Timing of regional deformation and development of the Moine Thrust Zone in the Scottish Caledonides: constraints from the U-Pb geochronology of alkaline intrusions

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Abstract

The Moine Thrust Zone in the Scottish Highlands developed during the Scandian Event of the Caledonian Orogeny, and now forms the boundary between the Caledonian orogenic belt and the undeformed foreland. The Scandian Event, and the formation of the Moine Thrust Zone, have previously been dated by a range of isotopic methods, and relatively imprecise ages on a suite of alkaline intrusions localised along the thrust zone have provided the best age constraints for deformation. Recent BGS mapping has improved our understanding of the structural relationships of some of these intrusions, and this work is combined with new U-Pb dates in this paper to provide significantly improved ages for the Moine Thrust Zone. Our work shows that a single early intrusion (the Glen Dessarry Pluton) was emplaced within the orogenic belt to the east of the Moine Thrust Zone at 447.9 ± 2.9 Ma. A more significant pulse of magmatism centred in the Assynt area, which temporally overlapped movement in the thrust zone, occurred at 430.7 ± 0.5 Ma. Movement in the thrust zone had largely ceased by the time of emplacement of the youngest intrusions, the late suite of the Loch Borralan Pluton, at 429.2 ± 0.5 Ma, and the Loch Loyal Syenite Complex.

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The Caledonian orogenic belt extends from Svalbard, through Scandinavia, Eastern Greenland and the British Isles, to the Appalachian mountains of North America, and is among the world's most well-studied collisional orogens. Caledonian orogenesis comprised a number of separate events, which are attributed to the closure of the Iapetus Ocean during Ordovician to Silurian time, and the subsequent oblique collision of three crustal blocks, Laurentia, Baltica and Eastern Avalonia (e.g. Soper & Hutton 1984; Pickering *et al*. 1988; Soper *et al*. 1992; McKerrow *et al*. 2000; Dewey & Strachan 2003). In Scotland and Ireland, which were part of Laurentia, early orogenic activity resulted from an Ordovician arc-continent collision, the Grampian Event (Lambert & McKerrow 1976; Soper *et al*. 1999). Metamorphism associated with this event has been dated at 465 – 470 Ma (Oliver *et al*. 2000; Chew *et al*. 2008). This was followed by collision of Baltica with Laurentia during the Silurian (c. 435-425 Ma), causing the Scandian Event, which was first defined in Scandinavia (Gee, 1975) and later recognised in Scotland (Coward 1990; Dallmeyer *et al*. 2001; Kinny *et al*. 2003). The western margin of the Caledonian Orogen in North-west Scotland is defined by the Moine Thrust Zone, which runs from Loch Eriboll on the north coast to the Isle of Skye (Fig. 1), and which formed during the Scandian Event.

Constraints on the timing of the Scandian Event in North-west Scotland are based on two methods: the application of U-Pb geochronology to igneous intrusions with well-defined structural relationships (e.g. van Breemen *et al*. 1979a,b; Halliday *et al*. 1987; Rogers & Dunning 1991; Stewart *et al*. 2001; Kinny *et al*. 2003; Kocks *et al*. 2006); and direct dating of minerals grown during ductile deformation (Kelley 1998; Freeman *et al.* 1998; Dallmeyer *et al.* 2001). In this paper we present the results of an integrated structural and geochronological study of alkaline intrusions that occupy differing structural settings along the Moine Thrust Zone. We focus in particular on the classic area of the Moine Thrust Zone in Assynt, which has recently been remapped (Goodenough *et al*. 2004; British Geological Survey 2007; Krabbendam & Leslie 2010). The data reported here place tight constraints on the age of the Moine Thrust Zone as well as the timing of ductile deformation within internal sectors of the orogen, and thus have implications for Caledonian tectonic models in this part of the North Atlantic region.

Regional setting

The Moine Thrust Zone defines the western margin of the Caledonian Orogen in Scotland (Fig. 1). To the west lies the undeformed foreland, first described by Peach *et al*. (1907). The foreland basement comprises Archaean to Palaeoproterozoic gneisses of the Lewisian Gneiss Complex (Park *et al*. 2002). An unconformity separates the basement from a thick succession of Meso- to Neoproterozoic clastic sedimentary rocks belonging to the Stoer, Sleat and Torridon groups, commonly grouped under the umbrella term 'Torridonian' (Stewart 2002). The basement gneisses and Torridonian succession are both unconformably overlain by a Cambro-Ordovician sedimentary sequence. This succession, which is dominated by quartz arenites in its lower part (Ardvreck Group) and dolostones in its upper part (Durness Group), was deposited on the passive margin of eastern Laurentia following opening of the Iapetus Ocean (Park *et al*. 2002). Structurally above, and to the east of, the Moine Thrust Zone lie metasedimentary rocks of the Early Neoproterozoic Moine Supergroup (Strachan et al. 2002).

The Moine Thrust Zone comprises a series of thrust sheets, made up of rocks that are correlated with the foreland sequences (Lapworth 1883; Peach *et al*. 1907; Elliott & Johnson 1980; Coward 1983; Butler 1987). It is widest in the Assynt Culmination (Figs 2, 3) where the component units of the foreland are interleaved in a series of major thrust sheets (Peach *et al*. 1907; Elliott & Johnson 1980; Krabbendam & Leslie 2004; British Geological Survey, 2007). The general consensus is that most thrusts propagated in 'piggy-back' sequence towards the foreland (Elliott & Johnson 1980; Coward 1985). The structurally highest and hence oldest thrust is the ductile Moine Thrust, with associated mylonites derived both from the foreland succession and the overlying Moine Supergroup. Below the Moine Thrust, the Ben More Thrust carries Lewisian gneisses, Torridon Group and Ardvreck Group rocks in its hangingwall. The underlying Glencoul Thrust carries Ardvreck Group quartz arenites and Lewisian gneisses. The Glencoul Thrust is well-defined in northern Assynt but becomes more difficult to trace southwards, splaying into a complex imbricate system to the east of Inchnadamph (Elliott & Johnson 1980; Krabbendam & Leslie 2010). The structurally lowest and youngest thrust is the Sole Thrust, with imbricates of the Durness Group and the upper part of the Ardvreck Group in its hangingwall (Fig. 4). The temperatures of deformation within the Moine Thrust Zone are difficult to establish, but studies of conodont colour indices and illite crystallinity have indicated a likely maximum temperature range in the lower thrust sheets of 225-325°C (Johnson *et al*. 1985; M.P. Smith pers. comm.). Deformation temperatures associated with ductile deformation in the Moine Thrust sheet were > 500°C (Thigpen *et al.* 2010).

A broadly foreland-propagating sequence of thrusting is indicated by the way in which the structurally highest thrusts are folded by the development of duplexes in their footwalls (Elliott & Johnson 1980; Fig. 4). Nonetheless, some structures have an 'out-of-sequence' geometry, that has been suggested to result from late movement (Coward 1982, 1983, 1985; see also Holdsworth *et al*. 2006) or simultaneous slip on an array of imbricate thrusts (Butler 2004). Thus the ductile Moine Thrust in central and northern Assynt is early in the structural sequence, but in southern Assynt it is represented by a late, out-of-sequence brittle structure (Coward 1985). However, the overall displacement on any out-of-sequence structures is not thought to be regionally significant. The construction of balanced cross-sections across the Assynt Culmination indicates a total displacement on the Moine Thrust and lower thrusts within the Moine Thrust Zone of up to 100 km (Elliott & Johnson 1980), to which can be added an unknown amount of displacement related to development of the mylonites within the overlying Moine rocks.

East of the Moine Thrust, metasedimentary rocks of the Neoproterozoic Moine Supergroup underlie much of the Northern Highlands (Fig. 1), and are disposed in a series of east-dipping ductile thrust nappes (e.g. Barr *et al*. 1986; Holdsworth 1989; Holdsworth *et al*. 2001; Strachan *et al*. 2002; Alsop *et al*. 2010; Leslie *et al*. 2010). The effects of the earlier Grampian Event appear to be restricted to the eastern and structurally higher Sgurr Beag and Naver nappes (Kinny *et al*. 1999; Rogers *et al*. 2001; Cutts *et al*. 2010). In contrast, in the western nappes below the Naver and Sgurr Beag thrusts (Fig. 1), widespread foreland-propagating ductile thrusting and folding accompanied by amphibolite-facies metamorphism is assigned to the Scandian Event, and culminated in the development of the Moine Thrust Zone (Strachan & Holdsworth 1988; Holdsworth 1989; Dallmeyer *et al*. 2001; Strachan *et al*. 2002; Kinny *et al*. 2003; Holdsworth *et al*. 2006, 2007; Alsop *et al*. 2010; Leslie *et al*. 2010; Krabbendam *et al.* in press). Above the Sgurr Beag Thrust, Scandian deformation led to the development of regional-scale upright folding in a zone known as the Northern Highland Steep Belt (Roberts *et al*. 1984; Strachan & Evans 2008).

Syn-tectonic metagranites within the western part of the Moine outcrop have yielded U-Pb (SIMS) zircon ages of c. 430-415 Ma (Kinny *et al*. 2003; Alsop *et al*. 2010), broadly constraining the age of the Scandian Event. Dating of micas in the Moine Thrust mylonites, using the Rb-Sr, K-Ar and Ar-Ar isotope systems (Kelley 1988; Freeman *et al*. 1998; Dallmeyer *et al*. 2001), has also yielded a range of Silurian to Devonian ages. All of these studies pointed to the continuation of deformation along the Moine Thrust after 430 Ma, and Freeman *et al*. (1998) suggested that transfer of movement from the Moine Thrust on to the underlying Ben More Thrust may have occurred at c. 430 Ma. In order to further constrain the timing of regional deformation and marginal thrusting we now focus on the structural setting and U-Pb geochronology of alkaline intrusions that intrude the Moine Thrust Zone and Moine Supergroup.

Alkaline to calc-alkaline magmatism in the North-west Highlands

The Ordovician - Silurian closure of the Iapetus Ocean was associated with voluminous calc-alkaline and minor alkaline magmatism in the Scottish Highlands (e.g. Read 1961; Stephenson *et al*. 1999). The calc-alkaline magmatism has been generally attributed to NW-directed subduction of oceanic lithosphere beneath the Laurentian margin (e.g. Dewey 1971; van Breemen & Bluck 1981; Fowler *et al*. 2001; Oliver *et al*. 2008), with a major magmatic pulse during the late Silurian and early Devonian being caused by slab break-off (Atherton & Ghani 2002; Neilson *et al*. 2009).

In the North-west Highlands, a number of alkaline plutons, together with abundant calc-alkaline to alkaline dykes and sills, intrude across the Moine Thrust Zone and into both the foreland and the Moine Supergroup (Peach *et al*. 1907; Parsons 1999). These magmas are generally thought to be shoshonitic in nature, generated at some distance from the active subduction zone (Thompson & Fowler 1986; Thirlwall & Burnard 1990; Fowler *et al*. 2008).

The most extensive alkaline magmatism occurred within the Assynt Culmination (Fig. 2). Two major syenite plutons intrude the culmination, the Loch Ailsh Pluton (Phemister 1926; Parsons 1965 a,b) and the Loch Borralan Pluton (Woolley 1970, 1973), as well as a wide range of sills and dykes (Sabine 1953; Goodenough *et al*.

2004). The Loch Ailsh Pluton and the majority of the minor intrusions are considered to have been deformed by thrust movement within the Moine Thrust Zone (Parsons 1999; Goodenough *et al*. 2004), whereas emplacement of the Loch Borralan Pluton, which comprises two separate magmatic suites, has been shown to have overlapped with thrusting, as described in detail below (Woolley 1970).

Above the Moine Thrust, the Loch Loyal Syenite Complex and the Glen Dessarry and Ratagain plutons intrude the Moine Supergroup (Fig. 1). The Glen Dessarry Pluton, the southern-most of the alkaline intrusions, has a penetrative Caledonian fabric that formed during upright folding and development of the Northern Highland Steep Belt (Roberts *et al*. 1984). In contrast, the Loch Loyal Syenite Complex clearly post-dates the main ductile deformation and metamorphism in the host Moine rocks (Holdsworth *et al*. 1999). All the main plutons have been dated by previous workers using U-Pb techniques on zircon (Fig. 6). The oldest, deformed Glen Dessarry Pluton has been dated at 456 ± 5 Ma (van Breemen *et al*. 1979b). The Loch Ailsh Pluton (439 ± 4 Ma; Halliday *et al*. 1987), and the Canisp Porphyry Sills (437 ± 5 Ma; Goodenough *et al*. 2006) pre-date movements in the Moine Thrust Zone (Parsons 1999; Goodenough et al. 2004) and these dates have been considered to provide a maximum age for the onset of thrusting. The Loch Borralan Pluton has been dated at 430 ± 4 Ma (van Breemen *et al*. 1979a), but this date was based on a number of samples derived from different intrusive phases with varied structural relationships (as mapped by Woolley 1970) and so the exact relationship of the age to thrusting was unclear. Later workers have generally assumed that this age post-dates movement within the Moine Thrust Zone (e.g. Halliday *et al*. 1987). The post-deformation Loch Loyal Syenite Complex has been dated at 426 ± 9 Ma (Halliday *et al*. 1987).

Many of the existing U-Pb zircon data are highly discordant, and record an apparently large spread in ages (from c. 456 to c. 426 Ma) for emplacement of geochemically similar intrusions. Recent years have seen advances in geochronological techniques, as well as an increased understanding of the field relationships in the Moine Thrust Zone, and so a new integrated structural and geochronological study of the Caledonian alkaline intrusions of North-west Scotland is timely.

Structural settings of the alkaline intrusions

These are described in their likely order from oldest to youngest, based on published geochronology where available (see above).

Glen Dessarry Pluton

The Glen Dessarry Pluton is located within the Sgurr Beag Nappe, over 100 km to the south of the other syenite plutons discussed here, and over 30 km east of the trace of the Moine Thrust to the south of the Isle of Skye (Fig. 1). Nonetheless it is typically grouped with the other syenite plutons, on the basis of similar petrology and geochemistry (e.g. Fowler *et al*. 2008). It comprises an outer mafic syenite, with a core of felsic syenite (Richardson 1968). The pluton intrudes Moine psammites assigned to the Loch Eil Group and occupies the core of a large, curvilinear synform (Roberts *et al*. 1984). The intrusion post-dates two early deformation phases in its host Moine rocks, but it carries a penetrative solid state deformation fabric that is related to the widespread tight to isoclinal upright folding of the Northern Highland Steep Belt (Roberts *et al*. 1984).

The Loch Ailsh Pluton

The syenites of the Loch Ailsh Pluton lie directly beneath the Moine Thrust and intrude Lewisian and Cambrian rocks of the Ben More Thrust sheet in the Assynt Culmination (Fig. 3). The pluton comprises three phases, termed S1, S2, and S3, which are considered to be broadly contemporaneous (Parsons 1965b; Fig. 3). Although their contact with the Moine Thrust is not exposed, geophysical evidence suggests that the plutonic rocks extend to the east beneath the thrust (Parsons 1965a). The syenites have been mylonitised in a number of localised shear zones associated with thrusting, with recrystallisation of large perthitic feldspars to fine-grained albite-rich aggregates (Parsons 1965b). The Ben More Thrust sheet has not been affected by significant internal deformation, and there are no exposed contacts between the Loch Ailsh Pluton and mappable thrusts. However, a rhyolite dyke which cuts the S2 syenites at [NC 3269 1365] is part of the Peralkaline Rhyolite Swarm, which was deformed by movement associated with the Glencoul and Ben More thrusts (Goodenough *et al*. 2004). If this dyke swarm represents a single intrusive episode, then the Loch Ailsh Pluton was emplaced prior to movement on these thrusts.

Minor intrusions

The minor intrusions of the Assynt Culmination comprise six swarms (Canisp Porphyry, Peralkaline Rhyolite, Hornblende Microdiorite, Nordmarkite, Vogesite and Porphyritic Trachyte swarms), most of which pre-date thrusting (Sabine 1953; Goodenough *et al*. 2004). The Canisp Porphyry sills are found below, and close to, the Sole Thrust (Parsons 1999) but do not appear above it, and so are considered to pre-date movement on that thrust. The Peralkaline Rhyolite, Hornblende Microdiorite, and Vogesite swarms outcrop within the Moine Thrust Zone in Assynt, and are affected by thrust-related deformation (Goodenough et al. 2004).

The intrusions of the Nordmarkite Swarm are unusual in that they crop out along, and on both sides of, the Moine Thrust and within the Moine rocks to the east (Parsons 1999; Goodenough *et al*. 2004). Since the rocks in the hangingwall of the Moine Thrust may have moved up to 100 km westwards to their present position (Elliott & Johnson 1980), the nordmarkite intrusions must post-date the main movement on the Moine Thrust. However, the intrusions close to the Moine Thrust have mylonitic margins, indicating that they were emplaced before final movement had ceased.

The Loch Borralan Pluton

The Loch Borralan Pluton includes a range of unusual rock-types such as ‘borolanite’ (a melanite-biotite nepheline-syenite with white spots that represent pseudomorphs after leucite) and ‘ledmorite’ (a melanite-augite nepheline-syenite) (Shand 1909, 1910, 1939). Woolley (1970) identified two separate suites, separated by an intrusive contact (Fig. 3). The early suite consists of a poorly-exposed ‘conformable sheeted complex’ (Woolley 1970) comprising locally foliated pseudoleucite syenites (‘borolanites’) and nepheline syenites (‘ledmorites’) as well as mafic to ultramafic rocks. In contrast, the late suite, which is rather better exposed on the hill of Cnoc na Sroine (Fig. 3), forms a steep-sided plug of syenite and quartz-syenite, undeformed except for some late fracturing. Woolley (1970) suggested that at least part of the early suite was intruded prior to movement on local thrusts, whilst the late suite post-dated thrusting. However, the structural relationships of the early suite have been the subject of debate, because some workers have suggested that the syenites form a single mass that has been deformed and transported by thrust movement (Coward 1985; Searle *et al.* 2010). The debate centres on a handful of key contact localities (Parsons 1999), which are briefly summarised here.

At the north-western margin of the pluton, the marble quarry at Ledbeg [NC 252 135] exposes sheets of pseudoleucite syenite 1-2 m across cutting metasomatised dolostones of the Durness Group in the Sole Thrust sheet. These outcrops lie in the footwall to the 'Borralan Thrust' of Searle *et al*. 2010, clearly indicating that this thrust is cross-cut by rocks of the early suite. Just north of the quarry around [NC 257 145] lies an isolated mass of nepheline syenite (the Loyne Mass of Woolley 1970), whose relationships to thrusts are not well exposed (Searle *et al*., 2010). In the north-east of the Loch Borralan Pluton, at the Four Burns locality [NC 293 132], nepheline-syenite sheets intrude dolostones and quartz arenites immediately beneath the Ben More Thrust (Woolley 1970; Woolley *et al*. 1972). These sedimentary rocks lie within an imbricate stack termed the Breabag Dome (Elliott and Johnson 1980; Coward 1984; British Geological Survey 2007; Krabbendam and Leslie 2010). The exposures at the Four Burns are thus significantly higher in the thrust pile than the exposures around Ledbeg (Figs. 3, 4). At the southern margin of the pluton, Ardvreck Group quartz arenites that have been fenitised by the syenite intrusion are exposed around [NC 285 284] (Woolley *et al*. 1972). Again, these quartz arenites are structurally higher than the dolostones around Ledbeg (British Geological Survey 2007).

A key contact of the Loch Borralan Pluton is exposed to the south of Loch Borralan, at Bad na h-Achlaise [NC 245 115], and has been excavated to improve the exposure (Parsons & McKirdy 1983). At this locality, syenites attributed to the early suite intrude Ardvreck Group quartz arenites that are part of the Cam Loch thrust klippe (Parsons & McKirdy 1983; British Geological Survey 2007) (Fig. 3). This klippe has been considered to be floored by the Ben More Thrust (Elliott & Johnson 1980; Coward 1985) but may equally be a separate thrust (Butler 2009; Searle *et al*. 2010). A short distance to the south-east of Bad na h-Achlaise, ultramafic rocks of the early suite, together with a small carbonatite body, intrude Durness Group dolostones in the footwall to the Cam Loch thrust (Shaw *et al*. 1992; Young *et al*. 1994).

The best single exposure of the early suite rocks occurs at the Aultivullin quarry [NC 2870 0965], where the pseudoleucite-syenites are well exposed. Here the white pseudoleucite spots are streaked and flattened into ellipses that define a south-easterly dipping foliation. Cross-cutting pegmatites appear undeformed, and this led Bailey & McCallien (1934) to suggest that the earlier parts of the Loch Borralan Pluton were emplaced prior to thrusting, with later intrusions post-dating thrusting. Woolley

(1970) studied the petrography of the pseudoleucite-syenites, and observed "a complete overlap of crystallisation by deformation", indicating a syn-tectonic age. Similarly, Elliott & Johnson (1980) noted that the foliation probably formed during emplacement of the pluton. However, Searle *et al.* (2010) argue that the foliation formed after crystallisation of the magmas.

The field evidence as described here indicates that intrusions belonging to the early suite of the Loch Borralan Pluton clearly cut across a number of thrusts between the Sole and Ben More thrusts (Fig. 3; Parsons & McKirdy 1983; Parsons 1999; British Geological Survey 2007). The overall outcrop pattern indicates that the Loch Borralan Pluton was intruded into quartzite-dominated imbricates to the north and dolostone-dominated imbricates to the south, and thus was probably focused along a lateral ramp. The contacts of the early suite of the Loch Borralan Pluton have a sheeted form (e.g. at the Four Burns and at Ledbeg Quarry) and the whole suite is considered to be formed of a series of sheets, emplaced along thrust planes during thrusting. We follow the detailed study of Woolley (1970) in concluding that emplacement of the early suite overlapped with thrust movement, but that the later suite clearly post-dates thrust movement; the observed field relationships do not fit with the proposal of Searle et al. (2010) for movement of the entire Loch Borralan Pluton on a Borralan Thrust.

The Loch Loyal Syenite Complex

The Loch Loyal Syenite Complex intrudes the Moine Supergroup c. 15 km east of the Moine Thrust (Fig. 1). It consists of three separate, but related, quartz-syenite bodies, the Ben Loyal, Ben Stumanadh and Cnoc nan Cuilean intrusions (Robertson and Parsons 1974; Holdsworth *et al.* 1999, 2001). Intrusion of the Loch Loyal syenites post-dated regional (Scandian) D2 and D3 folding and ductile thrusting in this part of the Moine (Read 1931; Holdsworth *et al.* 1999, 2001).

U-Pb Geochronology

Techniques for dating zircons using isotope-dilution thermal ionisation mass spectrometry (ID-TIMS) have improved significantly in recent years. The early studies of the Loch Borralan and Loch Ailsh plutons, by van Breemen *et al.* (1979a) and Halliday *et al.* (1987), required dissolution of multi-milligram zircon fractions that were highly discordant due to Pb-loss. Subsequently, methods have been developed to allow low-blank zircon dissolution and chemical separation of U and Pb (Krogh 1973; Parrish 1987), to reduce discordance due to Pb-loss using air abrasion (Krogh 1982), and to improve analytical precision and accuracy using gravimetrically well-calibrated synthetic isotope tracers (Parrish & Krogh 1987; Parrish *et al*. 2006). Recently, Mattinson (2005) reported a method of annealing and chemically abrading zircons (CA-TIMS), which in many cases eliminates discordance due to Pb-loss. Together, these advances allow increasingly precise (and accurate, subject to uncertainties in decay constants and tracer calibrations) ages to be determined on single zircon crystals or crystal fragments. Ongoing research, co-ordinated by the EARTHTIME initiative (www.earth-time.org), aims to improve the accuracy and precision of uranium decay constants and the natural $^{235}U/^{238}U$ ratio, calibrate and distribute interlaboratory standards, develop open-source universal data-reduction software, and intercalibrate U-Pb, Ar-Ar and cyclostratigraphic dating techniques.

Methodology

Zircons were separated using standard crushing and mineral separation techniques. The best quality zircons were picked, annealed, and subjected to chemical abrasion (CA: Mattinson 2005) to improve concordance. Single grains were spiked with a mixed $^{205}Pb/^{235}U$ tracer (Parrish & Krogh 1987) or mixed $^{205}Pb/^{235}U/^{233}U$ tracer (Parrish *et al*. 2006) and dissolved in teflon microcapsules (Parrish 1987). Titanites were separated from the Glen Dessarry sample using standard techniques, and dissolved in Savillex® beakers. U and Pb were separated following Corfu and Noble (1992) and references therein. U and Pb were loaded together onto single rhenium filaments using silica gel, and measured by peak-jumping using a secondary electron multiplier on a Thermo-Electron Triton thermal ionization mass spectrometer. Raw data were reprocessed offline using MATLAB® in order to allow time-interpolated correction of isobaric interferences. Data reduction was carried out using the UPbR spreadsheet derived from the algorithms of Schmitz & Schoene (2007). Ages were calculated using Isoplot 3.16 (Ludwig 2003).

Sample descriptions

A sample of felsic (meta)syenite (GDS-1) was collected from the Glen Dessarry Pluton at [NM 9515 9217]. The sample is coarse grained and carries a penetrative solid-state deformation fabric defined by augen of recrystallised alkali feldspar and sub-parallel grains of aligned hornblende and biotite. Magnetite, titanite and zircon are common accessory minerals.

A sample of the Loch Ailsh Pluton (KG014) was collected from outcrops in the River Oykel near the centre of the intrusion, within the S2 syenites, at [NC 3272 1319]. It is a coarse-grained syenite, consisting chiefly of plates of microperthitic alkali feldspar with small amounts (<10%) of a green pyroxene; titanite and zircon are common accessories. The feldspar plates appear largely undeformed, but do exhibit swapped rims, which are common in the Loch Ailsh Pluton and are considered to have formed during thrust movement (Parsons, 1965b)

A sample of Canisp Porphyry (KG023) was collected from a sill intruding Ardvreck Group quartz arenites below the Sole Thrust at [NC 2410 2128]. The sample is strongly porphyritic, with large (up to 1 cm) euhedral albite phenocrysts in a fine-grained, structureless quartzofeldspathic groundmass. Biotite is the main mafic mineral. This sample has previously yielded a U-Pb zircon age of 437 ± 4.8 Ma (Goodenough *et al*. 2006) and has been re-analysed as part of the present study.

A sample of a nordmarkite intrusion (KG050) was taken from a c. 1m-thick sill that intrudes dolostones of the Durness Group immediately beneath the Moine Thrust to the south of Loch Ailsh [NC 3010 0833]. The sample contains irregular, strongly sericitised plates of albite up to c. 2 mm, in a very fine-grained quartzofeldspathic matrix. The matrix has a penetrative solid-state deformation fabric defined by elongate aggregates of recrystallised quartz, and stringers of fine-grained chlorite and biotite.

Three samples were collected from the Loch Borralan Pluton. Sample IM2.1 was collected from Bad na h-Achlaise where early suite syenites cut quartz arenite of the Cam Loch thrust klippe [NC 2442 1152]. The sample is coarse grained and consists largely of plates of perthitic feldspar, with rare aegirine augite. Sample IM4.1 was collected from the early suite at Aultivullin Quarry [NC 2870 0965]. It is coarse grained, consisting of laths of perthitic feldspar with nepheline, brown melanite garnet, biotite and hornblende. Aggregates of fine-grained feldspar, nepheline and white mica form pseudoleucite spots. Accessory minerals include titanite, apatite and carbonates. In hand specimen, a foliation is visible, chiefly defined by flattened pseudoleucites; at thin-section scale, the foliation is only weakly defined by a broad parallelism of feldspar laths and biotite flakes. Feldspars are locally recrystallised to subgrains. Sample IM1.1 was collected from the late suite near the summit of Cnoc na Sroine [NC 2550 1225]. The sample is coarse grained and unfoliated, and consists chiefly of laths of perthitic feldspar with interstitial quartz.

A sample (Loyal1) of the Loch Loyal Syenite Complex was collected from [NC 6125 4980]. The sample was obtained from the outer marginal syenite of the Ben Loyal body. It is medium to coarse grained, and consists of alkali feldspar, albite, quartz and hornblende with minor titanite, apatite and opaque oxides. A magmatic-state deformation fabric is defined by the alignment of feldspar laths and hornblende.

Results and Interpretation

Glen Dessarry Pluton

Eight single zircon grains and three titanite fractions were analysed from the Glen Dessarry syenite (sample GDS-1, Table 1, Fig. 5a). Of these, two grains (GDS-1 z1 and z5; not plotted in Fig 5a) show reverse discordance and must contain inherited cores. Three further grains (GDS-1 z2, z3, z4; not plotted in Fig. 5a) were small (sub-microgram), and their analyses had low ratios of radiogenic to common lead, resulting in imprecise analyses that scatter around concordia, with a mean $^{206}Pb/^{238}U$ age of 448 Ma. Three larger grains (GDS-1 z6, z8, z9) give precise, concordant analyses, with a weighted mean $^{206}Pb/^{238}U$ age of 447.9 ± 2.9 Ma. The three analysed titanite fractions are relatively non-radiogenic ($^{206}Pb/^{204}Pb$ from 55 to 62). However, when corrected for common lead using the Stacey-Kramers model at 450 Ma, they yield concordant data, with a mean $^{206}Pb/^{238}U$ age of 445.7 ± 8.0 Ma, and a concordia age of 445.3 ± 1.9 Ma.

Loch Ailsh Pluton

Eight single zircon grains were analysed from the Loch Ailsh Pluton (sample KG014; Fig. 5b). Of these, one (KG014z3) is highly discordant, and appears to have suffered Pb-loss, despite having undergone chemical abrasion. Of the remaining seven grains, one (KG014z4) gave a relatively imprecise analysis, but is included as it overlaps the other analyses. The seven analyses all overlap concordia, with a weighted mean $^{206}Pb/^{238}U$ age of 430.6 ± 0.3 Ma. In detail, five fractions have near-identical

$^{206}Pb/^{238}U$ ages (fraction KG014z7 has a slightly younger $^{206}Pb/^{238}U$ age, and might have suffered Pb-loss, and KG014z5 has a slightly older $^{206}Pb/^{238}U$ age, perhaps indicating a small degree of inheritance). However, the weighted mean $^{206}Pb/^{238}U$ age of these five analyses (430.6 ± 0.2 Ma) is identical to the age given by all seven concordant fractions. Rather than over-interpreting the data, we prefer the age of 430.6 ± 0.3 Ma for the Loch Ailsh Pluton, derived from all seven concordant analyses.

Canisp Porphyry

Ten single zircon grains were analysed from the Canisp Porphyry sample (KG023; Fig. 5c). Of these, two (KG023z1, KG023z2) are highly reversely discordant and must contain inherited cores. Two fractions (KG023z3, KG023z5) are concordant, but with slightly older $^{206}Pb/^{238}U$ ages than the bulk of the zircon data, perhaps indicating a small degree of inheritance of slightly older zircon. The six remaining fractions are concordant, and form a cluster with a weighted mean $^{206}Pb/^{238}U$ age of 430.4 ± 0.4 Ma. Mixture modelling (Sambridge & Compston 1994, as implemented by Ludwig 2003) is consistent with the interpretation of these six analyses as forming a single normally-distributed age population, with the two slightly older concordant fractions representing a separate, older population.

Nordmarkite Swarm

Five single grains were analysed from a sample of nordmarkite (KG50; 5d). Three of the five analyses contained high levels (tens of picograms) of common Pb, and yielded imprecise analyses. All five grains are discordant, with a wide range of $^{206}Pb/^{238}U$ ages from 437 to 1979 Ma. The data scatter around a discordia with an upper intercept age of 2740 Ma, and a lower intercept of 420 Ma. A regression through the two analyses closest to the lower intercept intersects concordia at 430 Ma.

Loch Borralan early suite

Four single zircon grains were analysed from the Bad na h-Achlaise early suite syenite vein (sample IM.2.1; Fig. 5e). All four analyses are highly discordant. Forcing a regression line through 430 Ma yields an Archaean upper intercept at around 2580 Ma. Three of the grains define a discordia with upper and lower intercepts at 2939 ± 13 Ma and 1329 ± 19 Ma respectively (MSWD = 0.58). However, Mesoproterozoic events are not recorded by detrital zircons in Ardvreck

Group quartz arenites (Cawood et al. 2007), so this discordia is almost certainly coincidental and has no geological significance.

Four single zircon grains were analysed from the Loch Borralan pseudoleucite syenite at Aultivullin Quarry (sample IM.4.1; Fig. 5f). All four analyses overlap concordia, and give a weighted mean $^{206}Pb/^{238}U$ age of 431.1 ± 1.2 Ma.

Loch Borralan late suite

Four single zircon grains were analysed from the Loch Borralan quartz syenite (sample IM.1.1; Fig. 5g). All four analyses overlap concordia, and give a weighted mean $^{206}Pb/^{238}U$ age of 429.2 ± 0.5 Ma.

Loch Loyal Syenite Complex

Twelve single zircon grains were analysed from the Loch Loyal syenite complex (Sample Loyal1; Fig. 5h). All but one are highly discordant. Assuming a lower intercept age of 425 Ma, these indicate the presence of inherited components between 1000 and 2500 Ma in age. One single grain is concordant, with a $^{206}Pb/^{238}U$ age of c. 425 Ma.

Discussion

Comparison with previously published ages

The new age obtained for the Glen Dessarry Pluton of 447.9 ± 2.9 is significantly younger than the published age of 456 ± 5 Ma (van Breemen et al. 1979b). However, in detail, the zircon data of van Breemen et al. (1979b) are slightly discordant, and this was interpreted as resulting from a small, but similar degree of Pb-loss in all four analysed fractions (data are plotted in Fig. 5a, with nominal errors as these were not reported by van Breemen *et al*. 1979b). It is more likely that the shift to the right of concordia is caused by a slight inaccuracy in the applied common lead correction, together with uncertainty in uranium decay constants (see discussion of Canisp Porphyry below). If this is the case, the preferred age derived from the data of van Breemen et al. (1979b) would be defined by the mean $^{206}Pb/^{238}U$ model age, at around 448.5 Ma. Notably, the titanite age reported by van Breemen et al. (445 ± 5 Ma) is identical to that presented here (concordia age = 445.3 ± 1.9 Ma). The new date for the Glen Dessarry Pluton of 447.9 ± 2.9 Ma confirms that this intrusion is distinctly older than the syenite plutons to the north.

The age of 430.6 ± 0.3 Ma obtained here for the Loch Ailsh Pluton is significantly younger than the previously accepted age of 439 ± 4 Ma (Fig. 6), which was based on analysis of six large size fractions of zircon from two different syenite samples (Halliday *et al*. 1987). The resulting data were highly discordant, with $^{206}Pb/^{238}U$ ages between 337 and 382 Ma. Nonetheless, if modern Pb-loss is assumed, and a regression is forced through 0 Ma, these data would define a discordia with an upper intercept age of c. 435 Ma. Halliday *et al*. (1987) chose to derive their age using a Pb-Pb regression, which is highly dependent on the assumption of modern Pb-loss, and the common lead composition used for correction of the analyses. The age of 430.6 ± 0.3 Ma presented here is derived from seven concordant analyses of chemically abraded single zircon grains, and is clearly more reliable than the previously published age.

The zircons analysed from the nordmarkite sill were highly discordant, and do not yield a statistically meaningful age. However, the lower intercept of the least discordant analyses (c. 430 Ma) lies within the range defined by the other syenite bodies from Assynt.

The ages of 431.1 ± 1.2 Ma and 429.2 ± 0.5 Ma presented here, for the Loch Borralan Pluton early suite and late suite respectively, are within error of the age of 430 ± 4 Ma reported by van Breemen *et al*. (1979a), which was derived from four samples from both early and late intrusive phases (Fig. 6). However, the increased precision on our new dates allows us to resolve the age difference between the two suites.

The age of 430.4 ± 0.4 presented here for the Canisp Porphyry is significantly younger than the published age of 437 ± 5 Ma (Goodenough *et al*. 2006). The zircons analysed by Goodenough *et al*. (2006) were physically, but not chemically abraded, and show varying degrees of Pb-loss. The age of 437 ± 5 Ma was derived by forcing a regression line through 0 ± 10 Ma, and closely approximates to the mean $^{207}Pb/^{206}Pb$ model age of the zircons. In detail, however, the zircon fraction with the least apparent Pb-loss has a $^{206}Pb/^{238}U$ model age of 430.6 Ma, within error of the age of 430.4 ± 0.4 Ma presented here. It seems probable that a combination of analytical artefacts has shifted the data of Goodenough *et al*. (2006) slightly to the right (i.e. to high $^{207}Pb/^{235}U$) on the concordia diagram, leading to artificially high $^{207}Pb/^{206}Pb$ ages. There are three possible explanations for this: (1) Uncertainty in U decay constants, in particular that of ^{235}U, leads to a systematic bias (Schoene *et al*. 2006). $^{207}Pb/^{206}Pb$ ages are systematically older than $^{206}Pb/^{238}U$ ages by between 0.15% in Precambrian samples to as much as 3.3% in Mesozoic samples (Schoene *et al*. 2006). At c. 430 Ma, this effect would lead to $^{207}Pb/^{206}Pb$ ages being overestimated by c. 2-3 Ma. (2) Uncertainty in the correction applied for initial common Pb and/or blank can have a significant effect on the $^{207}Pb/^{206}Pb$ age of a zircon. Goodenough *et al*. (2006) used the model of Stacey & Kramers (1975) to estimate the initial common Pb composition at 430 Ma, whereas in this study we use the measured feldspar values of van Breemen *et al*. (1979a). (3) At the time of analysis of the zircons described by Goodenough *et al*. (2006), organic interferences were affecting some analyses at the NERC Isotope Geosciences Laboratory. The effect of these interferences was to shift data ellipses towards the right on Concordia diagrams. This problem was eliminated before the analyses presented here were carried out, by the use of oil-free pumps throughout the laboratory. We therefore feel that our weighted mean $^{206}Pb/^{238}U$ age of 430.4 ± 0.4 Ma, based on six concordant zircon analyses, is the best estimate for the age of the Canisp Porphyry.

Only one concordant analysis was obtained from the Loch Loyal syenite complex, indicating an age of around 425 Ma. This is in agreement with the published age of 426 ± 9 Ma, based on three normally discordant zircon size fractions (Halliday et al. 1987).

Timing of Caledonian deformation

The Glen Dessarry Pluton post-dates early, regional deformation in the host Moine rocks, but pre-dates the formation of the Northern Highland Steep Belt (Roberts *et al.* 1984). The new date of 447.9 ± 2.9 Ma thus supports the existing consensus that the earlier deformation is Grampian (Ordovician) in age, but that the Northern Highland Steep Belt formed during the Scandian Event (Strachan & Evans, 2008).

The new date for the Loch Ailsh Pluton of 430.6 ± 0.3 Ma, the revised date for the Canisp Porphyry of 430.4 ± 0.4 Ma, and the new date for the early suite at Loch Borralan (431.1 ± 1.2 Ma) are all within error of each other and indicate a pulse of alkaline magmatism at c. 430.5 to 431 Ma. The weighted mean $^{206}Pb/^{238}U$ age of all 19 concordant analyses from these samples is 430.7 ± 0.5 Ma, which is the preferred age for this earlier pulse of magmatism in the Assynt area. Field relationships show that the Loch Ailsh Pluton and the Canisp Porphyry sills were emplaced before or during thrusting in the Moine Thrust Zone, whilst emplacement of the early suite of the Loch Borralan Pluton overlapped with thrusting. Overall, then, the early pulse of magmatism overlapped with movement in the Moine Thrust Zone.

The late suite of the Loch Borralan Pluton, which is undeformed and can be shown to post-date thrust movement, is also clearly younger than the other intrusions, at 429.2 ± 0.5 Ma. Although a reliable new date for the Loch Loyal Syenite Complex has not been obtained, the presence of a single concordant zircon at c. 425 Ma, together with the observed field relationships, indicate that this is likely to be part of the same, slightly later, pulse of magmatism as the late suite of the Loch Borralan Pluton.

The new dates allow us to place detailed constraints on the timing of collision-related deformation in the Moine Thrust Zone. The earliest ductile movements on the Moine Thrust itself are not constrained, but it is evident that such movements continued after 430.6 ± 0.3 Ma, since the rocks of the Loch Ailsh Pluton are locally mylonitised. Within the Moine Thrust Zone (ie between the Moine and Sole thrusts), thrust movement overlapped with emplacement of the Loch Ailsh Pluton, the Canisp Porphyry sills, and the early suite of the Loch Borralan Pluton at 430.7 ± 0.5 Ma. However, movement on these thrusts had ceased by the time the late suite of the Loch Borralan Pluton was emplaced at 429.2 ± 0.5 Ma. It is conceivable that minor deformation could have continued along the Sole Thrust after this time, and late, out-of-sequence movement along the Moine Thrust may also post-date this intrusion.

Deformed metagranites within Moine metasedimentary rocks to the NE of the Assynt Culmination were emplaced and penetratively deformed during NW-directed, foreland-propagating ductile thrusting and nappe assembly. These yield ion microprobe zircon ages (Kinny et al. 2003) ranging from 429 ± 11 Ma (Strathnaver granite) to 420 ± 6 Ma (Klibreck granite). The Klibreck granite appears to be anomalously young if ductile deformation within the Moine Thrust Zone ceased by 429.2 ± 0.5 Ma. However, on closer analysis, the Klibreck granite ion probe data shows clear evidence for Pb-loss (as is the case with the Strathnaver granite; Kinny et al. 2003). It is therefore probably the case that the true age of the Klibreck granite is older than the weighted mean $^{206}Pb/^{238}U$ age of 420 ± 6 Ma, and may lie closer to the upper intercept of a regression line passed through the data, indicating an age of 430 ± 11 Ma.

A metagranite sampled from within the Moine rocks north-east of Assynt, with thrust-related ductile deformation, has yielded an ion microprobe zircon age of 415 ± 6 Ma (Alsop *et al.* 2010). While this sample has less systematic evidence for Pb-loss, the data are rather scattered. Verification of the published age would be desirable in order to test the evidence for ductile deformation after 415 Ma.

The revised ages presented here for the Glen Dessarry and Loch Ailsh plutons, and for the Canisp Porphyry, demonstrate the pitfalls involved in interpretation of zircon data that is even slightly discordant. Clearly, unambiguous discrimination between events that occurred within a few million years (e.g. intrusion of the early and late syenites of Assynt) requires precise, concordant zircon data with minimal Pb-loss, such that $^{206}Pb/^{238}U$ ages can be used with confidence, thereby avoiding the inherent bias in $^{207}Pb/^{206}Pb$ ages due to uncertainty in common Pb corrections and the ^{235}U decay constant.

On the basis of Rb-Sr dating of muscovites in Moine mylonites, Freeman *et al*. (1998) suggested that transfer of displacement from the ductile Moine Thrust to the underlying thrusts occurred at c. 430 Ma; this conclusion is corroborated by the new data presented here. More difficult to explain are the suggestions that thrusting continued until c. 408 Ma to the south of Assynt (Freeman *et al*. 1998), and until c. 413 Ma further north (Dallmeyer *et al*. 2001). It is known that, in southern Assynt, the Moine Thrust was reactivated at a late stage in the history of the thrust zone, by a component of largely brittle movement (Coward, 1983, 1985) and this reactivation may explain some of the younger ages in this area; the dates presented in the present paper do not provide a constraint on the age of this brittle reactivation. However, the Rb-Sr data of Freeman *et al*. (1998) from south of Assynt require that micas with indistinguishable phengite chemistry crystallised at very similar depths over a period of c. 21 Ma during active thrusting. This seems geologically improbable, and it seems more likely that their ages, which are defined by statistically poorly constrained two-point isochrons, are rendered inaccurate by the use of bulk feldspar separates rather than microsampling of synkinematic overgrowths to constrain initial ratios (which was not technically feasible at the time). Notably, the feldspar analyses of Freeman et al. (1998) show considerable variation (and indeed, scatter around a trend with an 'age' of c. 920 Ma).

The total amount of displacement on the Glencoul and Ben More thrusts is estimated at c. 50 km (Elliott and Johnson 1980). This displacement occurred between the emplacement of the Loch Ailsh Pluton and the late suite of the Loch Borralan Pluton, a period of 2.2-0.6 Ma, taking into account the errors. This would suggest a movement rate of between 20 and 80 mm per year. Although the upper end of this spectrum is rather high, the lower end accords well with known modern slip rates in the Himalaya (20 mm/yr; Mugnier *et al.* 2004) and New Zealand (30 mm/year; Norris and Cooper 1997). It should be noted that Scandian orogenesis in general was relatively rapid, and associated with fast, but realistic, plate motions (Dewey & Strachan 2003).

In the Scandinavian Caledonides, pre- to syn-tectonic subduction-related magmatism occurred at 445 – 435 Ma (Corfu *et al.* 2006), but the main collisional stages took place between 430 – 400 Ma (Tucker *et al*., 2004). In Greenland, syn-tectonic magmatism is dated at 430 – 425 Ma (Strachan *et al*., 2001; Andresen *et al.* 2007), but plate convergence is known to have continued through the Devonian (Dallmeyer et al. 1994; Gilotti & McClelland 2007). This contrasts with the new evidence, presented here, that the Scandian collisional event in Scotland was largely completed by c. 429 Ma. With the levels of geochronological precision now achievable, it is possible to recognise different phases of orogenic activity within the Scandian Event along the length of the Caledonian Orogen.

Conclusions

The data presented here constrain the timing of deformation associated with the Moine Thrust Zone in the North-west Highlands of Scotland. Early ductile movement on the Moine Thrust, possibly associated with the formation of the Northern Highland Steep Belt, occurred after the emplacement of the Glen Dessarry Pluton at 447.9 ± 2.9 Ma. Movement within the Moine Thrust Zone in Assynt overlapped in space and time with a pulse of syn-tectonic alkaline magmatism, including the Loch Ailsh Pluton, the Canisp Porphyry sills, and the early suite of the Loch Borralan Pluton, at 430.7 ± 0.5 Ma. Deformation within the Moine Thrust Zone was completed by the emplacement of the undeformed late suite of the Loch Borralan pluton at 429.2 ± 0.5 Ma. Late brittle movement on the Moine Thrust may post-date this magmatism.

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Figures

1) Simplified geological map of the Northern Highlands, showing the main structures and intrusions. Major thrusts: MT – Moine Thrust; BHT – Ben Hope Thrust; NT – Naver Thrust; SBT – Sgurr Beag Thrust. Alkaline plutons: GDP – Glen Dessarry Pluton; LBP – Loch Borralan Pluton; LAP – Loch Ailsh Pluton; LLSC – Loch Loyal Syenite Complex.

2) Simplified map of the Assynt Culmination, showing the major thrust structures and the location of the Loch Ailsh and Loch Borralan plutons. CLT – Cam Loch Thrust. Dashed box indicates area of Fig. 3. Dashed line indicates location of section in Fig. 4.

3) Simplified extract from the Assynt 1:50 000 geological map sheet (British Geological Survey 2007) showing the geology around the Loch Ailsh and Loch Borralan plutons. CLT – Cam Loch Thrust; ST – Sole Thrust; BMT – Ben More Thrust; MT – Moine Thrust.

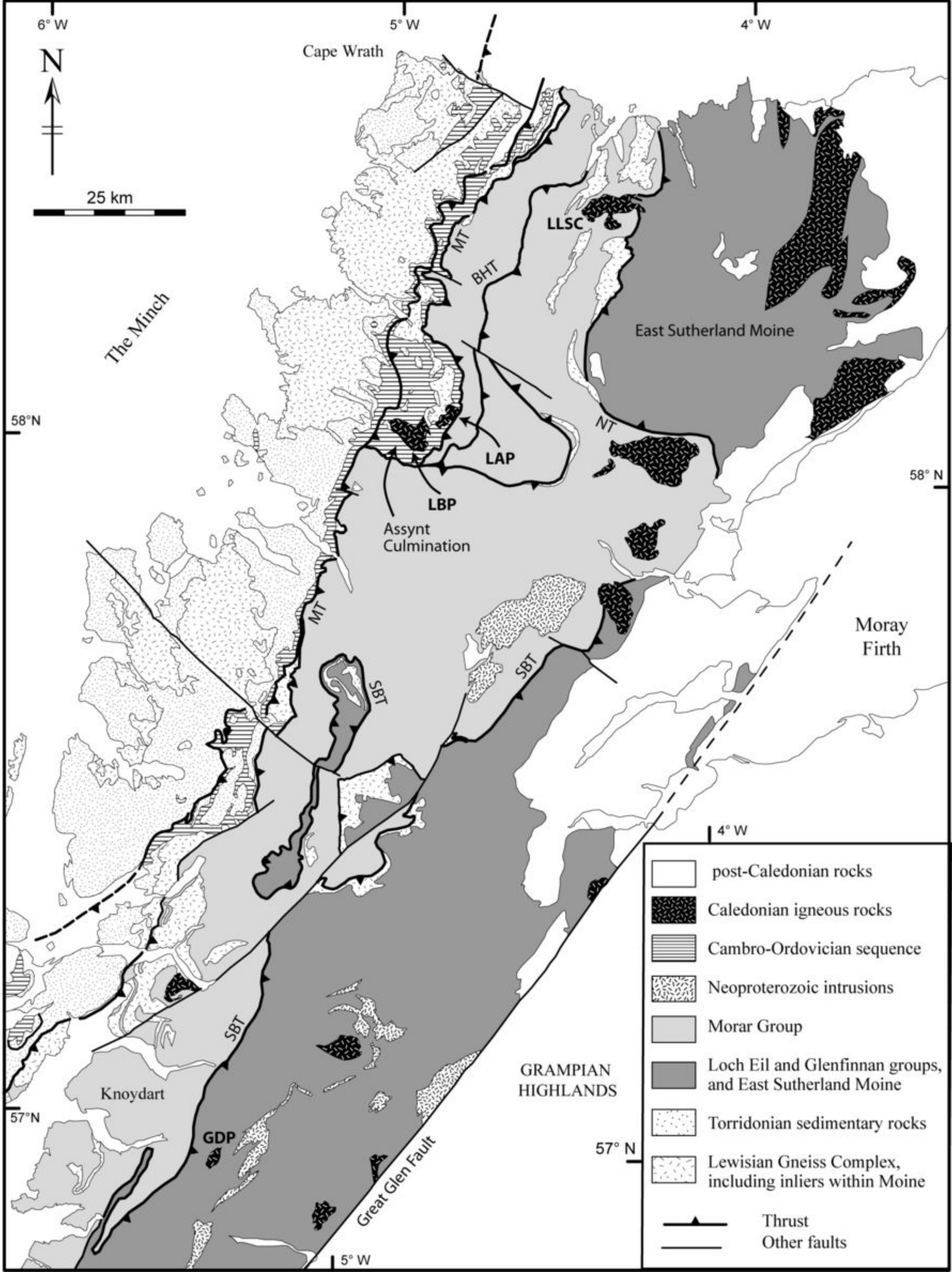
4) Simplified cross-section through the Assynt area, from British Geological Survey (2007). The Loch Borralan pluton lies to the south of this cross-section, where it clearly cuts across the Breabag Dome.

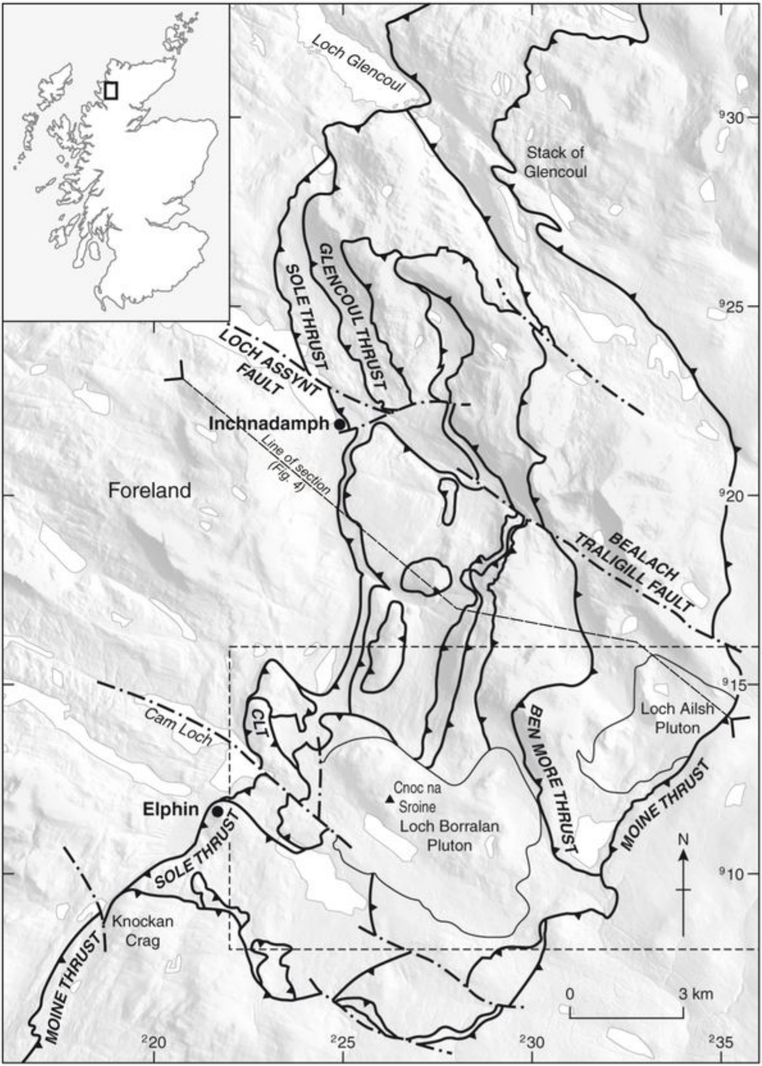
5) U-Pb concordia diagrams for the dated samples from the syenites of the North-west Highlands. All error ellipses are plotted at the 2σ level.

6) Summary of the dates for the alkaline plutons of the North-west Highlands. Dates from this paper shown in black; dates from previous papers (van Breemen *et al.* 1979a,b; Halliday *et al*. 1987; Goodenough *et al*. 2006) shown in grey.

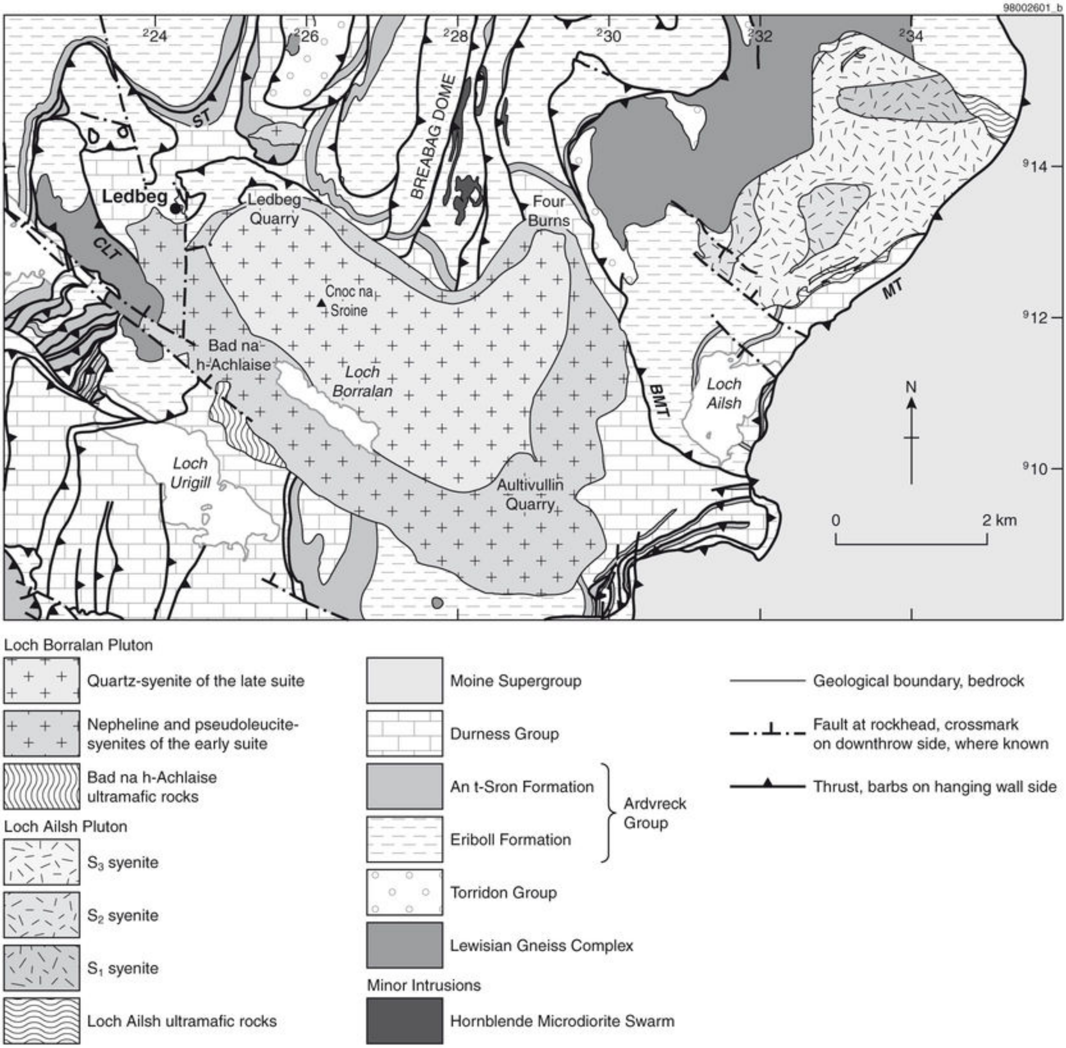
Tables

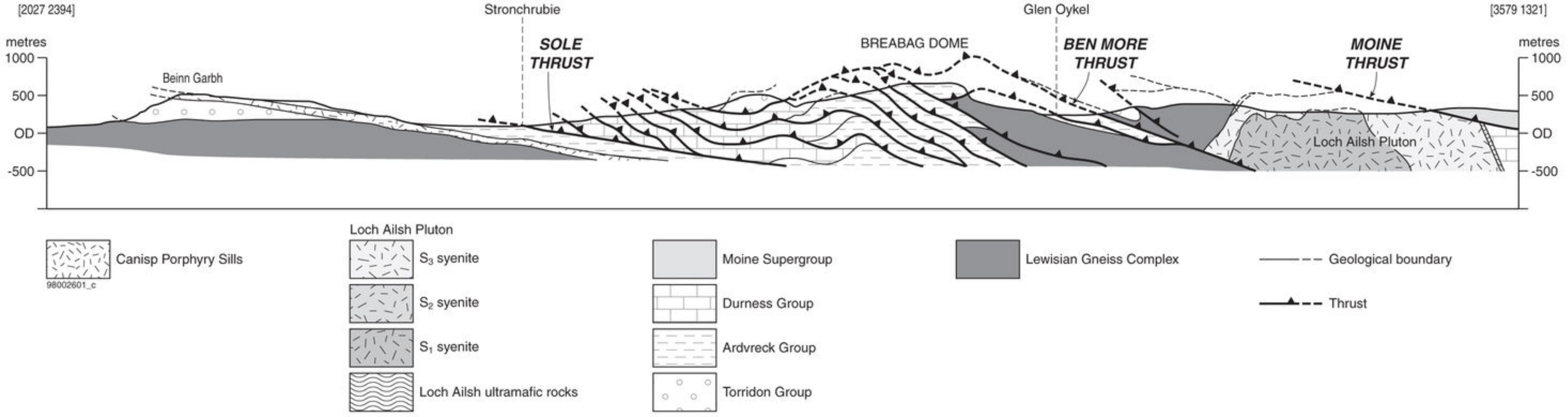
1) U-Pb analytical data for zircons from syenite intrusions dated in this study.


6° W
5° W
4° W
N
25 km
Cape Wrath
The Minch
MT
BHT
LLSC
East Sutherland Moine
NT
LAP
LBP
Assynt Culmination
58°N
58° N
MT
SBT
SBT
Moray Firth
4° W
SBT
GRAMPIAN HIGHLANDS
Knoydart
57°N
GDP
Great Glen Fault
57° N
5° W
post-Caledonian rocks
Caledonian igneous rocks
Cambro-Ordovician sequence
Neoproterozoic intrusions
Morar Group
Loch Eil and Glenfinnan groups, and East Sutherland Moine
Torridonian sedimentary rocks
Lewisian Gneiss Complex, including inliers within Moine
Thrust
Other faults

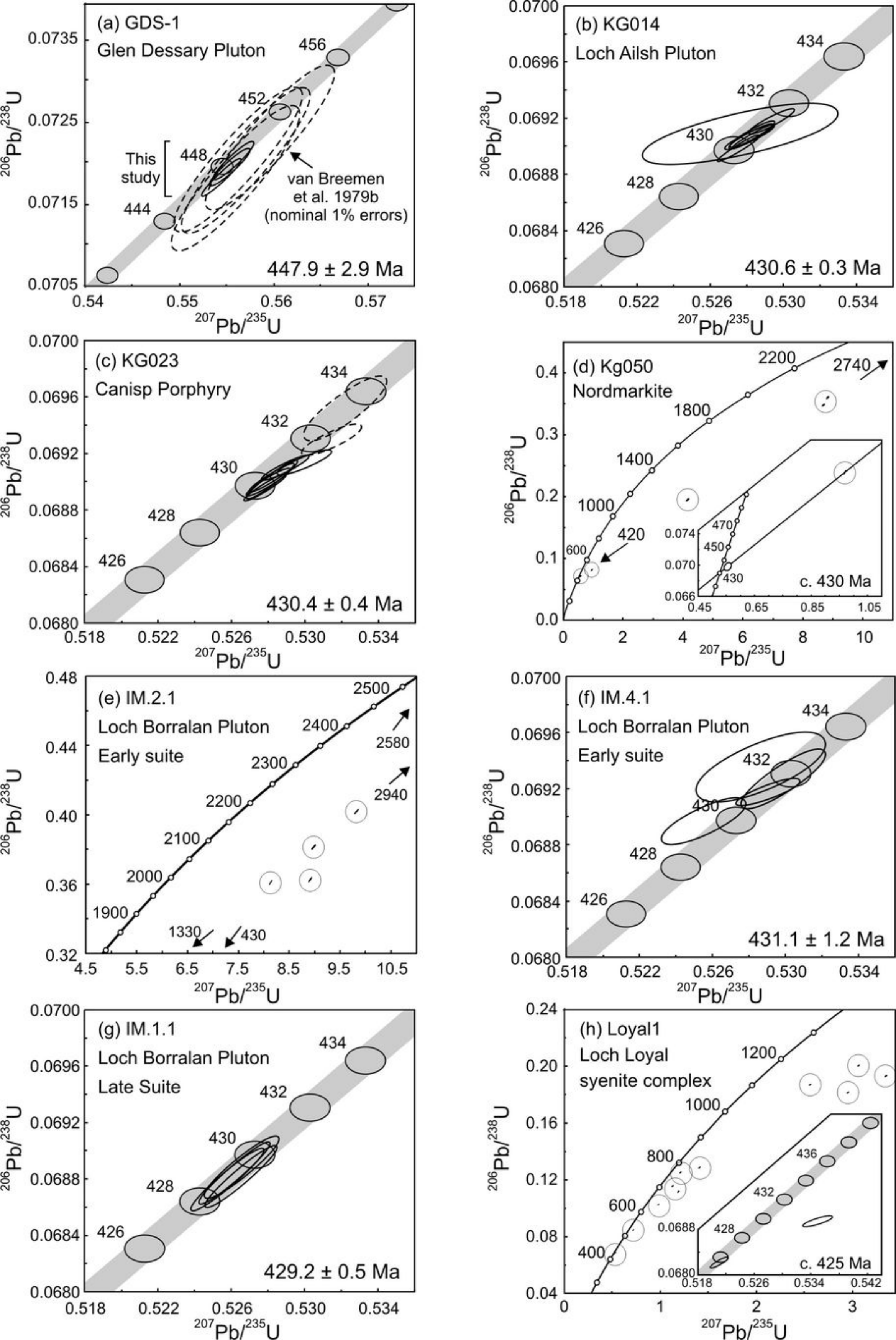


Loch Glencoul
Stack of Glencoul
SOLE THRUST
GLENCOUL THRUST
LOCH ASSYNT FAULT
Inchnadamph
Line of section (Fig. 4)
Foreland
BEALACH TRALIGILL FAULT
Cam Loch
CLT
BEN MORE THRUST
Loch Ailsh Pluton
MOINE THRUST
Cnoc na Sroine
Loch Borralan Pluton
Elphin
SOLE THRUST
Knockan Crag
MOINE THRUST
N
0
3 km
930
925
920
915
910
220
225
230
235

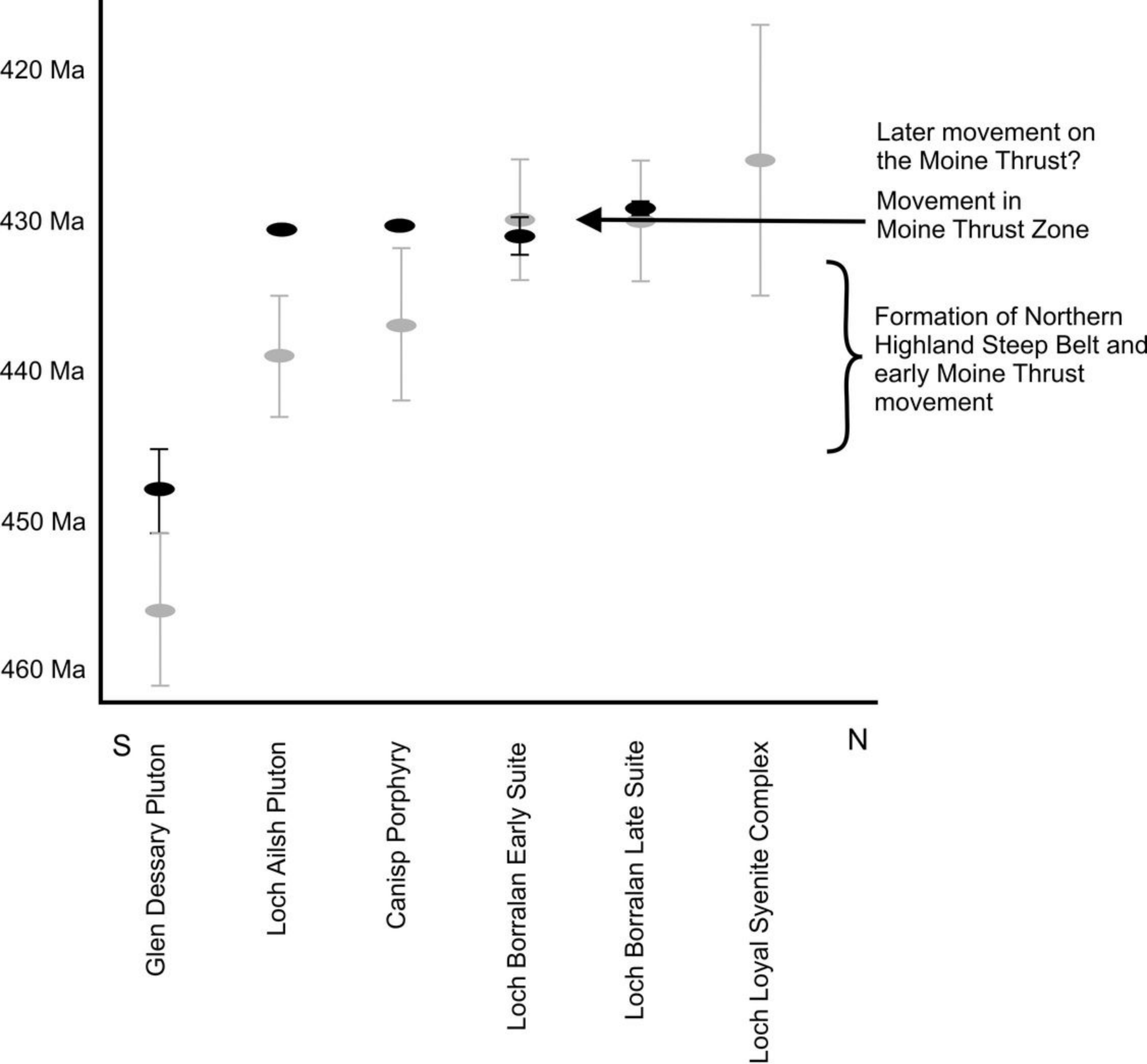

98002601_b
224
226
228
230
232
234
914
912
910
Ledbeg
ST
CLT
Ledbeg Quarry
BREABAG DOME
Four Burns
Cnoc na Sroine
Bad na h-Achlaise
Loch Borralan
Loch Urigill
Aultivullin Quarry
BMT
MT
Loch Ailsh
N
0
2 km
Loch Borralan Pluton
Quartz-syenite of the late suite
Nepheline and pseudoleucite-syenites of the early suite
Bad na h-Achlaise ultramafic rocks
Loch Ailsh Pluton
S_3 syenite
S_2 syenite
S_1 syenite
Loch Ailsh ultramafic rocks
Moine Supergroup
Durness Group
An t-Sron Formation
Eriboll Formation
Ardvreck Group
Torridon Group
Lewisian Gneiss Complex
Minor Intrusions
Hornblende Microdiorite Swarm
Geological boundary, bedrock
Fault at rockhead, crossmark on downthrow side, where known
Thrust, barbs on hanging wall side



[2027 2394]
Stronchrubie
Glen Oykel
[3579 1321]
metres
1000
500
OD
-500
SOLE THRUST
BREABAG DOME
BEN MORE THRUST
MOINE THRUST
Beinn Garbh
Loch Ailsh Pluton
Canisp Porphyry Sills
98002601_c
Loch Ailsh Pluton
S3 syenite
S2 syenite
S1 syenite
Loch Ailsh ultramafic rocks
Moine Supergroup
Durness Group
Ardvreck Group
Torridon Group
Lewisian Gneiss Complex
Geological boundary
Thrust



(a) GDS-1
Glen Dessary Pluton
This study
van Breemen et al. 1979b (nominal 1% errors)
447.9 ± 2.9 Ma
(b) KG014
Loch Ailsh Pluton
430.6 ± 0.3 Ma
(c) KG023
Canisp Porphyry
430.4 ± 0.4 Ma
(d) Kg050
Nordmarkite
c. 430 Ma
(e) IM.2.1
Loch Borralan Pluton
Early suite
(f) IM.4.1
Loch Borralan Pluton
Early suite
431.1 ± 1.2 Ma
(g) IM.1.1
Loch Borralan Pluton
Late Suite
429.2 ± 0.5 Ma
(h) Loyal1
Loch Loyal
syenite complex
c. 425 Ma
^{206}Pb/^{238}U
^{207}Pb/^{235}U



420 Ma
430 Ma
440 Ma
450 Ma
460 Ma
Later movement on the Moine Thrust?
Movement in Moine Thrust Zone
Formation of Northern Highland Steep Belt and early Moine Thrust movement
S
N
Glen Dessary Pluton
Loch Ailsh Pluton
Canisp Porphyry
Loch Borralan Early Suite
Loch Borralan Late Suite
Loch Loyal Syenite Complex

	Compositional Parameters							Radiogenic Isotope Ratios									Isotopic Ages					
Sample	Wt. mg	U ppm	Th/U	Pb ppm	$\frac{Pb^*}{Pbc}$	Pbc (pg)	$\frac{^{206}Pb}{^{204}Pb}$	$\frac{^{208}Pb}{^{206}Pb}$	$\frac{^{207}Pb}{^{206}Pb}$	% err	$\frac{^{207}Pb}{^{235}U}$	% err	$\frac{^{206}Pb}{^{238}U}$	% err	corr. coef.	$\frac{^{207}Pb}{^{206}Pb}$	±	$\frac{^{207}Pb}{^{235}U}$	±	$\frac{^{206}Pb}{^{238}U}$	±
(a)	(b)	(c)	(d)	(c)	(e)	(e)	(f)	(g)	(g)	(h)	(g)	(h)	(g)	(h)		(i)	(h)	(i)	(h)	(i)	(h)
Glen Dessary Syenite – GDS-1																					
Zircons																					
z1	0.001	2418	0.249	504.2	74	3.38	4666	0.076	0.083338	0.103	2.370269	0.307	0.206277	0.260	0.948	1277.15	2.00	1233.68	2.19	1208.95	2.87
z2	0.001	359	0.516	34.0	4	5.35	262	0.165	0.057404	0.696	0.571562	0.835	0.072214	0.279	0.625	507.08	15.30	459.02	3.08	449.48	1.21
z3	0.001	1304	0.094	97.2	9	6.99	607	0.030	0.056042	0.308	0.553864	0.457	0.071678	0.263	0.763	454.04	6.83	447.52	1.65	446.26	1.13
z4	0.001	668	0.089	50.9	7	4.36	503	0.028	0.055449	0.506	0.549371	0.639	0.071857	0.266	0.656	430.38	11.27	444.58	2.30	447.33	1.15
z5	0.0005	945	0.182	133.5	6	7.72	375	0.089	0.122676	0.223	1.961128	0.393	0.115943	0.269	0.837	1995.50	3.97	1102.27	2.64	707.17	1.80
z6	0.002	2196	0.102	150.7	50	5.87	3404	0.032	0.055979	0.127	0.555399	0.319	0.071958	0.261	0.924	451.54	2.82	448.53	1.16	447.94	1.13
z8	0.002	1912	0.321	139.0	67	4.07	4285	0.101	0.055957	0.121	0.555824	0.317	0.072041	0.261	0.930	450.68	2.69	448.80	1.15	448.44	1.13
z9	0.002	2829	0.218	198.7	86	4.57	5610	0.069	0.055989	0.100	0.554547	0.308	0.071835	0.262	0.951	451.92	2.22	447.97	1.12	447.20	1.13
Titanites																					
t1	0.100	14	2.337	2.8	1.1	136.38	62	0.724	0.054988	2.111	0.541392	2.130	0.071408	0.664	0.184	411.72	47.21	439.34	7.60	444.63	2.85
t2	0.100	8	2.764	2.0	1.0	99.02	55	0.865	0.055683	2.887	0.549342	2.941	0.071552	0.801	0.203	439.73	64.24	444.57	10.59	445.50	3.45
t3	0.100	7	4.072	1.9	1.2	86.83	55	1.250	0.054438	2.524	0.539585	2.535	0.071888	0.776	0.168	389.20	56.66	438.15	9.02	447.52	3.36
Loch Ailsh syenite – KG14																					
z1	0.001	3447	0.495	249.3	196	1.64	11957	0.156	0.055457	0.097	0.528287	0.188	0.069090	0.110	0.920	430.68	2.16	430.67	0.66	430.67	0.46
z2	0.001	3182	0.412	226.0	111	2.02	6923	0.130	0.055461	0.104	0.528222	0.191	0.069076	0.102	0.921	430.85	2.32	430.63	0.67	430.59	0.43
z3	0.0005	6648	0.192	411.5	13	2.93	867	0.062	0.056363	0.402	0.464499	0.488	0.059771	0.153	0.669	466.70	8.90	387.38	1.57	374.23	0.56
z4	0.0005	2550	0.266	196.6	7	2.41	479	0.083	0.055385	0.676	0.527606	0.825	0.069090	0.250	0.692	427.82	15.08	430.22	2.89	430.67	1.04
z5	0.001	5496	0.410	391.1	100	1.93	6267	0.129	0.055493	0.109	0.529330	0.196	0.069181	0.105	0.911	432.14	2.43	431.37	0.69	431.22	0.44
z6	0.0005	19003	0.435	1368.1	60	2.24	3714	0.137	0.055457	0.124	0.528138	0.211	0.069070	0.104	0.908	430.71	2.76	430.57	0.74	430.55	0.44
z7	0.002	3047	0.458	217.4	395	1.32	24274	0.144	0.055456	0.080	0.527525	0.179	0.068991	0.111	0.956	430.66	1.78	430.17	0.63	430.07	0.46
z8	0.001	6197	0.500	447.9	337	1.46	20514	0.157	0.055473	0.083	0.528330	0.175	0.069075	0.102	0.958	431.34	1.84	430.70	0.61	430.58	0.42
Canisp porphyry – KG23																					
z1	0.002	131	0.230	19.2	17	2.11	1070	0.097	0.105603	0.216	1.948881	0.428	0.133847	0.291	0.888	1724.84	3.96	1098.06	2.87	809.77	2.21
z2	0.002	107	0.374	36.3	20	3.45	1093	0.136	0.157588	0.131	6.341717	0.356	0.291865	0.285	0.941	2429.95	2.21	2024.24	3.12	1650.84	4.15
z3	0.002	5029	0.143	335.2	74	8.88	4877	0.045	0.055517	0.188	0.532162	0.345	0.069521	0.267	0.840	433.12	4.20	433.24	1.22	433.27	1.12
z4	0.002	1594	0.123	105.8	47	4.41	3123	0.039	0.055511	0.114	0.528910	0.202	0.069104	0.104	0.918	432.85	2.55	431.09	0.71	430.76	0.43
z5	0.002	893	0.143	60.4	31	3.75	2078	0.045	0.055617	0.160	0.531431	0.251	0.069301	0.130	0.829	437.10	3.57	432.76	0.88	431.94	0.54
z6	0.002	1142	0.127	77.0	28	5.38	1839	0.040	0.055589	0.147	0.529943	0.230	0.069141	0.106	0.872	436.00	3.27	431.77	0.81	430.98	0.44
z7	0.002	6846	0.139	447.8	337	2.65	22439	0.044	0.055490	0.083	0.528178	0.186	0.069034	0.121	0.943	432.02	1.84	430.60	0.65	430.34	0.50
z8	0.002	7196	0.138	471.9	158	5.93	10397	0.043	0.055494	0.089	0.527981	0.186	0.069004	0.114	0.937	432.16	1.98	430.47	0.65	430.15	0.48
z9	0.002	6385	0.140	417.6	286	2.91	19008	0.044	0.055509	0.083	0.527822	0.182	0.068964	0.114	0.948	432.78	1.84	430.36	0.64	429.91	0.47
z10	0.002	11665	0.130	762.4	201	7.55	13199	0.041	0.055501	0.079	0.528179	0.215	0.069021	0.162	0.950	432.45	1.77	430.60	0.75	430.25	0.67

	Compositional Parameters							Radiogenic Isotope Ratios								Isotopic Ages					
Sample	Wt. mg	U ppm	Th/U	Pb ppm	$\frac{Pb^*}{Pbc}$	Pbc (pg)	$\frac{^{206}Pb}{^{204}Pb}$	$\frac{^{208}Pb}{^{206}Pb}$	$\frac{^{207}Pb}{^{206}Pb}$	% err	$\frac{^{207}Pb}{^{235}U}$	% err	$\frac{^{206}Pb}{^{238}U}$	% err	corr. coef.	$\frac{^{207}Pb}{^{206}Pb}$	±	$\frac{^{207}Pb}{^{235}U}$	±	$\frac{^{206}Pb}{^{238}U}$	±
(a)	(b)	(c)	(d)	(c)	(e)	(e)	(f)	(g)	(g)	(h)	(g)	(h)	(g)	(h)		(i)	(h)	(i)	(h)	(i)	(h)
Nordmarkite dyke – KG50																					
z3	0.001	636	0.327	258.9	20	12.25	1024	0.115	0.181397	0.110	8.695388	0.311	0.347663	0.262	0.941	2665.68	1.82	2306.60	2.83	1923.43	4.35
z4	0.001	633	0.506	209.6	2	62.85	122	0.225	0.154668	0.577	4.160143	0.726	0.195077	0.475	0.609	2398.19	9.81	1666.21	5.95	1148.82	5.00
z5	0.003	239	0.714	106.4	75	4.77	3564	0.244	0.178276	0.088	8.833624	0.298	0.359373	0.258	0.960	2636.90	1.47	2320.97	2.71	1979.20	4.39
z6	0.002	291	0.503	39.0	1	29.96	88	0.162	0.057450	1.954	0.555231	2.066	0.070095	0.702	0.325	508.84	42.96	448.42	7.49	436.73	2.96
z8	0.0005	5268	0.277	455.2	51	2.63	3093	0.118	0.085851	0.115	0.968703	0.313	0.081836	0.256	0.938	1334.84	2.22	687.80	1.57	507.07	1.25
Loch Borralan late suite syenite (quarry) – IM.4.1																					
z1	0.001	701	2.111	77.0	14	5.02	619	0.661	0.055279	0.412	0.528641	0.548	0.069358	0.287	0.677	423.53	9.18	430.91	1.92	432.29	1.20
z4	0.001	1228	1.974	126.0	37	3.33	1611	0.620	0.055461	0.187	0.529000	0.269	0.069178	0.112	0.827	430.86	4.17	431.15	0.95	431.20	0.47
z6	0.001	1066	2.437	118.5	47	2.47	1903	0.765	0.055475	0.195	0.529864	0.355	0.069273	0.249	0.849	431.43	4.35	431.72	1.25	431.77	1.04
z7	0.001	1084	2.709	127.0	30	4.14	1142	0.848	0.055259	0.244	0.525499	0.358	0.068972	0.196	0.765	422.71	5.44	428.82	1.25	429.96	0.82
z8	0.001	1013	1.395	93.9	34	2.72	1642	0.449	0.057146	0.195	0.546399	0.348	0.069347	0.238	0.844	497.16	4.30	442.64	1.25	432.22	0.99
Loch Borralan late suite leucosyenite (marginal) – IM.2.1																					
z1	0.002	782	0.884	361.5	842	0.99	41932	0.300	0.178248	0.083	8.912908	0.304	0.362655	0.269	0.965	2636.63	1.38	2329.12	2.77	1994.75	4.61
z2	0.002	226	0.550	103.6	26	6.48	1302	0.178	0.170804	0.097	8.978652	0.310	0.381252	0.262	0.957	2565.54	1.62	2335.84	2.84	2082.13	4.67
z4	0.003	142	0.761	70.7	82	2.38	4172	0.243	0.177272	0.076	9.826409	0.300	0.402026	0.260	0.973	2627.51	1.26	2418.63	2.76	2178.36	4.81
z5	0.004	117	1.091	55.8	163	1.36	7881	0.358	0.163455	0.037	8.134328	0.290	0.360930	0.257	0.998	2491.72	0.62	2246.07	2.62	1986.58	4.40
Loch Borralan early suite leucosyenite – IM.1.1																					
z1	0.005	1161	1.380	103.1	167	3.13	8157	0.434	0.055486	0.102	0.526517	0.305	0.068822	0.259	0.947	431.86	2.28	429.50	1.07	429.05	1.07
z2	0.004	1811	0.820	141.1	620	0.84	34751	0.257	0.055429	0.093	0.526181	0.300	0.068849	0.260	0.955	429.56	2.08	429.27	1.05	429.22	1.08
z3	0.002	920	0.840	72.3	188	0.88	10493	0.264	0.055435	0.127	0.526547	0.317	0.068889	0.258	0.923	429.81	2.83	429.52	1.11	429.46	1.07
z5	0.004	1554	0.899	123.9	173	3.13	9418	0.282	0.055427	0.101	0.525802	0.306	0.068802	0.262	0.949	429.47	2.24	429.02	1.07	428.94	1.09
Loch Loyal – Loyal1																					
z3	0.002	394	0.161	75.0	29	4.24	1737	0.064	0.118243	0.123	2.952429	0.326	0.181094	0.269	0.933	1929.84	2.20	1395.47	2.47	1072.95	2.65
z4	0.004	363	0.259	46.1	52	3.04	3299	0.085	0.070395	0.123	1.217917	0.315	0.125480	0.256	0.928	939.89	2.52	808.82	1.76	762.03	1.84
z5	0.002	415	0.245	49.4	29	3.80	1828	0.083	0.071196	0.148	1.137373	0.333	0.115864	0.256	0.906	963.04	3.03	771.26	1.80	706.71	1.72
z6	0.002	894	0.349	122.2	43	5.60	2561	0.124	0.079531	0.117	1.414408	0.312	0.128985	0.257	0.933	1185.37	2.32	895.01	1.86	782.07	1.89
z7	0.002	427	0.361	91.4	67	2.67	3830	0.145	0.126463	0.098	3.358259	0.305	0.192596	0.259	0.953	2049.38	1.72	1494.72	2.39	1135.42	2.70
z8	0.002	471	0.351	61.7	8	14.19	472	0.127	0.077432	0.238	1.195219	0.398	0.111950	0.264	0.817	1132.34	4.73	798.38	2.20	684.07	1.71
z9	0.002	2924	0.099	584.5	74	15.57	4390	0.036	0.111048	0.047	3.061107	0.214	0.199924	0.168	0.998	1816.64	0.86	1423.01	1.64	1174.91	1.81
z10	0.002	3437	0.831	269.1	80	6.66	4378	0.261	0.055400	0.118	0.521083	0.204	0.068217	0.112	0.882	428.41	2.62	425.87	0.71	425.41	0.46
z11	0.002	725	0.266	152.9	10	27.27	603	0.094	0.099322	0.159	2.561892	0.244	0.187074	0.115	0.845	1611.42	2.97	1289.83	1.78	1105.50	1.17
z12	0.002	422	0.392	47.5	18	5.01	1090	0.135	0.069579	0.162	0.987379	0.246	0.102921	0.099	0.904	915.95	3.34	697.38	1.24	631.51	0.59
z13	0.002	2117	0.396	186.5	80	4.58	4870	0.131	0.062254	0.102	0.728034	0.189	0.084817	0.103	0.926	682.85	2.18	555.40	0.81	524.81	0.52
z14	0.002	674	0.571	54.4	10	9.86	599	0.182	0.056283	0.242	0.534968	0.323	0.068936	0.111	0.809	463.56	5.37	435.10	1.14	429.74	0.46

(a) z1, z2, t1 etc. are labels for fractions composed of single zircon grains (z) or titanite fractions (t); all zircons were annealed and chemically abraded after Mattinson (2005).
(b) Nominal fraction weights estimated from photomicrographic grain dimensions, adjusted for partial dissolution during chemical abrasion.
(c) Nominal U and total Pb concentrations subject to uncertainty in photomicrographic estimation of weight and partial dissolution during chemical abrasion.
(d) Model Th/U ratio calculated from radiogenic $^{208}Pb/^{206}Pb$ ratio and $^{207}Pb/^{235}U$ age.
(e) Pb* and Pbc represent radiogenic and common Pb, respectively.
(f) Measured ratio corrected for spike and fractionation only.
(g) Corrected for fractionation, spike, and common Pb; up to 2 pg of common Pb was assumed to be procedural blank: $^{206}Pb/^{204}Pb = 18.50 \pm 0.50\%$; $^{207}Pb/^{204}Pb = 15.59 \pm 0.32\%$; $^{208}Pb/^{204}Pb = 38.02 \pm 0.50\%$ (all uncertainties 1-sigma). Excess over blank was assigned to initial common Pb.
(h) Errors are 2-sigma, propagated using the algorithms of Schmitz and Schoene (2007) and Crowley et al. (2007).
(i) Calculations are based on the decay constants of Jaffey et al. (1971). $^{206}Pb/^{238}U$ and $^{207}Pb/^{206}Pb$ ages corrected for initial disequilibrium in $^{230}Th/^{238}U$ using Th/U [magma] = 3.
(j) Corrected for fractionation, spike, and blank Pb only.