraints and timing of Barrovian metamorphism in the Shetland Islands, Scottish Caledonides: implications for the structural setting of the Unst ophiolite. *Journal of the Geological Society*, *London,* **168**, 1265-1284.

Dallmeyer, R.D., Strachan, R.A., Rogers, G., Watt, G.R. & Friend, C.R.L. 2001. Dating deformation and cooling in the Caledonian thrust nappes of north Sutherland, Scotland: Insights from ^{40}Ar/^{39}Ar and Rb–Sr chronology. *Journal of the Geological Society*, *London,* **158**, 501-512.

Dewey, J.F., Dalziel, I.W.D., Reavy, R.J. & Strachan, R.A. 2015. The Neoproterozoic to Mid-Devonian evolution of Scotland: a review and unresolved issues. *Scottish Journal of Geology*, **51**, 5-30.

Dewey, J.F. & Strachan, R.A. 2003. Changing Silurian-Devonian relative plate motion in the Caledonides: Sinistral transpression to sinistral transtension. *Journal of the Geological Society*, *London,* **160**, 219-229.

Dichiarante, A.M., Holdsworth, R.E., Dempsey, E.D., Selby, D., McCaffrey, K.J.W., Michie, U. McL., Morgan, G. & Bonniface, J. 2016. New structural and Re-Os geochronological evidence constraining the age of faulting and associated mineralisation in the Devonian Orcadian Basin, Scotland. *Journal of the Geological Society*, *London,* **173**, 457-473.

D'Lemos, R.S., Brown, M. & Strachan, R.A. 1992. Granite generation, ascent and emplacement within a transpressional orogen. *Journal of the Geological Society, London*, **149**, 487-490.

Flinn, D. 1961. Continuation of the Great Glen Fault beyond the Moray Firth. *Nature*, **191**, 589-591.

Flinn, D. 1977. Transcurrent faults and associated cataclasis in Shetland. *Journal of the Geological Society*, *London,* **133**, 231-247.

Flinn, D. 1985. The Caledonides of Shetland. *In:* Gee, D.G., Stuart, B.A. (eds) *The Caledonide Orogen—Scandinavia and Related Areas*, Wiley, Chichester, 1158-1171.

Flinn, D. 1988. The Moine rocks of Shetland. *In:* Winchester, J.A. (ed) *Later Proterozoic Stratigraphy of the Northern Atlantic Regions*, Blackie, Glasgow, 74-85.

Flinn, D. 1992. The history of the Walls Boundary fault, Shetland: the northward continuation of the Great Glen fault from Scotland. *Journal of the Geological Society*, **149**, 721-726.

Flinn, D. 1993. Discussion on the location and history of the Walls Boundary fault and Moine thrust north and south of Shetland: Reply. *Journal of the Geological Society*, *London,* **150**, 1006-1008.

Flinn, D. 1994. Geology of Yell and some neighbouring islands in Shetland: Memoir for 1:50,000 Geological Sheet 130 (Scotland), British Geological Survey.

Flinn, D. 2014. Geology of Unst and Fetlar in Shetland: Memoir for 1:50,000 Geological Sheet 131 (Scotland), British Geological Survey.

Flinn, D., Frank, P.L., Brook, M. & Pringle, I.R. 1979. Basement-cover relations in Shetland. *In:* Harris, A.L., Holland, C.H., Leake, B.E. (eds) *The Caledonides of the British Isles - Reviewed*. Geological Society, London, Special Publications, **8**, London, 109-115.

Flinn, D., May, F., Roberts, J.L. & Treagus, J.E. 1972. A revision of the stratigraphic succession of the East Mainland of Shetland. *Scottish Journal of Geology*, **8**, 335-343.

Fowler, M.B., Kocks, H., Darbyshire, D.P.F. & Greenwood, P.B. 2008. Petrogenesis of high Ba–Sr plutons from the Northern Highlands Terrane of the British Caledonian Province. *Lithos*, **105**, 129-148.

Gee, D.G. 1975. A tectonic model for the central part of the Scandinavian Caledonides. *American Journal of Science*, **275**, 468-515.

Goodenough, K.M., Millar, I.L., Strachan, R.A., Krabbendam, M. & Evans, J.A. 2011. Timing of regional deformation and development of the Moine Thrust Zone in the Scottish Caledonides: constraints from the U–Pb geochronology of alkaline intrusions. *Journal of the Geological Society*, *London,* **168**, 99-114.

Holdsworth, R.E., Dempsey, E., Selby, D., Darling, J.R., Feely, M., Costanzo, A., Strachan, R.A., Waters, P., Finlay, A.J. & Porter, S.J. 2015. Silurian-Devonian magmatism, mineralization, regional exhumation and brittle strike-slip deformation along the Loch Shin Line, NW Scotland. *Journal of the Geological Society, London*, **172**, 748-762.

Hutton, D.H.W. 1982. A tectonic model for the emplacement of the Main Donegal Granite, NW Ireland. *Journal of the Geological Society*, *London,* **139**, 615-631.

Jacques, J.M. & Reavy, R.J. 1994. Caledonian plutonism and major lineaments in the SW Scottish Highlands. *Journal of the Geological Society*, *London,* **151**, 955-969.

Kalsbeek, F., Higgins, A.K., Jepsen, H.F., Frei, R. & Nutman, A.P. 2008. Granites and granites in the East Greenland Caledonides. *In:* Higgins, A.K., Gilotti, J.A. & Smith, M.P. (eds) *The Greenland Caledonides: Evolution of the northeast margin of Laurentia*, Geological Society of America Memoir **202**, 227-250.

Kocks, H., Strachan, R.A. & Evans, J.A. 2006. Heterogeneous reworking of Grampian metamorphic complexes during Scandian thrusting in the Scottish Caledonides: insights from the structural setting and U–Pb geochronology of the Strath Halladale Granite. *Journal of the Geological Society*, *London,* **163**, 525-538.

Kocks, H., Strachan, R.A., Evans, J.A. & Fowler, M.B. 2014. Contrasting magma emplacement mechanisms within the Rogart igneous complex, NW Scotland, record the switch from regional contraction to strike-slip during the Caledonian orogeny. *Geological Magazine*, **151**, 899-915.

Kokelaar, B.P. & Moore, I.D. 2006. *Glencoe caldera volcano, Scotland*. British Geological Survey, Nottingham, UK.

Lambert, R.S.J., McKerrow, W.S. 1976. The Grampian Orogeny. *Scottish Journal of Geology*, **12**, 271-292.

Lister, G.S., Etheridge, M.A. & Symonds, P.A. 1991. Detachment models for the formation of passive continental margins. *Tectonics*, **10**, 1038-1064.

Marshall, J.E.A. 2000. Devonian (Givetian) miospores from the Walls Group, Shetland. *In:* Friend, Peter F. & Williams, B.P.J. (eds) *New Perspectives on the Old Red Sandstone*. Geological Society, London, Special Publications, **180**, 473-483.

McBride, J.H. & England, R.W. 1994. Deep seismic reflection structure of the Caledonian orogenic front west of Shetland. *Journal of the Geological Society*, *London,* **151**, 9-16.

Mendum, J.R. & Noble, S.R. 2010. Mid-Devonian sinistral transpressional movements on the Great Glen Fault: The rise of the Rosemarkie Inlier and the Acadian Event in Scotland. *In:* Law, R.D., Butler, R.W.H., Holdsworth, R.E., Krabbendam, M. & Strachan, R.A. (eds) *Continental Tectonics and Mountain Building: The Legacy of Peach and Horne*. Geological Society, London, Special Publications, **335**, 161-187.

Miles, A.J., Woodcock, N.H. & Hawkesworth, C.J. 2016. Tectonic controls on post-subduction granite genesis and emplacement: The late Caledonian suite of Britain and Ireland. *Gondwana Research*, in press.

Miller, J.A. & Flinn, D. 1966. A survey of the age relations of Shetland Rocks. *Geological Journal*, **5**, 95-116.

Miller, J.M., Norvick, M.S. & Wilson, C.J.L. 2002. Basement controls on rifting and the associated formation of ocean transform faults – Cretaceous continental extension of the southern margin of Australia. *Tectonophysics*, **359**, 131-155.

Mykura, W. 1976. British regional geology: Orkney and Shetland, HMSO, Edinburgh, 149.

Mykura, W. & Phemister, J. 1976. *The Geology of Western Shetland*. HMSO, Edinburgh.

Neilson, J.C., Kokelaar, B.P. & Crowley, Q.G. 2009. Timing, relations and cause of plutonic and volcanic activity of the Siluro-Devonian post-collision magmatic episode in the Grampian Terrane, Scotland. *Journal of the Geological Society*, *London,* **166**, 545-561.

Oliver, G.J.H., Chen, F., Buchwaldt, R. & Hegner, E. 2000. Fast tectonometamorphism and exhumation in the type area of the Barrovian and Buchan zones. *Geology*, **28**, 459-462.

Oliver, G.J.H., Wilde, S.A. & Wan, Y. 2008. Geochronology and geodynamics of Scottish granitoids from the late Neoproterozoic break-up of Rodinia to Palaeozoic collision. *Journal of the Geological Society*, *London,* **165**, 661-674.

Osmundsen, P.T., Braathen, A., Nordgulen, O., Roberts, D., Meyer, G.B. & Eide, E. 2003. The Devonian Nesna shear zone, North-Central Norwegian Caledonides. *Journal of the Geological Society, London*, **160**, 137-150.

Phemister, J., Harvey, C.O. & Sabine, P.A. 1950. The riebeckite-bearing dikes of Shetland. *Mineralogical Magazine*, **29**, 359-373.

Phillips, E.R., Smith, R.A., Stone, P., Pashley, V. & Horstwood, M.S.A. 2009. Zircon age constraints on the provenance of Llandovery to Wenlock sandstones from the Midland Valley terrane of the Scottish Caledonides. *Scottish Journal of Geology*, **45**, 131-146.

Pickering, K.T., Bassett, M.G. & Siveter, D.J. 1988. Late Ordovician–early Silurian destruction of the Iapetus Ocean: Newfoundland, British Isles and Scandinavia—a discussion. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, **79**, 361-382.

Pilger, R.H. 1981. Plate reconstructions, aseismic ridges, and low-angle subduction beneath the Andes. *Geological Society of America Bulletin*, **92**, 448-456.

Pitcher, W.S. & Berger, A.R. 1972. *The geology of Donegal: a study of granite emplacement and unroofing*. John Wiley & Sons, New York.

Prave, A.R., Strachan, R.A. & Fallick, A.E. 2009. Global C cycle perturbations recorded in marbles: a record of Neoproterozoic Earth history within the Dalradian succession of the Shetland Islands, Scotland. *Journal of the Geological Society*, *London,* **166**, 129-135.

Pringle, I.R. 1970. The structural geology of the North Roe area of Shetland. *Geological Journal*, **7**, 147-170.

Read, H.H. 1961. Aspects of Caledonian magmatism in Britain. *Geological Journal*, **2**, 653-683.

Rehnström, E.F. 2010. Prolonged Paleozoic magmatism in the East Greenland Caledonides: Some constraints from U–Pb ages and Hf isotopes. *The Journal of Geology*, **118**, 447-465.

Riley, P., Tikoff, B. & Hildreth, W. 2012. Transtensional deformation and structural control of contiguous but independent magmatic systems: Mono-Inyo Craters, Mammoth Mountain, and Long Valley Caldera, California. *Geosphere*, **8**, 740-751.

Ritchie, J.D., Hitchen, K. & Mitchell, J.G. 1987. The offshore continuation of the Moine Thrust north of Shetland as deduced from basement isotopic ages. *Scottish Journal of Geology*, **23**, 163-173.

Roberts, D. 2003. The Scandinavian Caledonides: event chronology, palaeogeographic settings and likely modern analogues. *Tectonophysics*, **365**, 283-299.

Ryan, P.D. & Dewey, J.F. 1991. A geological and tectonic cross-section of the Caledonides of western Ireland. *Journal of the Geological Society, London*, **148**, 173-180.

Seranne, M. 1992. Devonian extensional tectonics versus Carboniferous inversion in the northern Orcadian basin. *Journal of the Geological Society*, *London,* **149**, 27-37.

Shackleton, R.M. 1958. Downward-facing structures of the Highland Border. *Quarterly Journal of the Geological Society of London*, **113**, 361-392.

Slagstad, T., Davidsen, B. & Daly, J.S. 2011. Age and composition of crystalline basement rocks on the Norwegian continental margin: Offshore extension and continuity of the Caledonian–Appalachian orogenic belt. *Journal of the Geological Society*, *London,* **168**, 1167-1185.

Soper, N.J., Strachan, R.A., Holdsworth, R.E., Gayer, R.A. & Greiling, R.O. 1992. Sinistral transpression and the Silurian closure of Iapetus. *Journal of the Geological Society*, *London,* **149**, 871-880.

Soper, N.J. & Woodcock, N.H. 1990. Silurian collision and sediment dispersal patterns in southern Britain. *Geological Magazine*, **127**, 527-542.

Soper, N.J. & Woodcock, N.H. 2003. The lost Lower Old Red Sandstone of England and Wales: a record of post-Iapetan flexure or Early Devonian transtension? *Geological Magazine*, **140**, 627-647.

Spray, J.G. 1988. Thrust-related metamorphism beneath the Shetland Islands oceanic fragment, northeast Scotland. *Canadian Journal of Earth Sciences*, **25**, 1760-1776.

Stephens, W.E. & Halliday, A.N. 1984. Geochemical contrasts between late Caledonian granitoid plutons of northern, central and southern Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, **75**, 259-273.

Stephenson, D. 1999. Eshaness Coast. *In:* Stephenson, D., Bevins, R.E., Millward, D., Highton, A.J., Parson, I., Stone, P. & Wadsworth, W.J. (eds) *Caledonian Igneous Rocks of Great Britain*, Joint Nature Conservation Committee, Peterborough, 559-565.

Stewart, M., Strachan, R.A., Martin, M.W. & Holdsworth, R.E. 2001. Constraints on early sinistral displacements along the Great Glen Fault Zone, Scotland: structural setting, U–Pb geochronology and emplacement of the syn-tectonic Clunes tonalite. *Journal of the Geological Society*, *London,* **158**, 821-830.

Strachan, R.A., Prave, A.R., Kirkland, C.L. & Storey, C.D. 2013. U–Pb detrital zircon geochronology of the Dalradian Supergroup, Shetland Islands, Scotland: Implications for regional correlations and Neoproterozoic–Palaeozoic basin development. *Journal of the Geological Society*, *London,* **170**, 905-916.

Tanner, P.W.G. 2014. A kinematic model for the Grampian Orogeny, Scotland. *In:* Corfu, F., Gasser, D. & Chew, D.M. (eds) *New Perspectives on the Caledonides of Scandinavia and Related Areas*. Geological Society, London, Special Publications, **390**, 467-511.

Thirlwall, M.F. 1988. Geochronology of Late Caledonian magmatism in northern Britain. *Journal of the Geological Society*, *London,* **145**, 951-967.

Thompson, R.N. & Fowler, M.B. 1986. Subduction-related shoshonitic and ultrapotassic magmatism: a study of Siluro-Ordovician syenites from the Scottish Caledonides. *Contributions to Mineralogy and Petrology*, **94**, 507-522.

Till, A.B., Roeske, S.M., Bradley, D.C., Friedman, R. & Layer, P. W. 2007. Early Tertiary transtension-related deformation and magmatism along the Tintina fault system, Alaska. *In*: Roeske, S.M., Till, A.B., Foster, D.A. & Sample, J.C. (eds) *Exhumation along Continental Strike-slip Fault Systems*. Geological Society of America Special Papers, **434**, 233-264.

Walker, S., Thirlwall, M.F., Strachan, R.A. & Bird, A.F. 2016. Evidence from Rb–Sr mineral ages for multiple orogenic events in the Caledonides of Shetland, Scotland. *Journal of the Geological Society*, *London,* **173**, 489-503.

Watts, L.M., Holdsworth, R.E., Sleight, J.A., Strachan, R.A. & Smith, S.A.F. 2007. The movement history and fault rock evolution of a reactivated crustal-scale strike-slip fault: the Walls Boundary Fault Zone, Shetland. *Journal of the Geological Society*, London, **164**, 1037-1058.

Wilson, R.W., Holdsworth, R.E., Wild, L.E., McCaffrey, K.J.W., England, R.W., Imber, J. & Strachan, R.A. 2010. Basement-influenced rifting and basin development: A reappraisal of post-Caledonian faulting patterns from the North Coast Transfer Zone, Scotland. *In:* Law, R.D., Butler, R.W.H., Holdsworth, R.E., Krabbendam, M. & Strachan, R.A. (eds) *Continental Tectonics and Mountain Building: The Legacy of Peach and Horne*. Geological Society, London, Special Publications, **335**, 795-826.

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.

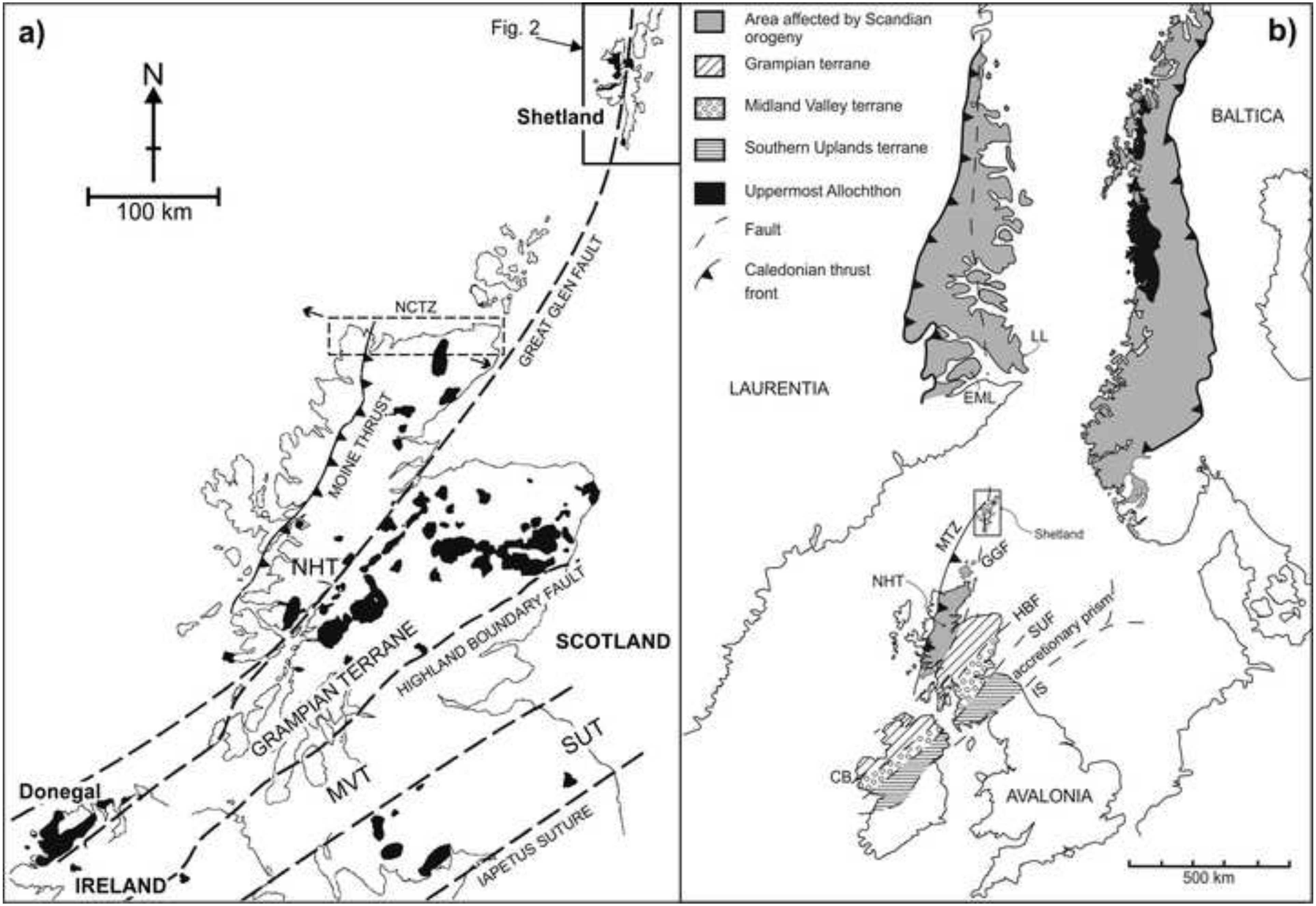
Fig. 2. Simplified geology map of Shetland with locations of samples. USZ, Uyea Shear Zone; WKSZ, Wester Keolka Shear Zone.

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 ± 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).

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

Figure 1


a)
N
100 km
Fig. 2
Shetland
NCTZ
GREAT GLEN FAULT
MOINE THRUST
NHT
GRAMPIAN TERRANE
HIGHLAND BOUNDARY FAULT
SCOTLAND
MVT
SUT
IAPETUS SUTURE
Donegal
IRELAND
b)
Area affected by Scandian orogeny
Grampian terrane
Midland Valley terrane
Southern Uplands terrane
Uppermost Allochthon
Fault
Caledonian thrust front
BALTICA
LAURENTIA
LL
EML
Shetland
MTZ
GGF
NHT
HBF
SUF
accretionary prism
IS
CB
AVALONIA
500 km

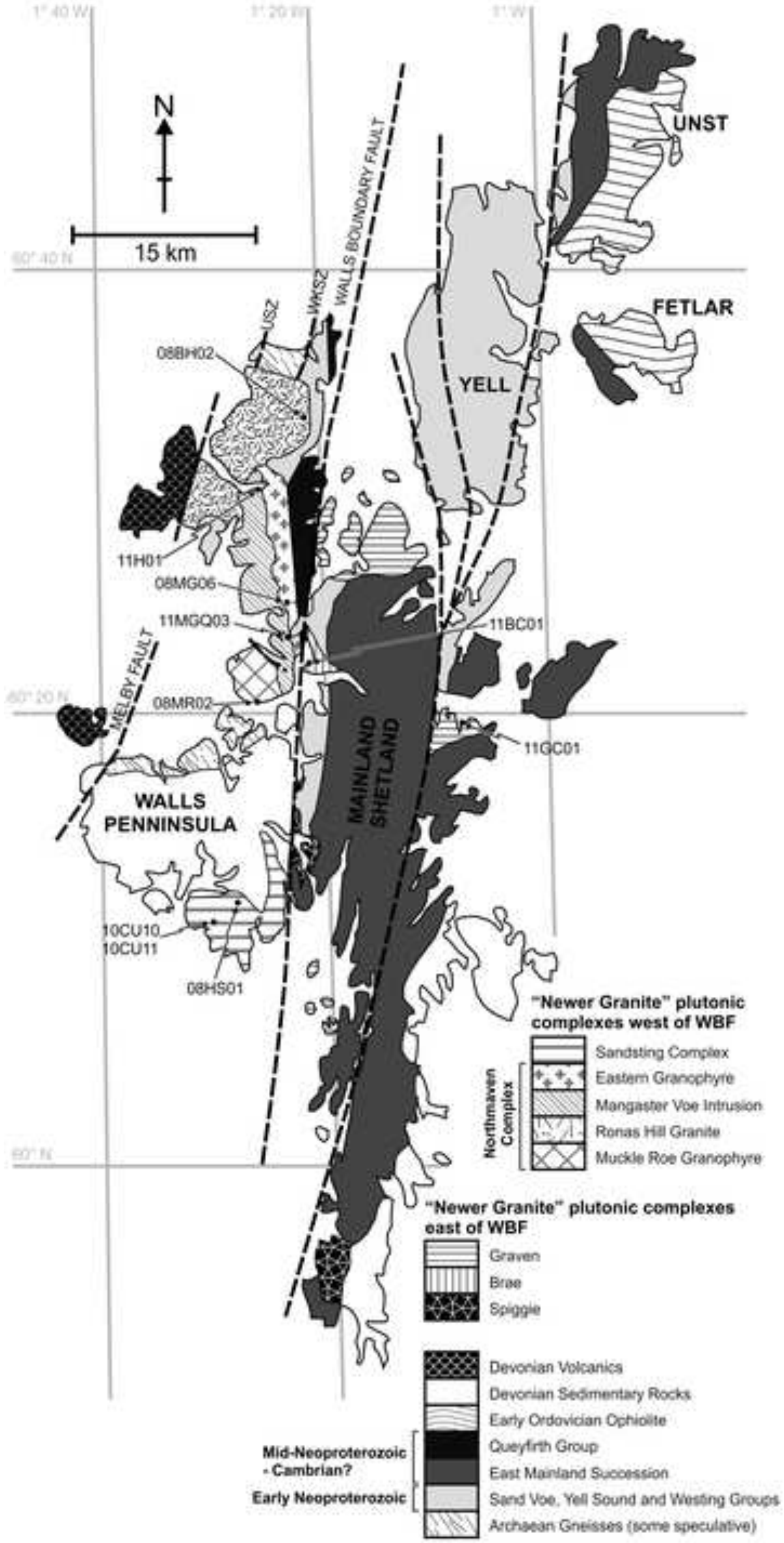

1° 40 W
1° 20 W
1° W
N
15 km
60° 40 N
60° 20 N
60° N
WALLS BOUNDARY FAULT
WKSZ
USZ
MELBY FAULT
UNST
FETLAR
YELL
MAINLAND SHETLAND
WALLS PENNINSULA
08BH02
11H01
08MG06
11MGQ03
11BC01
08MR02
11GC01
10CU10
10CU11
08HS01
"Newer Granite" plutonic complexes west of WBF
Sandsting Complex
Northmaven Complex
Eastern Granophyre
Mangaster Voe Intrusion
Ronas Hill Granite
Muckle Roe Granophyre
"Newer Granite" plutonic complexes east of WBF
Graven
Brae
Spiggie
Devonian Volcanics
Devonian Sedimentary Rocks
Early Ordovician Ophiolite
Mid-Neoproterozoic - Cambrian?
Queyfirth Group
East Mainland Succession
Early Neoproterozoic
Sand Voe, Yell Sound and Westing Groups
Archaean Gneisses (some speculative)

Figure 3a

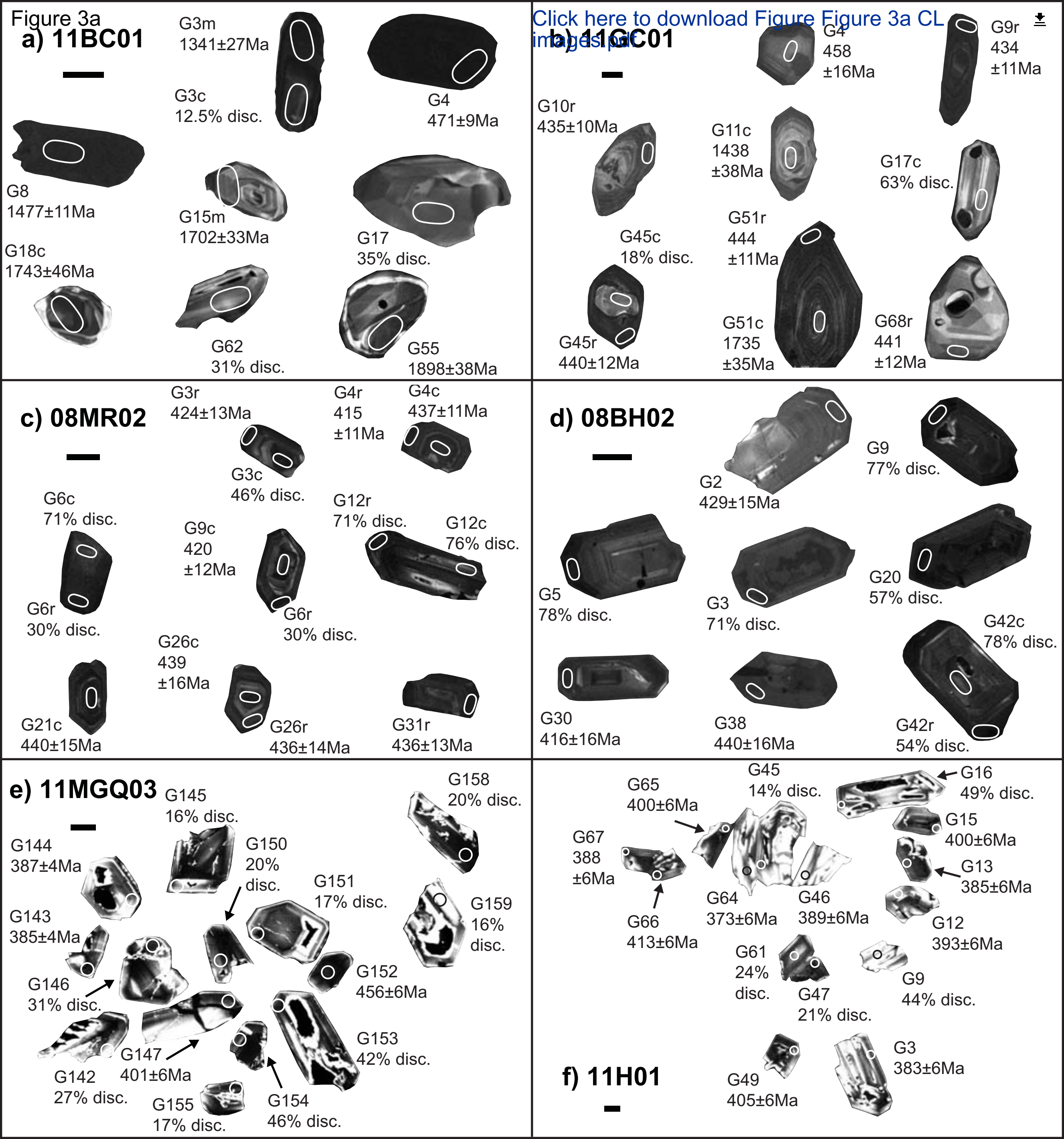

a) 11BC01
G3m
1341±27Ma
G3c
12.5% disc.
G4
471±9Ma
G8
1477±11Ma
G15m
1702±33Ma
G17
35% disc.
G18c
1743±46Ma
G62
31% disc.
G55
1898±38Ma
b) 11GC01
G4
458
±16Ma
G9r
434
±11Ma
G10r
435±10Ma
G11c
1438
±38Ma
G17c
63% disc.
G45c
18% disc.
G51r
444
±11Ma
G45r
440±12Ma
G51c
1735
±35Ma
G68r
441
±12Ma
c) 08MR02
G3r
424±13Ma
G4r
415
±11Ma
G4c
437±11Ma
G3c
46% disc.
G6c
71% disc.
G9c
420
±12Ma
G12r
71% disc.
G12c
76% disc.
G6r
30% disc.
G6r
30% disc.
G26c
439
±16Ma
G21c
440±15Ma
G26r
436±14Ma
G31r
436±13Ma
d) 08BH02
G2
429±15Ma
G9
77% disc.
G5
78% disc.
G3
71% disc.
G20
57% disc.
G42c
78% disc.
G30
416±16Ma
G38
440±16Ma
G42r
54% disc.
e) 11MGQ03
G145
16% disc.
G158
20% disc.
G144
387±4Ma
G150
20%
disc.
G151
17% disc.
G159
16%
disc.
G143
385±4Ma
G152
456±6Ma
G146
31% disc.
G147
401±6Ma
G153
42% disc.
G142
27% disc.
G155
17% disc.
G154
46% disc.
f) 11H01
G65
400±6Ma
G45
14% disc.
G16
49% disc.
G15
400±6Ma
G67
388
±6Ma
G13
385±6Ma
G66
413±6Ma
G64
373±6Ma
G46
389±6Ma
G12
393±6Ma
G61
24%
disc.
G47
21% disc.
G9
44% disc.
G49
405±6Ma
G3
383±6Ma

Figure 3b

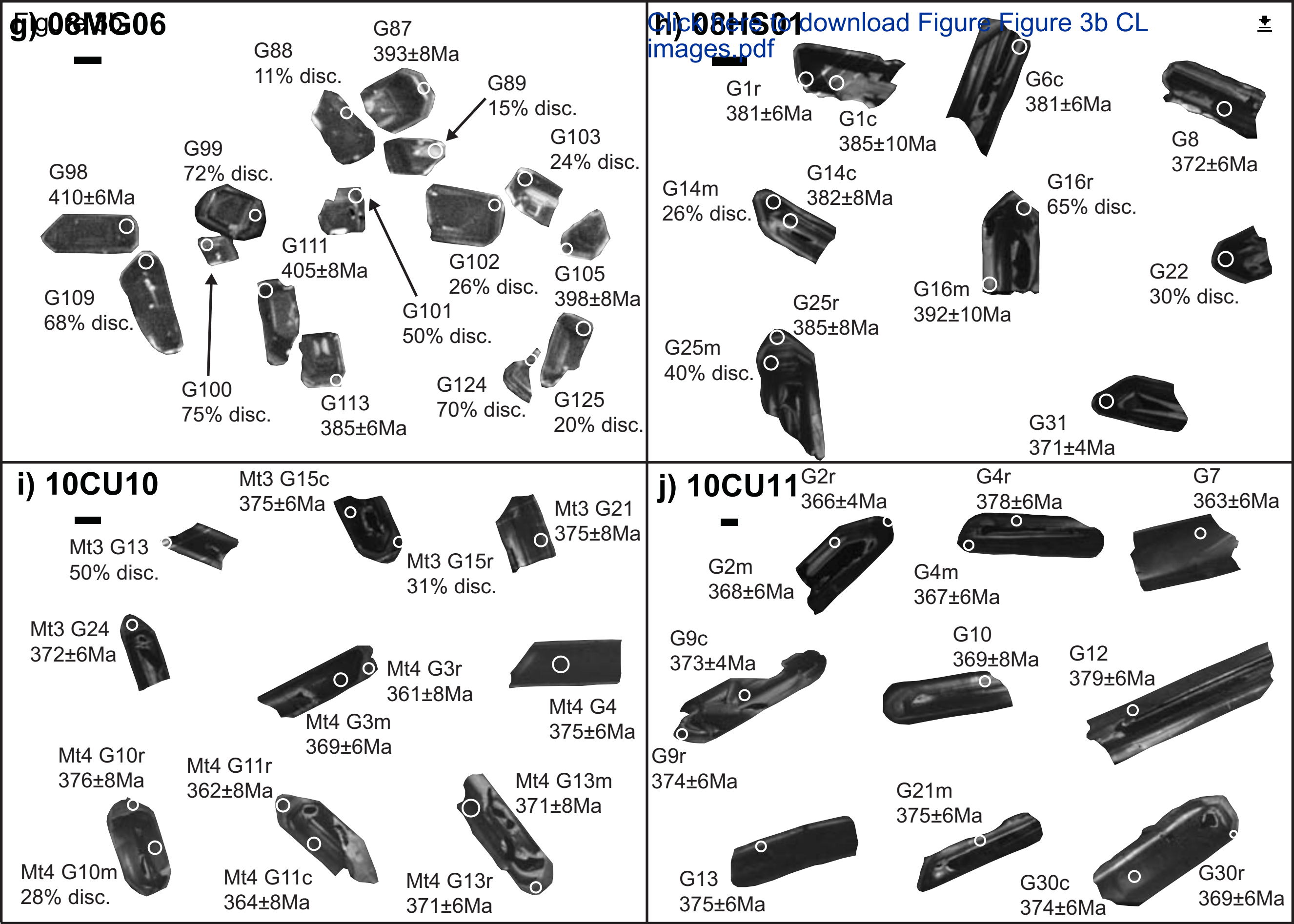

g) 08MG06
G88
11% disc.
G87
393±8Ma
G89
15% disc.
G103
24% disc.
G99
72% disc.
G98
410±6Ma
G111
405±8Ma
G102
26% disc.
G105
398±8Ma
G109
68% disc.
G101
50% disc.
G100
75% disc.
G113
385±6Ma
G124
70% disc.
G125
20% disc.
h) 08HS01
G1r
381±6Ma
G1c
385±10Ma
G6c
381±6Ma
G8
372±6Ma
G14m
26% disc.
G14c
382±8Ma
G16r
65% disc.
G16m
392±10Ma
G22
30% disc.
G25r
385±8Ma
G25m
40% disc.
G31
371±4Ma
i) 10CU10
Mt3 G15c
375±6Ma
Mt3 G21
375±8Ma
Mt3 G13
50% disc.
Mt3 G15r
31% disc.
Mt3 G24
372±6Ma
Mt4 G3r
361±8Ma
Mt4 G3m
369±6Ma
Mt4 G4
375±6Ma
Mt4 G10r
376±8Ma
Mt4 G11r
362±8Ma
Mt4 G13m
371±8Ma
Mt4 G10m
28% disc.
Mt4 G11c
364±8Ma
Mt4 G13r
371±6Ma
j) 10CU11
G2r
366±4Ma
G4r
378±6Ma
G7
363±6Ma
G2m
368±6Ma
G4m
367±6Ma
G9c
373±4Ma
G10
369±8Ma
G12
379±6Ma
G9r
374±6Ma
G21m
375±6Ma
G13
375±6Ma
G30c
374±6Ma
G30r
369±6Ma

Figure 4a

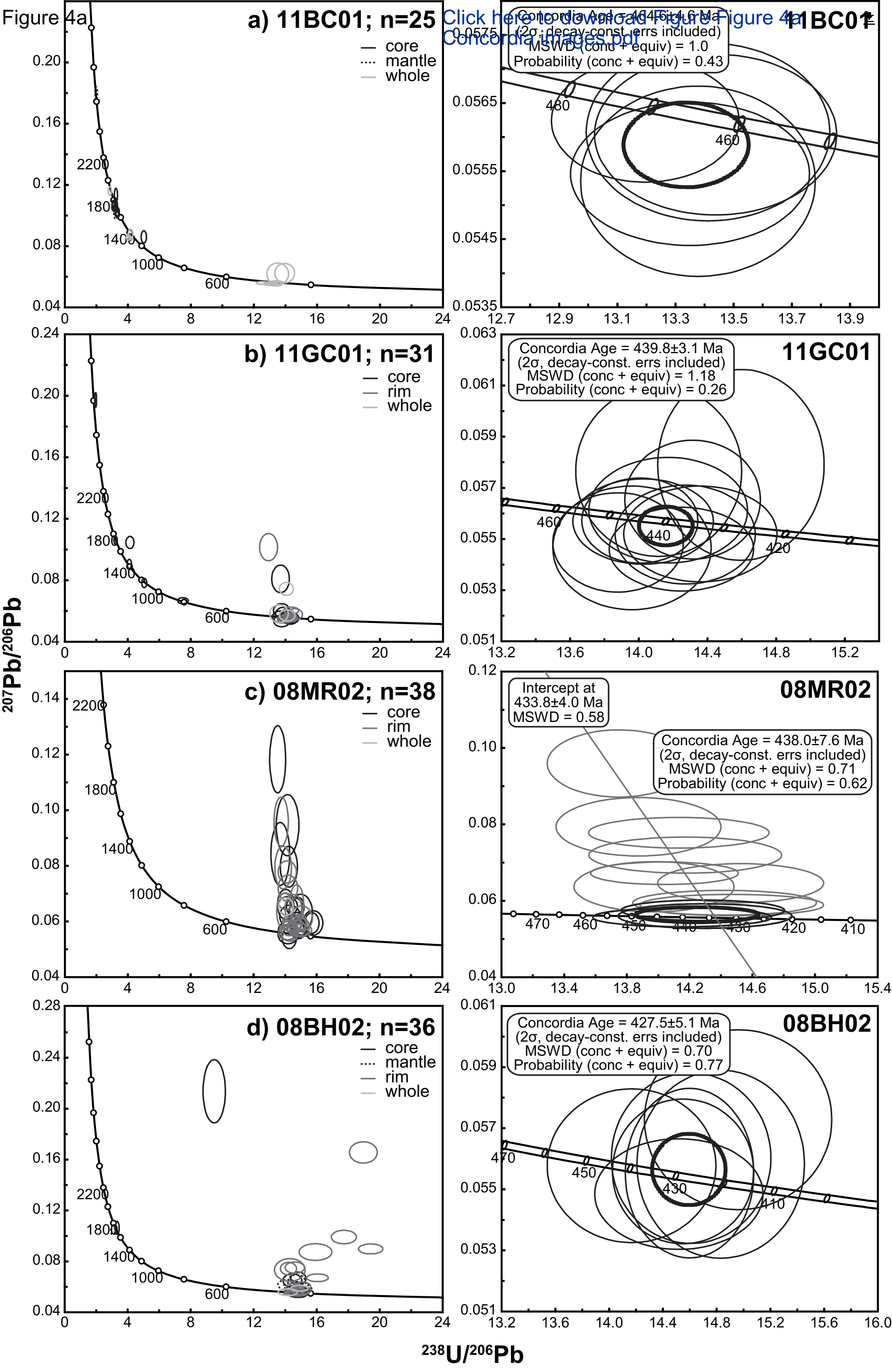

a) 11BC01; n=25
core
mantle
whole
2200
1800
1400
1000
600
11BC01
Concordia Age = 464.6±4.6 Ma
(2σ, decay-const. errs included)
MSWD (conc + equiv) = 1.0
Probability (conc + equiv) = 0.43
480
460
b) 11GC01; n=31
core
rim
whole
11GC01
Concordia Age = 439.8±3.1 Ma
(2σ, decay-const. errs included)
MSWD (conc + equiv) = 1.18
Probability (conc + equiv) = 0.26
460
440
420
c) 08MR02; n=38
core
rim
whole
08MR02
Intercept at
433.8±4.0 Ma
MSWD = 0.58
Concordia Age = 438.0±7.6 Ma
(2σ, decay-const. errs included)
MSWD (conc + equiv) = 0.71
Probability (conc + equiv) = 0.62
470
460
450
440
430
420
410
d) 08BH02; n=36
core
mantle
rim
whole
08BH02
Concordia Age = 427.5±5.1 Ma
(2σ, decay-const. errs included)
MSWD (conc + equiv) = 0.70
Probability (conc + equiv) = 0.77
470
450
430
410
^{207}Pb/^{206}Pb
^{238}U/^{206}Pb
0
4
8
12
16
20
24
12.7
12.9
13.1
13.3
13.5
13.7
13.9
13.2
13.6
14.0
14.4
14.8
15.2
13.0
13.4
13.8
14.2
14.6
15.0
15.4
16.0
0.04
0.08
0.12
0.16
0.20
0.24
0.28
0.06
0.10
0.14
0.0535
0.0545
0.0555
0.0565
0.0575
0.051
0.053
0.055
0.057
0.059
0.061
0.063

Figure 4b

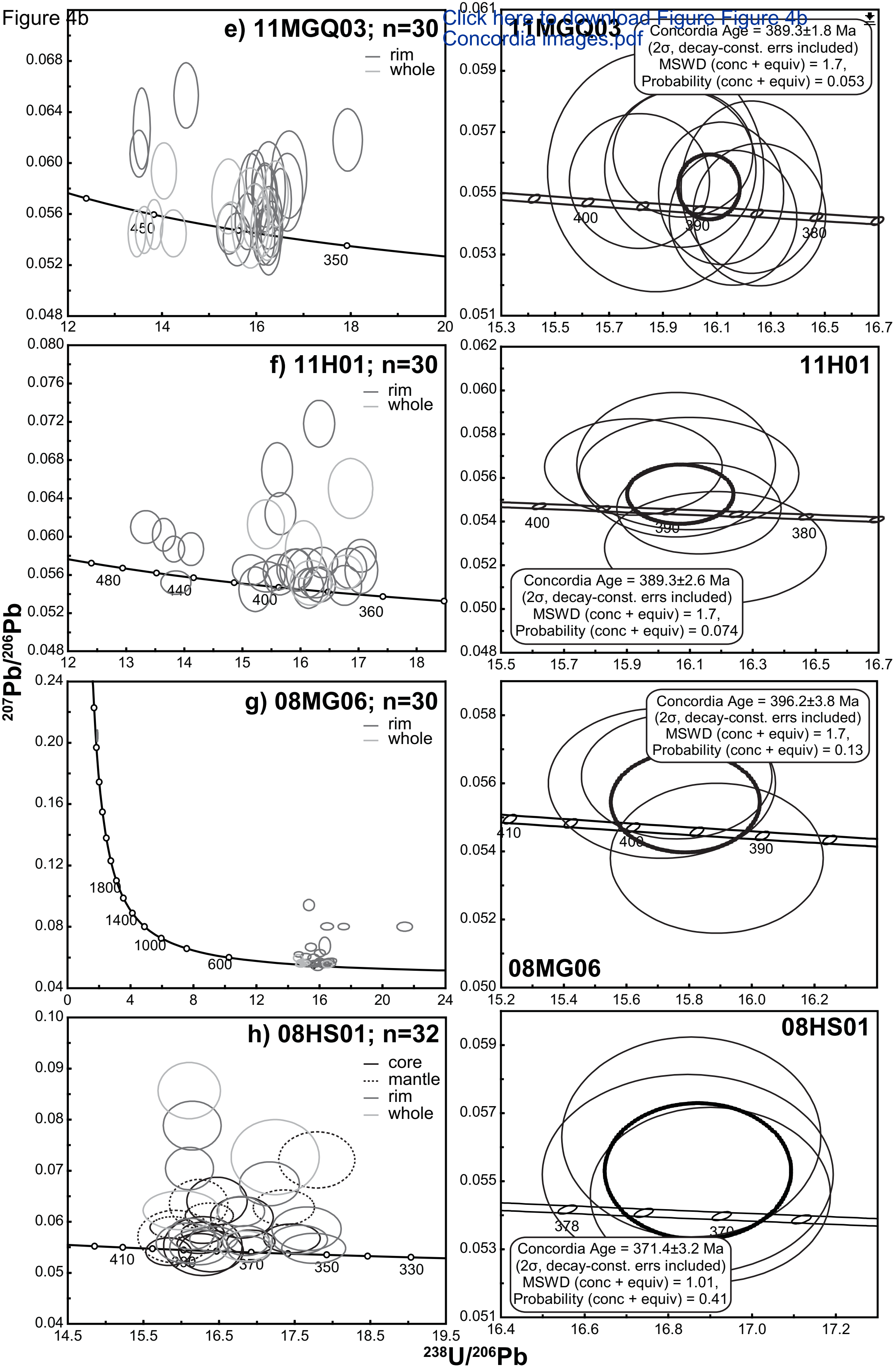

e) 11MGQ03; n=30
rim
whole
450
350
0.048
0.052
0.056
0.060
0.064
0.068
12
14
16
18
20
11MGQ03
Concordia Age = 389.3±1.8 Ma
(2σ, decay-const. errs included)
MSWD (conc + equiv) = 1.7,
Probability (conc + equiv) = 0.053
400
390
380
0.051
0.053
0.055
0.057
0.059
0.061
15.3
15.5
15.7
15.9
16.1
16.3
16.5
16.7
f) 11H01; n=30
rim
whole
480
440
400
360
0.048
0.052
0.056
0.060
0.064
0.068
0.072
0.076
0.080
12
13
14
15
16
17
18
11H01
Concordia Age = 389.3±2.6 Ma
(2σ, decay-const. errs included)
MSWD (conc + equiv) = 1.7,
Probability (conc + equiv) = 0.074
400
390
380
0.048
0.050
0.052
0.054
0.056
0.058
0.060
0.062
15.5
15.7
15.9
16.1
16.3
16.5
16.7
^{207}Pb/^{206}Pb
g) 08MG06; n=30
rim
whole
1800
1400
1000
600
0.04
0.08
0.12
0.16
0.20
0.24
0
4
8
12
16
20
24
Concordia Age = 396.2±3.8 Ma
(2σ, decay-const. errs included)
MSWD (conc + equiv) = 1.7,
Probability (conc + equiv) = 0.13
410
400
390
08MG06
0.050
0.052
0.054
0.056
0.058
15.2
15.4
15.6
15.8
16.0
16.2
h) 08HS01; n=32
core
mantle
rim
whole
410
390
370
350
330
0.04
0.05
0.06
0.07
0.08
0.09
0.10
14.5
15.5
16.5
17.5
18.5
19.5
08HS01
378
370
Concordia Age = 371.4±3.2 Ma
(2σ, decay-const. errs included)
MSWD (conc + equiv) = 1.01,
Probability (conc + equiv) = 0.41
0.051
0.053
0.055
0.057
0.059
16.4
16.6
16.8
17.0
17.2
^{238}U/^{206}Pb

Figure 4c

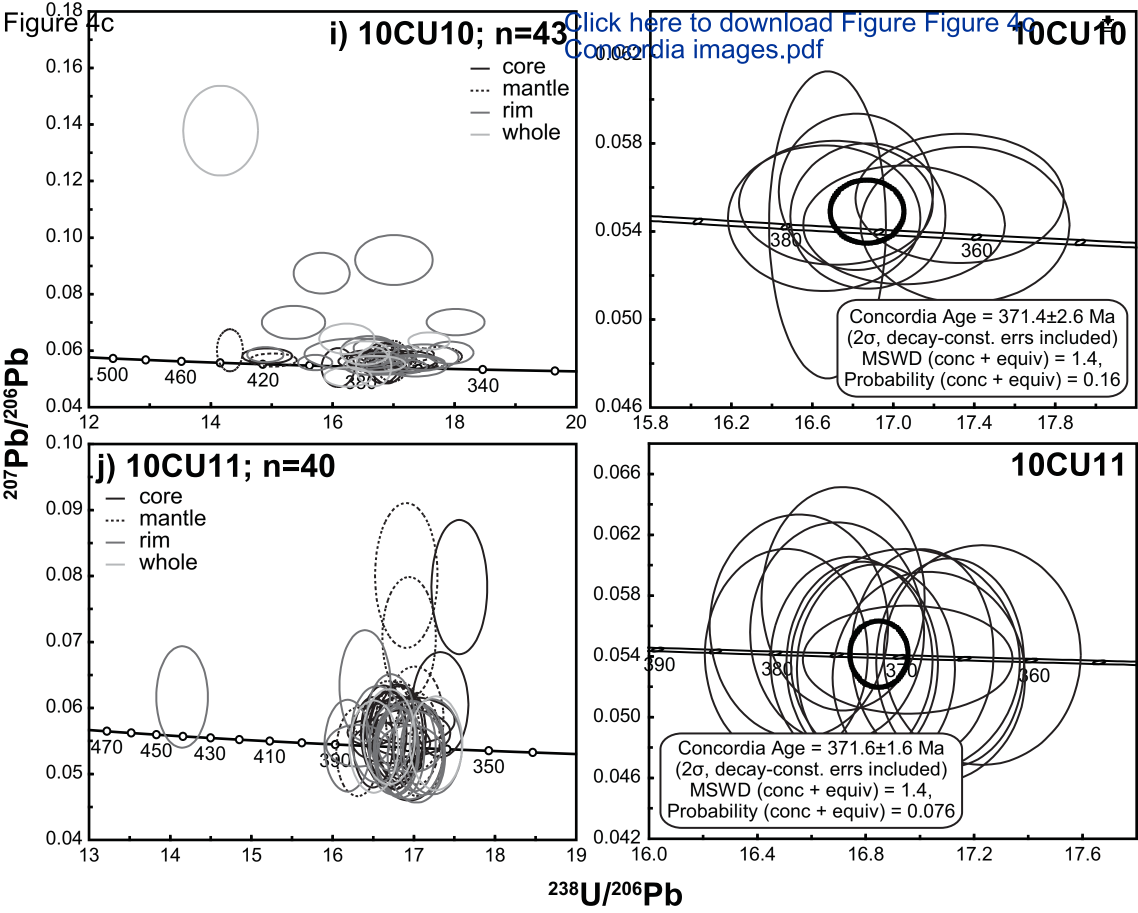
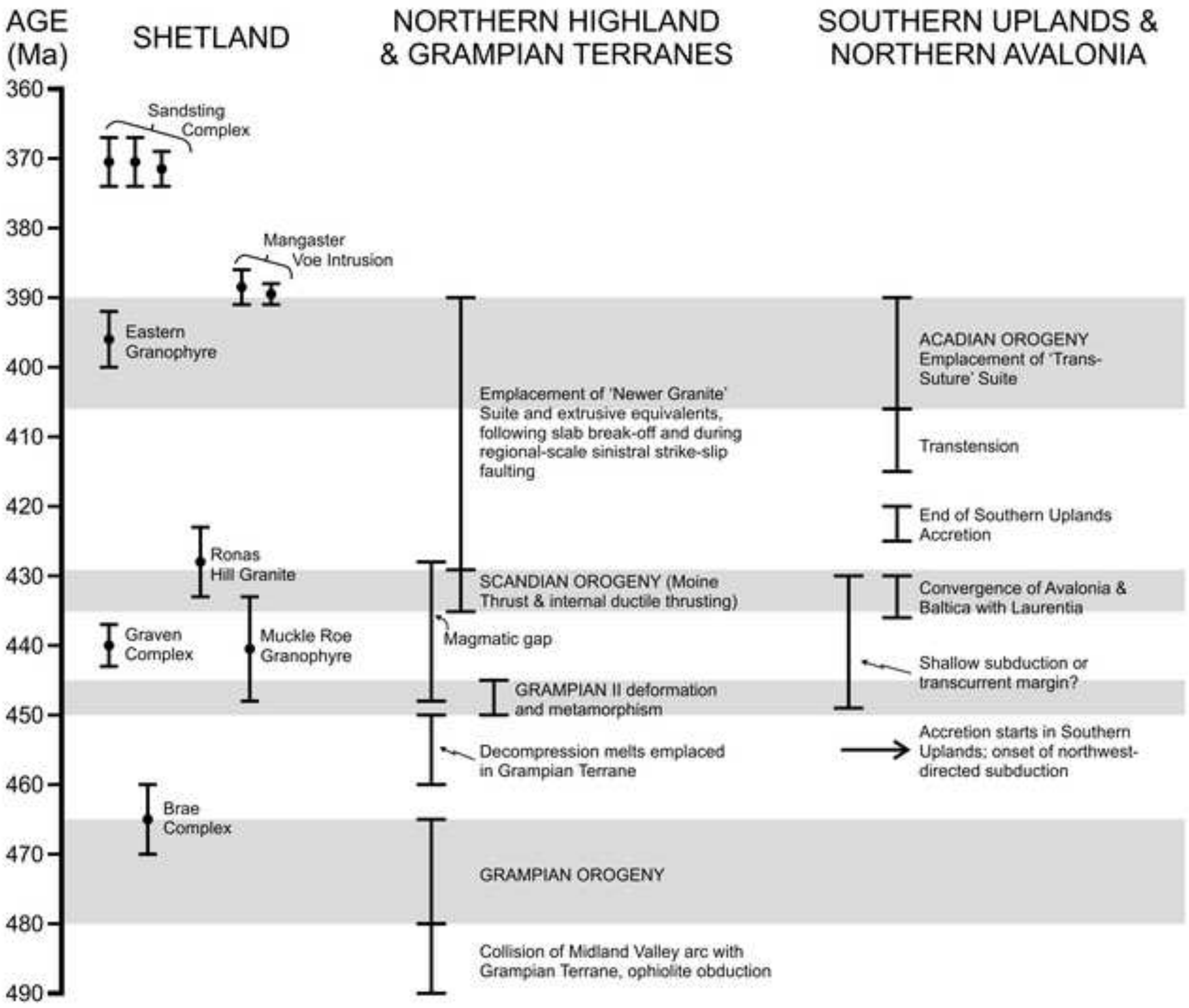

i) 10CU10; n=43
core
mantle
rim
whole
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
500
460
420
380
340
12
14
16
18
20
10CU10
0.062
0.058
0.054
0.050
0.046
380
360
15.8
16.2
16.6
17.0
17.4
17.8
Concordia Age = 371.4±2.6 Ma
(2σ, decay-const. errs included)
MSWD (conc + equiv) = 1.4,
Probability (conc + equiv) = 0.16
j) 10CU11; n=40
core
mantle
rim
whole
0.10
0.09
0.08
0.07
0.06
0.05
0.04
470
450
430
410
390
350
13
14
15
16
17
18
19
10CU11
0.066
0.062
0.058
0.054
0.050
0.046
0.042
390
380
370
360
16.0
16.4
16.8
17.2
17.6
Concordia Age = 371.6±1.6 Ma
(2σ, decay-const. errs included)
MSWD (conc + equiv) = 1.4,
Probability (conc + equiv) = 0.076
^{207}Pb/^{206}Pb
^{238}U/^{206}Pb

Figure 5


AGE (Ma)
SHETLAND
NORTHERN HIGHLAND & GRAMPIAN TERRANES
SOUTHERN UPLANDS & NORTHERN AVALONIA
360
370
380
390
400
410
420
430
440
450
460
470
480
490
Sandsting Complex
Mangaster Voe Intrusion
Eastern Granophyre
Ronas Hill Granite
Graven Complex
Muckle Roe Granophyre
Brae Complex
Emplacement of 'Newer Granite' Suite and extrusive equivalents, following slab break-off and during regional-scale sinistral strike-slip faulting
SCANDIAN OROGENY (Moine Thrust & internal ductile thrusting)
Magmatic gap
GRAMPIAN II deformation and metamorphism
Decompression melts emplaced in Grampian Terrane
GRAMPIAN OROGENY
Collision of Midland Valley arc with Grampian Terrane, ophiolite obduction
ACADIAN OROGENY Emplacement of 'Trans-Suture' Suite
Transtension
End of Southern Uplands Accretion
Convergence of Avalonia & Baltica with Laurentia
Shallow subduction or transcurrent margin?
Accretion starts in Southern Uplands; onset of northwest-directed subduction

Click here to access/download

Dataset

Supplementary material analytical data tables.xls

Click here to access/download

Supplementary material (not datasets)

Supp material - petrology and methods.doc