U-Pb zircon dating of basement inliers within the Moine Supergroup, Scottish Caledonides: implications of Archaean protolith ages

C.R.L. Friend [1], R.A. Strachan[2], P.D. Kinny [3]

1. 45, Stanway Rd., Risinghurst, Headington, Oxford OX3 8HU, UK

2. School of Earth & Environmental Sciences, University of Portsmouth, Burnaby Road, Portsmouth PO1 3QL, UK

3. The Institute for Geoscience Research, Department of Applied Geology, Curtin University of Technology, GPO Box U1987, Perth, WA 6845, Australia

Abstract: Basement gneiss inliers within the Scottish Caledonides have been conventionally correlated with the Archaean Lewisian Gneiss Complex of the Caledonian foreland. Alternatively, the inliers could represent allochthonous terranes accreted to Laurentia before or during the Caledonian orogeny. SIMS U-Pb zircon dating indicates that the Ribigill, Borgie, Farr and Western Glenelg basement inliers are characterized by late Archaean protolith ages, and a period of isotopic disturbance in the late Palaeoproterozoic. The data are broadly consistent with correlation between the inliers and components of the Lewisian Gneiss Complex of the Caledonian foreland. The *c*. 2900 Ma protolith ages support correlation of the Borgie and Farr inliers with the Assynt terrane, and a younger, *c*. 2800 Ma age for the Ribigill inlier supports correlation with the Rhiconich terrane. None of the studied inliers shows a complete match of protolith and early metamorphic histories with any of the Lewisian basement terranes, but differences between the inliers and the foreland are no greater than those recorded within the foreland basement terranes themselves. Therefore, it remains probable that the dated inlier gneisses formed a distal part of the Laurentian margin prior to final telescoping during the Caledonian orogeny. **[end of abstract]**

The complexity of many collisional orogens results, at least in part, from the tectonic assembly of disparate crustal blocks to result in collages of fault-bounded ‘suspect’ or ‘allochthonous’ terranes that have become detached from the cratons from whence they originated. One of the main challenges in such a setting involves the identification of individual terranes and their possible cratonic sources, and hence an evaluation of the likely displacements along the terrane-bounding faults. In some Phanerozoic orogens the history of terrane accretion and estimates of likely displacements along terrane boundaries can be resolved by palaeomagnetic and palaeontological methods. In older orogens, particularly those characterized by unfossiliferous strata and/or medium to high-grade metamorphic rocks, identification of terranes and the nature of their original relationship to cratonic foreland rocks is considerably more difficult. Correlation of a terrane with a cratonic foreland requires the identification of common geological features, many of which may have been eroded in older orogens. In such cases, a potential method of analysis involves the characterization of basement rocks in a given terrane, and comparison with the basement rocks of adjacent cratonic forelands. This method may encounter problems as a result of the extensive reworking and resetting of isotopic systems that are common in basement complexes and in orogens, but may be the only tool available for terrane analysis. Despite the potential difficulties, this is the approach adopted in this paper where U-Pb geochronology has been used to characterize basement inliers within the Lower Palaeozoic Caledonide orogen of northwest Scotland, and to assess potential linkages with the Laurentian foreland west of the Moine Thrust Zone (Fig 1).

Within the Caledonide orogen in northwest Scotland (Fig. 1), there are numerous inliers of highly deformed gneissic rocks that differ markedly in their lithological characteristics and structural and metamorphic histories from the adjacent metasedimentary rocks of the Neoproterozoic Moine Supergroup (e.g. Flett 1905; Peach *et al*. 1910). These inliers have the appearance of crystalline basement now variably overprinted with younger structures, many of which have been interpreted as Caledonian (Ordovician-Silurian) in age (e.g. Rathbone & Harris 1979; Strachan & Holdsworth 1988; Holdsworth 1989). A central problem within the Scottish Caledonides concerns the extent to which the basement inliers and the Moine Supergroup are allochthonous with respect to the Laurentian foreland west of the Moine Thrust Zone (Fig. 1). The foreland comprises the Archaean – Palaeoproterozoic Lewisian Gneiss Complex (e.g. Friend & Kinny 2001; Park *et al*. 2002; Kinny *et al*. 2005) that is overlain unconformably by the late Mesoproterozoic to Neoproterozoic Torridonian sedimentary rocks (e.g. Stewart 2002). Mainly on lithological grounds, the basement inliers have been correlated previously with the Lewisian Gneiss Complex (e.g. Johnstone 1975; Rathbone & Harris 1979), and the Moine Supergroup sediments with the Torridonian (e.g. Cheeney & Matthews 1965). If such correlations are correct, they imply that the basement inliers and the Moine rocks evolved as part of Laurentia during the Precambrian. An alternative view is that these rock units form part of an allochthonous terrane that was accreted to the Laurentian margin either prior to or during the Caledonian orogeny (e.g. Bluck *et al*. 1997).

Attempts to evaluate Moine-Torridonian linkages have noted that the two sequences have slightly different detrital zircon suites (Rainbird *et al*. 2001; Friend *et al*. 2003; see however, Krabbendam *et al.* 2008), and moreover the Moine rocks were affected by mid-Neoproterozoic (Knoydartian) orogenic events that are apparently absent on the foreland (e.g. Rogers *et al.* 1998; Vance *et al.* 1998; Tanner & Evans 2003). Nevertheless, neither of these differences necessarily precludes a Laurentian origin for the Moine rocks (Cawood *et al*. 2004). As an alternative method of evaluating potential linkages across the Moine Thrust Zone we provide in this paper new isotopic age data for four basement inliers within the Moine Supergroup. We assess the resultant implications for possible linkages with the Lewisian Gneiss Complex of the Laurentian foreland and regional tectonic models for this part of the Caledonides.

Regional setting of basement inliers within the Caledonides of NW Scotland

Lithologies and structural setting

Inliers of basement rocks occur widely within the Moine Supergroup, mainly in the Moine and Sgurr Beag nappes, and largely in contact with metasediments assigned to the Morar and Glenfinnan groups. There are three main concentrations of inliers: those in northern Sutherland below the Naver Thrust; those in the Scardroy-Fannich area; and those immediately above the Moine Thrust in the Attadale – Glenelg – south Skye area (Fig. 1). Numerous smaller inliers are also present within other parts of the Moine and Sgurr Beag nappes. The inliers lie consistently at the lowest structural levels of local stratigraphical successions once the effects of thrusting and/or folding are removed. Some inliers apparently lie in the cores of isoclinal folds e.g. Morar (Kennedy 1955; Powell 1966) and Naver (Strachan & Holdsworth 1988), whereas others are allochthonous slices underlain by Caledonian thrusts such as the Sgurr Beag Thrust (e.g. Tanner *et al*. 1970; Rathbone & Harris 1979) and the Ben Hope Thrust (Holdsworth 1989).

Most inliers are dominated by tonalitic to dioritic hornblende-rich gneisses that are commonly highly deformed and variably banded with polyphase pegmatitic material. Thin strips of pelitic metasediment and marble have been recognized in some inliers (e.g. Loch Shin, Eastern Glenelg) and appear to represent an integral part of the basement assemblage. Throughout all of the inliers, the dominant metamorphic assemblages now present are amphibolite facies or lower, as the gneisses have been extensively reworked and retrogressed during Knoydartian (820-730 Ma) and Caledonian (470-420 Ma) orogenic events. Some inliers locally preserve evidence of high-grade, pre-Caledonian metamorphic assemblages. These include the Western Glenelg inlier where relict granulite facies mineralogies are preserved (e.g. Barber & May 1975; Sanders 1979) and the Eastern Glenelg inlier where eclogite facies rocks are present (e.g. Teall 1891; Alderman 1936; Mercy & O'Hara, 1969; Sanders 1979; Sanders *et al*. 1984). Early high-grade assemblages have also been reported from the Borgie inlier where garnet and clinopyroxene-bearing mafic gneisses were retrogressed into amphibole-plagioclase assemblages during the Caledonian orogeny (Moorhouse 1976; Holdsworth *et al.* 2001).

Affinities of the basement inliers and relationships with the Moine Supergroup

When the basement inliers within the Moine Supergroup were first mapped they were interpreted to be sub-Moine, Lewisian rocks because of their lithological similarity to the Lewisian gneisses of the Caledonian foreland (e.g. Flett 1905; Peach *et al*. 1907, 1910, 1913). This correlation was challenged by Sutton & Watson (1953, 1954), who interpreted the gneissic rocks of central Ross-shire as integral parts of the Moine succession. However, subsequent research in the Glenelg area showed this to be incorrect (Ramsay 1958) and correlation with the Lewisian of the foreland was reinstated and continued in later studies of the Moine nappes (e.g. Sutton & Watson 1962; Barber & May 1975; Rathbone & Harris 1979; Strachan & Holdsworth 1988; Holdsworth 1989; Temperley & Windley 1997). It has been tacitly assumed on the basis of broad lithological similarities that all of the inliers belong to essentially the same portion of the Lewisian (e.g. Sutton & Watson 1962; Watson 1975). However, the use of lithology alone as a basis for correlation of complex gneissic rocks is no longer considered acceptable. This is particularly the case when considering units that (prior to Caledonian thrusting) may have formerly been separated by many tens or even hundreds of kilometres. Furthermore, it has been shown that the Lewisian Complex itself comprises a variety of terranes of differing age and history, some added in the Proterozoic (Kinny *et al*. 2005).

Following the early work that suggested that a tectonised unconformity existed between the Moine and the basement (*e.g*. Peach *et al*. 1910, 1913), the present consensus is that the Moine Supergroup was deposited unconformably on the basement inliers (Barr *et al.* 1988; Holdsworth *et al*. 1994; Soper *et al.* 1998). In some places, way-up evidence clearly shows that the Moine sedimentary rocks young away from the basement (e.g. Bailey & Tilley 1952; Kennedy 1955; Ramsay 1958; Holdsworth 1989; Moorhouse *et al*. 1988), and basal Moine conglomerates are described from several localities, for example, at Glenelg (*e.g*. Bailey & Tilley 1952; Ramsay 1958) and Attadale (Barber & May 1975). Others, such as at Strathan (Mendum 1976) are more contentious. Some of the reported 'basal conglomerates' (e.g. Glen Strathfarrar, Strathan) are now interpreted as being partly of tectonic origin, probably arising from the disruption of quartz veins (Holdsworth *et al.* 2001; Friend & Strachan unpublished data) but this does not necessarily undermine the essentially autochthonous status of the sub-Moine basement. As suggested by Tanner *et al.* (1970), those inliers occurring along the trace of the Sgurr Beag Thrust in Ross-shire may represent tectonically detached slices of a 'basement high', possibly representing rift shoulders that separated the Morar and Glenfinnan-Loch Eil sedimentary basins (see also Soper *et al*. 1998).

Previous isotopic data

To date, there have been few isotopic age determinations on the basement inliers, their heterogeneity and complex metamorphic history creating difficulties for both whole rock and mineral isotope studies. Moorbath & Taylor (1974) obtained a Rb-Sr whole-rock isochron age of 2810 ± 120 Ma for the Scardroy inlier (Fig. 1) which they claimed to "……prove beyond any doubt that the rocks of the Scardroy sheet are, indeed, Lewisian." Moorbath & Taylor (1974) also produced K-Ar dates on hornblendes and biotites from Scardroy in the range 459-420 Ma (with one sample at 535 Ma interpreted to have incompletely outgassed). These results were compared to unpublished data that Moorbath and Taylor had obtained from the Eastern Glenelg inlier where similar Caledonian K-Ar ages had been obtained, and contrasted with data from the Western Glenelg inlier where K-Ar ages were in the range 2200-1600 Ma. Miller *et al.* (1963) produced a 1515 ± 104

Ma K-Ar age date on omphacite from the eclogitic rocks in the Eastern Glenelg inlier. A subsequent study provided Sm-Nd mineral regression ages on the eclogites of 1082 ± 22 and 1010 ± 13 Ma that were interpreted to date a high-grade Grenvillian metamorphic event (Sanders *et al*. 1984). The existence of this event has been broadly substantiated by U-Pb titanite ages of *c*. 1000 Ma obtained from the Eastern Glenelg inlier (Brewer *et al*. 2003).

Analytical techniques

Zircons separated from the rock samples were mounted in epoxy resin, sectioned, imaged by cathodoluminescence, and dated using the SHRIMP-II ion microprobe at the John de Laeter Centre, Curtin University, Perth, Western Australia. Operating conditions for SHRIMP were routine, namely 25 μm analytical spot size, primary beam current 2 to 5 nA, mass resolution 5000 (1% valley), and sensitivity for Pb isotopes approximately 15 cps/ppm/nA. Correction of isotope ratios for common Pb was based on the measured ^{204}Pb, representing in most cases less than 1% correction to the ^{206}Pb counts (see %com.^{206}Pb, Table 1), with the common Pb composition modelled upon that of Broken Hill ore Pb. Pb/U isotopic ratios were corrected for instrumental inter-element discrimination using the observed co-variation between ^{206}Pb/^{238}U and UO/U (Compston *et al.* 1984, 1992) determined from interspersed analyses of the Perth standard zircon CZ3 (564 Ma; ^{206}Pb/^{238}U = 0.0914). The uncertainty in Pb/U ratios associated with this correction procedure was in the range 1.5 to 2.5%, whereas uncertainties in Pb/Pb ratios were generally lower, being governed principally by counting statistics. Isotope ratios and corresponding ages (calculated using standard decay constants) are listed in Table 1, together with 1σ uncertainties. Unless otherwise stated, all ages discussed in the text are given with 95% confidence limits.

Results

S99/2: Ribigill inlier [National Grid Reference: NC 580547]

The Ribigill inlier (Fig. 1) occupies an antiformal fold core in the hanging wall of the Ben Hope Thrust (Moorhouse & Moorhouse 1977; Holdsworth 1989; British Geological

Survey 1997; Holdsworth *et al.* 2001). Of the three inliers examined along the north coast, the Ribigill inlier is the structurally lowest and the least far travelled with respect to the Caledonian foreland. The sample analysed was collected from a quarry in the central portion of the inlier that is dominated by banded, quartzo-feldspathic gneisses that are broadly granodioritic in composition. The gneissic layering consists of mm–cm scale alternations of mafic- and felsic-dominated layers. Some of the latter comprise deformed concordant layers and lenticles of granitic pegmatite suggesting either that the rocks were invaded by melt, or that they underwent a metamorphic event that induced a low degree of partial melting. This melt material was avoided in the sampling. In thin-section, the sample comprises a medium- to coarse-grained, granoblastic assemblage of plagioclase and K-feldspar, hornblende, biotite, epidote and quartz.

The separated zircons were euhedral to subhedral prismatic grains. CL imaging revealed regular internal growth zoning in most grains and occasional structural cores (Figure 2). The analysed zircons produced a range of ^{207}Pb/^{206}Pb ages, and plot either overlapping concordia or slightly below (Fig. 2). Of the three analyses with highest ^{207}Pb/^{206}Pb, two (1.1, 4.1, Table 1) were situated in discrete structural cores, suggesting that they may represent inherited components in the protolith. The combined age of these three analyses is 2822 ± 28 Ma. The main group of analyses record ^{207}Pb/^{206}Pb ages of between 2760 and 2660 Ma. These probably represent the main protolith population. In addition, three analyses of tips of grains with high U content and low Th/U ratio (3.2, 2.3, 5.1, Table 1) and appearing dark in CL (Fig. 2), record younger apparent ages, appearing to lie on a discordance line trending towards a *c.* 1600 Ma intercept age, adjacent to analysis 5.1. The formation of these rims could be related to the episode responsible for the granite-pegmatite layers observed in the host rock.

S96/12: Borgie inlier [NC 689573]

The Borgie inlier is the largest on the north coast (Fig. 1) and occupies a structurally higher antiformal fold core between the Ben Hope Thrust and the Naver Thrust (Moorhouse 1976; British Geological Survey 1997; Holdsworth *et al.* 2001). It contains a range of different lithologies. The banded felsic gneisses of the inlier are K-feldspar poor, and variably hornblende- and biotite-bearing; locally they enclose rafts of mafic and ultramafic rocks. Some of the mafic rafts are characterized by garnet-clinopyroxene metamorphic assemblages (Moorhouse 1976; Holdsworth *et al*. 2001). In thin section, the analysed sample is banded and comprises a coarse, granoblastic assemblage of plagioclase feldspar and quartz with finer-grained, porphyroblastic hornblende and oriented flakes of biotite with minor chlorite. Some mafic-dominated layers comprise aligned biotite and granular epidote. The quartz-rich domains are dominated by annealed ribbon textures, suggesting that the gneiss has undergone high strain.

The separated zircons typically have sub-rounded, modified shapes, and CL imaging revealed that numerous grains have a brightly luminescent mantle over a zoned interior. On a concordia diagram, the analysed points form a coherent discordance array that projects on a shallow trajectory from a late Archaean upper intercept age towards an approximately end-of-Palaeoproterozoic lower intercept age (Fig. 3). The data are interpreted to represent a single disturbed population. The least discordant analyses have $^{207}Pb/^{206}Pb$ ages of *c*. 2880 Ma, but there are too few of them to allow a more accurate assessment of the protolith age. The projected lower intercept is *c*. 1600 Ma, suggesting significant isotopic disturbance at about that time.

S99/1: Farr inlier [NC 687614]

The Farr inlier (Fig. 1) occupies the core of an isoclinal fold within the migmatitic Moine rocks of the Naver Nappe (Moorhouse 1979; Moorhouse *et al.* 1988). It represents the structurally highest inlier examined and is likely to be the furthest travelled relative to the Caledonian foreland. The inlier is dominated by banded, mafic and intermediate hornblendic gneisses that are highly deformed. The sample dated is coarse-grained gneiss and in thin section comprises sub-equigranular, granoblastic plagioclase feldspar, quartz and hornblende. Minor biotite may be retrogressive and accessory phases include opaques, apatite and zircon.

The separated zircons were typically elongate, subhedral, prismatic grains, with a narrow CL-bright rim evident on most grains, developed over regularly zoned interiors (Fig. 4). Two SHRIMP analyses were undertaken on most grains, one spot in the core and one on the rim. On a concordia diagram, the combined analyses form a broad, essentially continuous discordant array projecting from a late Archaean upper intercept age to an end-of-Palaeoproterozoic lower intercept age (Fig. 4). There is no clear distinction between the age spectra for cores and rims other than that the analyses of rims tend to be the most highly discordant. The four least-discordant analyses of grain cores have a combined age of 2905 ± 24 Ma, which can be considered as a reasonable estimate of the protolith age of this gneiss. The shallow slope of the discordance array suggests isotopic disturbance of the zircons involving Pb-loss as early as *c*. 1600 Ma.

S96/41: Western Glenelg inlier, at Dornie [NG 912226]

This sample was taken from one of the high strain zones within the retrogressed gneisses exposed in road cuttings near Dornie along the shore of Loch Duich (Fig. 1). The sample is blastomylonitic and fine-grained with granoblastic quartz grains pseudomorphing ribbon fabrics. The sample was taken in the hope that some indication of the metamorphism associated with the shearing event might be present.

The zircons from this sample showed typical igneous zonation features under CL imaging, a minority of grains possessing a structural core (Fig. 5). Analyses produced a range of late Archaean to Mesoproterozoic apparent ages. The oldest age obtained (*c*. 2800 Ma) was recorded from a spot within a structural core (analysis 5.1, Table 1). The main population of least disturbed zircon is represented by five analyses (10.1, 11.1, 12.1, 15.1, 17.1, Table 1), which record a mean $^{207}Pb/^{206}Pb$ age of 2677 ± 16 Ma (Fig. 5). Numerous discordant points trend to lower $^{207}Pb/^{206}Pb$ ages, following discordant arrays that trending towards different lower intercept ages. The analyses recording the youngest apparent ages include rim analyses (e.g. 14.2, 16.2) and three analyses of grain 9 (Table 1). These analyses appear to lie on a secondary discordance line projecting from a late Palaeoproterozoic upper intercept to younger apparent ages, implying a complex multistage history of isotopic disturbance.

Comparison with the Lewisian Gneiss Complex of the foreland

The new data show that each of the inliers dated has an Archaean protolith. The wide geographic distribution of the inliers dated suggests that the intervening inliers are of similar age, although this remains to be proven. Amongst the northern inliers, the Ribigill (*c*. 2760 Ma with *c*. 2820 Ma inherited components) appears to be younger than the Borgie and Farr inliers (*c*. 2900 Ma), whilst the western Glenelg sample appears still younger at *c*. 2680 Ma (with one *c*. 2800 Ma core). All three of the northern inliers show similar discordant patterns, reflecting disturbance of protolith grains in latest Palaeoproterozoic times. The zircons from Glenelg show a broadly similar pattern, but with evidence for additional disturbance during younger events. Distinct rims on the Farr and Ribigill inlier zircons appear to have formed in the late Archaean and to have been disturbed in the Proterozoic along with the enclosed cores, whereas some young components in the Glenelg sample may represent components newly grown during Proterozoic events.

Are there any points of similarity between these inliers and the various components of the Lewisian Gneiss Complex of the Caledonian foreland? The age range of the least disturbed protolith zircons within the Ribigill inlier falls within that of the known protoliths of the geographically adjacent Rhiconich terrane on the foreland (2840–2680 Ma). However, the Ribigill gneisses do not appear to contain any examples of the extensive *c*. 1855 Ma granite sheets that are found throughout the Rhiconich terrane (e.g. Kinny & Friend 1997; Kinny *et al.* 2005) and the analysed zircons do not appear to show any new growth at this time. On the other hand, the timing of amphibolite facies metamorphism in the Rhiconich terrane, *c*. 1740 Ma, is broadly consistent with the age of some ancient Pb loss from the Ribigill zircons. The Ribigill inlier therefore displays some similarities with the foreland basement.

The *c*. 2900 Ma protolith ages obtained from the Farr and Borgie inliers are older than the typical protolith ages of the Rhiconich terrane. However, given that they represent minimum age estimates from disturbed populations, they are a closer match to protolith ages of the Assynt terrane (3030–2960 Ma). Significantly, there is no conclusive evidence in the analysed zircons from any of the inliers for any major disturbance or new zircon growth during either of the high-grade metamorphic events now recognized in the Lewisian Gneiss Complex on the foreland: *c*. 2730 Ma in the Gruinard terrane (Love *et al.* 2003) and *c*. 2490 Ma in the Assynt terrane (Friend & Kinny 1995). Both events caused U-depletion, and in the case of the *c*. 2490 Ma event, it was particularly intense and is very easily recognised analytically in the zircons. Although the metamorphic assemblages of the inliers are largely now amphibolite facies, it might be expected that the zircons would have preserved evidence of this severe U-depletion, as found in extensive overgrowth development in both the granulite and retrogressed granulite facies gneisses of the foreland (e.g. Friend & Kinny 1995; Love *et al.* 2003). That such effects are absent is strong evidence to suggest that the rocks did not experience either of these events. The Borgie and Farr inliers could, therefore, have been derived from crustal material similar to the

Assynt terrane with protolith ages of *c*. 2900 Ma but which never attained granulite facies conditions at 2490 Ma. Alternatively, they may have been derived from a different crustal block that underwent a different tectono-metamorphic history.

The protolith age of the Western Glenelg inlier (*c*. 2680 Ma) is younger than the majority of protolith ages obtained from the mainland Lewisian Gneiss Complex as well as from the Outer Hebrides (e.g. Kinny *et al*. 2005). However, given the high degree of isotopic disturbance to the zircons, the potential affinities of this inlier with the Lewisian foreland terranes cannot be determined with confidence.

In summary, although the zircon age spectra might support correlation of the Borgie and Farr inliers with the Assynt terrane and the Ribigill inlier with the Rhiconich terrane, there is no complete match of both protolith and metamorphic histories of any of the inliers with any of the foreland basement terranes. However, these differences are no greater than those between the individual terranes that form the Lewisian Gneiss Complex itself. The lack of specific correlation is not unexpected given the likely *c*. 100 km displacements along the Caledonian Moine Thrust Zone (e.g. Elliott & Johnson 1980; Soper & Barber 1982; Butler & Coward 1984). It is noteworthy that the main period of isotopic disturbance to the zircon populations in all four inlier samples was in the late Palaeoproterozoic, broadly corresponding to the timing of episodes of amphibolite facies reworking in the Lewisian foreland terranes (1740 – 1670 Ma) (e.g. Friend & Kinny 2001; Kinny *et al.* 2005).

Conclusions

U-Pb zircon geochronology has shown that the Ribigill, Borgie, Farr and Western Glenelg basement inliers are all characterized by late Archaean protolith ages and a period of isotopic disturbance in the late Palaeoproterozoic. In broad terms, the data are consistent with correlation between the inliers and components of the Lewisian Gneiss Complex of the Caledonian foreland. In particular, the older, *c*. 2900 Ma protolith ages support correlation of the Borgie and Farr inliers with the Assynt terrane, whilst the younger, *c*. 2800 Ma age for the Ribigill inlier supports correlation with the Rhiconich terrane. None of the studied inliers shows a complete match of both its protolith and early metamorphic histories with any of the Lewisian basement terranes, but differences between the inliers and the foreland are no greater than those recorded within the foreland basement terranes themselves. It is therefore probable that the dated inlier gneisses formed a distal part of the Laurentian margin prior to final telescoping during the Caledonian orogeny. The results of this study demonstrate the difficulty in assessing potential basement terrane linkages across an orogenic front such as the Moine Thrust when reworking has substantially disturbed isotopic systematics such that pre-thrusting protolith and metamorphic histories cannot be matched with confidence.

Acknowledgements,

We thank Ian Burns for assistance in sample collection, and participants in the 2003 Highland Field Workshop for discussions in the field. John Mendum, Martin Whitehouse and Maarten Krabbendam are thanked for constructive reviews that improved the paper.

References

Alderman, A.R. 1936. Eclogites from the neighbourhood of Glenelg, Inverness-shire. *Quarterly Journal of the Geological Society of Lond*on, **120**, 153-192.

Bailey, E.B. & Tilley, C.E. 1952. Rocks claimed as conglomerate at the Moinian-Lewisian junction. *Report XVIII International Geological Congress G.B*, 1948, part XIII, 272.

Barber, A.J. & May, F. 1975. The history of the Western Lewisian in the Glenelg inlier, Lochalsh, Northern Highlands. *Scottish Journal of Geology*, **12**, 35-50.

Barr, D., Strachan, R.A., Holdsworth, R.E. & Roberts, A.M. 1988. Summary of the Geology. *In:* Allison, I., May, F. & Strachan, R.A. (eds) *An Excursion Guide to the Moine Geology of the Scottish Highlands*. Scottish Academic Press, Edinburgh, 11-38.

Bluck, B.J., Dempster, T.J. & Rogers 1997. Allochthonous metamorphic blocks on the Hebridean passive margin, Scotland. *Journal of the Geological Society, London*, **154**, 921-924.

Brewer, T.S., Storey, C.D., Parrish, R.R., Temperley, S. & Windley, B.F. 2003. Grenvillian age decompression of eclogites in the Glenelg-Attadale inlier, NW Scotland. *Journal of the Geological Society, London*, **160**, 565-574.

British Geological Survey. 1997. *Tongue. Scotland Sheet 114E. Solid Geology. 1:50,000.* British Geological Survey, Keyworth, Nottingham.

Butler, R.W.H. & Coward, M.P. 1984. Geological constraints, structural evolution and the deep geology of the NW Scottish Caledonides. *Tectonics,* **3,** 347-365.

Cheeney, R.F. & Matthews, D.W. 1965. The structural evolution of the Taskavaig and Moine nappes in Skye. *Scottish Journal of Geology*, **1**, 256-281.

Compston, W., Williams, I.S. & Meyer, C. 1984. U-Pb geochronology of zircons from Lunar breccia 73217 using a sensitive high mass-resolution ion microprobe. *Proceedings of the Fourteenth Lunar and Planetary Conference, Pt. 2.* Journal of Geophysical Research, **89,** Supplement, B525-534.

Compston, W., Williams, I.S., Kirschvink, J.L., Zhang Zichao & Ma Guogan. 1992. Zircon U-Pb ages for the early Cambrian timescale. *Journal of the Geological Society, London,* **149,** 171-184.

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

Elliott, D. & Johnson, M.R.W. 1980. Structural evolution in the northern part of the Moine Thrust belt, NW Scotland. *Transactions Royal Society of Edinburgh*, **71**, 69-96.

Flett, J.S. 1905. *On the Petrographic Characters of the Inliers of Lewisian Rocks among the Moine Gneisses of the North of Scotland.* Memoirs of the Geological Survey. Summary of progress for 1905, 155-167.

Friend, C. R. L. & Kinny, P.D. 1995. New evidence for the protolith ages of Lewisian granulites, northwest Scotland. *Geology*, **23**, 1027-1030.

Friend, C.R.L. & Kinny, P.D. 2001. A reappraisal of the Lewisian Gneiss Complex: geochronological evidence for tectonic assembly of disparate terranes in the Proterozoic. *Contributions to Mineralogy and Petrology*, **142**, 198-218.

Friend, C.R.L., Strachan, R.A., Kinny, P.D. & Watt, G.R. 2003. Provenance of the Moine Supergroup of NW Scotland: evidence from geochronology of detrital and inherited zircons from sediments, granites and migmatites. *Journal of the Geological Society, London*, **160**, 247-258.

Holdsworth, R.E. 1989. The geology and structural evolution of a Caledonian fold and ductile thrust zone, Kyle of Tongue region, Sutherland, northern Scotland. *Journal of the Geological Society, London*, **146**, 809-823.

Holdsworth, R.E., Strachan, R.A. & Harris, A.L. 1994. Precambrian rocks in northern Scotland east of the Moine Thrust: the Moine Supergroup. *In*: Gibbons, W. & Harris, A.L. (eds*) A revised correlation of Precambrian rocks in the British Isles.* Geological Society, London, Special Reports, **22**, 23-32.

Holdsworth, R.E., Strachan, R.A. & Alsop, G.I. 2001. *Geology of the Tongue District*. Memoir of the British Geological Survey, HMSO.

Johnstone, G.S. 1975. The Moine Succession. *In:* Harris, A.L., Shackleton, R.M., Watson, J.V., Downie, C., Harland, W.B. & Moorbath, S. (eds) *A Correlation of Precambrian Rocks in the British Isles.* Geological Society, London, Special Report, **6**, 30-42.

Kennedy, W.Q. 1955. The tectonics of the Morar anticline and the problem of the North-West Caledonian Front. *Quarterly Journal of the Geological Society, London,* **110**, 357-382.

Kinny, P.D. & Friend, C.R.L.1997. U-Pb isotopic evidence for the accretion of different crustal blocks to form the Lewisian Complex of Northwest Scotland. *Contributions to Mineralogy and Petrology*, **129**, 326-340.

Kinny, P.D., Friend, C.R.L. & Love, G.J. 2005. Proposal for a terrane-based nomenclature for the Lewisian Gneiss Complex of NW Scotland. *Journal of the Geological Society, London,* **162**, 175-186.

Krabbendam, M., Prave, A.R. & Cheer, D. 2008. A fluvial origin for the Neoproterozoic Morar Group, NW Scotland: implications for Torridon-Morar group correlation and the Grenville Orogen foreland basin. *Journal of the Geological Society, London*, in press.

Love, G.J., Kinny, P.D. & Friend, C.R.L. 2003. Timing of magmatism and metamorphism in the Gruinard Bay area of the Lewisian Gneiss Complex: comparisons with the Assynt Terrane and implications for terrane accretion. *Contributions to Mineralogy and Petrology*, **146**, 620-636.

Mendum, J. 1976. A strain study of the Strathan conglomerate, north Sutherland. *Scottish Journal of Geology*, **12**, 159-165.

Mercy E.L.P. & O'Hara, M.J. 1969. Nepheline normative eclogite from Loch Duich, Ross-shire. *Scottish Journal of Geology*, **4**, 1-9.

Miller, J.A., Barber, A.J. & Kempton, N.H. 1963. A potassium/argon age determination from a Lewisian inlier. *Nature*, **197**, 1095-1096.

Moorbath, S. & Taylor, P.N. 1974. A Lewisian age for the Scardroy mass. *Nature* 250, 41-43.

Moorhouse, S.J. 1976. The geochemistry of the Lewisian and Moinian of the Borgie area, North Sutherland. *Scottish Journal of Geology*, **12**, 159-165.

Moorhouse, S.J. & Moorhouse, V.E. 1977. A Lewisian basement sheet at Ribigill, north Sutherland. *Scottish Journal of Geology*, **13**, 289-300.

Moorhouse, S.J., Moorhouse, V.E., & Holdsworth, R.E. 1988. Excursion 12. North Sutherland. *In*: Allison, I., May, F. & Strachan, R.A. (eds) *An Excursion Guide to the Moine Geology of the Scottish Highlands*. Scottish Academic Press, Edinburgh, 216-248.

Moorhouse, V.E. 1979. *The geology and geochemistry of the Bettyhill-Strathy area of north-east Sutherland.* PhD thesis, University of Hull.

Park, R.G., Stewart, A.D. & Wright, D.T. 2002. The Hebridean Terrane. *In:* Trewin, N. (ed) *The Geology of Scotland*. Geological Society, London, 45-80.

Peach, B.N., Horne, J., Gunn, W., Clough, C.T., Hinxman, L.W. & Teall, J.J.H. 1907. The Geological Structure of the North West Highlands of Scotland. *Memoir of the Geological Survey, United Kingdom*.

Peach, B.N., Horne, J., Woodward, H.B., Clough, C.T., Harker, A. & Wedd, C.B. 1910. The geology of Glenelg, Lochalsh and South-east part of Skye. *Memoir of the Geological Survey, United Kingdom*.

Peach, B.N., Horne, J., Hinxman, L.W., Crampton, C.B. Anderson, E.M. & Carruthers, R.G. 1913. The geology of central Ross-shire. *Memoir Geological Survey United Kingdom*.

Powell, D. 1966. The structure of the south-eastern part of the Morar antiform, Inverness-shire. *Proceedings of the Geologists Association*, **77,** 79–100.

Rainbird, R.H., Hamilton, M.A. & Young, G.M. 2001. Detrital zircon geochronology and provenance of the Torridonian, NW Scotland. *Journal of the Geological Society, London,* **158**, 15-27.

Ramsay, J. G. 1958. Moine-Lewisian relations at Glenelg, Invernessshire. *Quarterly Journal of the Geological Society, London,* **113**, 99-106.

Rathbone, P.A. & Harris, A.L. 1979. Basement-cover relationships at Lewisian inliers in the Moine rocks. In: Harris, A.L., Holland, C.H. & Leake, B.E. (eds), *The Caledonides of the British Isles - reviewed*. Geological Society of London, Special Publication **8**, 101-107.

Rogers, G., Hyslop, E.K., Strachan, R.A., Paterson, B.A. & Holdsworth, R.E. 1998. The structural setting and U-Pb geochronology of Knoydartian pegmatites in Inverness-shire: evidence for Neoproterozoic tectonothermal events in the Moine of NW Scotland. *Journal of the Geological Society, London*, **155**, 685-696.

Sanders, I.S. 1979. Observations on eclogite- and granulite-facies rocks in the basement of the Caledonides. *In:* Harris, A.L., Holland, C.H. & Leake, B.E. (eds), *The Caledonides of the British Isles reviewed*. Geological Society of London, Special Publication **8**, 97-101.

Sanders, I.S., van Calsteren, P.W.C. & Hawksworth, C.J. 1984. A Grenville Sm-Nd age for the Glenelg eclogite in north-west Scotland. *Nature 312*, 439-440.

Soper, N.J. & Barber, A.J. 1982. A model for the deep structure of the Moine thrust zone . *Journal of the Geological Society, London*, **139**, 127-138.

Soper, N.J., Harris, A.L. & Strachan, R.A. 1998. Tectonostratigraphy of the Moine Supergroup: a synthesis. *Journal of the Geological Society, London.* **155**, 13-24.

Stewart, A.D. 2002. *The later Proterozoic Torridonian rocks of Scotland: their sedimentology, geochemistry and origin*. Geological Society, London, Memoir, **24**.

Strachan, R.A. & Holdsworth, R.E. 1988. Basement-cover relationships and structure within the Moine rocks of central and southeast Sutherland. *Journal of the Geological Society, London*, **145**, 23-36.

Sutton, J. & Watson, J. 1953. The supposed Lewisian inlier of Scardroy, central Ross-shire, and its relations with the surrounding Moine rocks. *Quarterly Journal of the Geological Society, London,* **108**, 99-106.

Sutton, J. & Watson, J. 1954. The structure and stratigraphical succession of the Moines of Fannich Forest and Strath Bran, Ross-shire. *Quarterly Journal of the Geological Society, London,* **110**, 21-54.

Sutton, J. & Watson, J. 1962. An interpretation of Moine-Lewisian relations in central Ross-shire. *Geological Magazine* **99**, 527-541.

Tanner, P.W.G. & Evans, J.A. 2003. Late Precambrian U-Pb titanite age for peak regional metamorphism and deformation (Knoydartian orogeny) in the western Moine, Scotland. *Journal of the Geological Society* **160**, 555-564.

Tanner, P.W.G., Johnstone, G.S., Smith, D.I. & Harris, A.L. 1970. Moinian Stratigraphy and the problem of the Central Ross-shire Inliers. *Bulletin of the Geological Society of America*, 81, 299-306.

Teall, J.J.H. 1891. On eclogite from Loch Duich. *Mineralogical Magazine*, **9**, 217-218.

Temperley, S. & Windley, B.F. 1997. Grenvillian extensional tectonics in northwest Scotland. *Geology*, **25**, 53-56.

Vance, D., Strachan, R.A. & Jones, K.A. 1998. Extensional versus compressional settings for metamorphism: garnet chronometry and pressure-temperature-time histories in the Moine Supergroup, northwest Scotland. *Geology*, **26**, 927-930.

Watson, J.V. 1975. The Lewisian Complex. *In:* Harris, A.L., Shackleton, R.M., Watson, J.V., Downie, C., Harland, W.B. & Moorbath, S. (eds) *A Correlation of Precambrian Rocks in the British Isles.* Geological Society, London, Special Report, **6**, 15-29.

Tables

Table 1. SIMS U-Th-Pb data for the analysed zircons from basement inliers. Key to spot positions: unless otherwise stated, analytical spots were centrally located. ‘Core’ implies a visible structural core and ‘rim’ implies a distinct overgrowth. Otherwise, the terms ‘centre’ and ‘outer’ and/or ‘tip’ are used. ‘Patchy’ indicates a domain lacking in concentric growth zonation. Detailed spot locations are unfortunately not available for the Borgie sample.

Figure captions

Figure 1. Sketch map of northern Scotland showing the position of the Moine Supergroup with the main basement inliers, and the locations of the analysed samples. Abbreviations: MT, Moine Thrust; NT, Naver Thrust; SBT, Sgurr Beag Thrust; SkT, Skinsdale Thrust; St, Strathan; LS, Loch Shin; F, Fannich; SC, Scardroy; S, Glen Strathfarrar; G, Glenelg; A, Attadale. Inset box shows position of the study area.

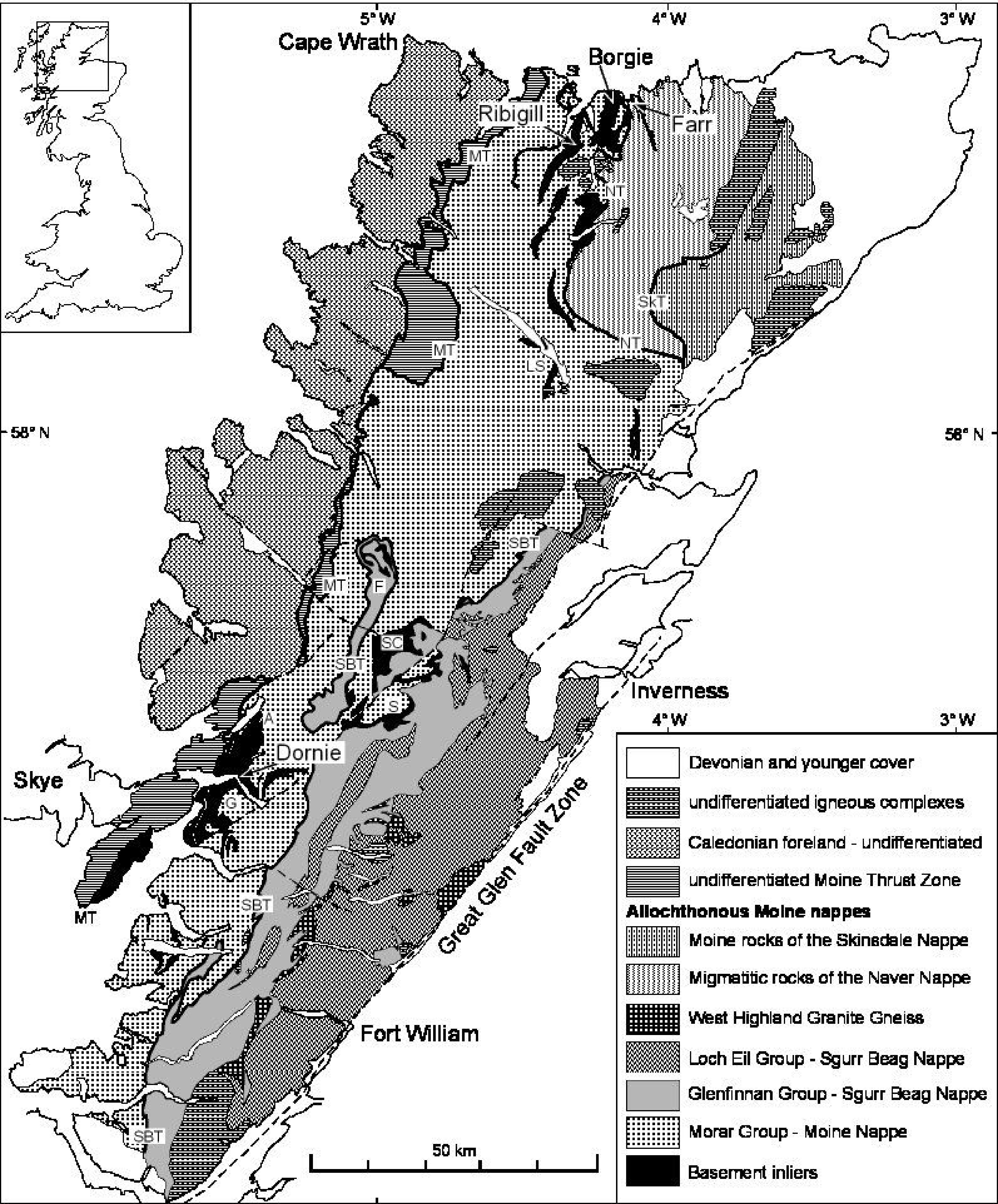
Figure 2. Concordia plot for sample S99/2 Ribigill inlier, including cathodoluminescence images of representative grains. Identified grain numbers are listed in Table 1, with the approximate locations of SHRIMP analytical spots indicated by white circles.

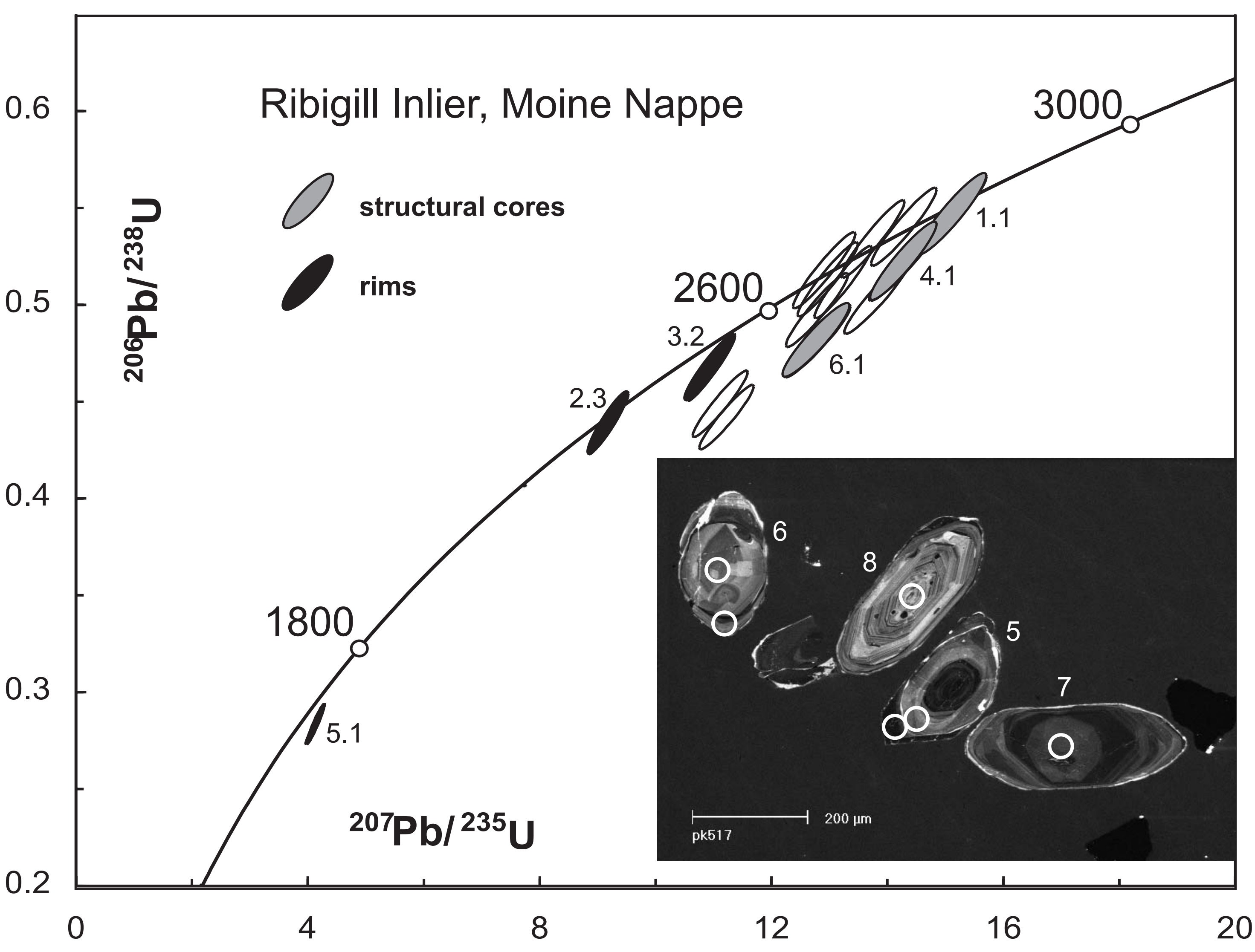
Figure 3. Concordia plot for sample S96/12 Borgie inlier.

Figure 4. Concordia plot for sample S99/1 Farr inlier, including cathodoluminescence images of representative grains. Identified grain numbers are listed in Table 1, with the approximate locations of SHRIMP analytical spots indicated by white circles.

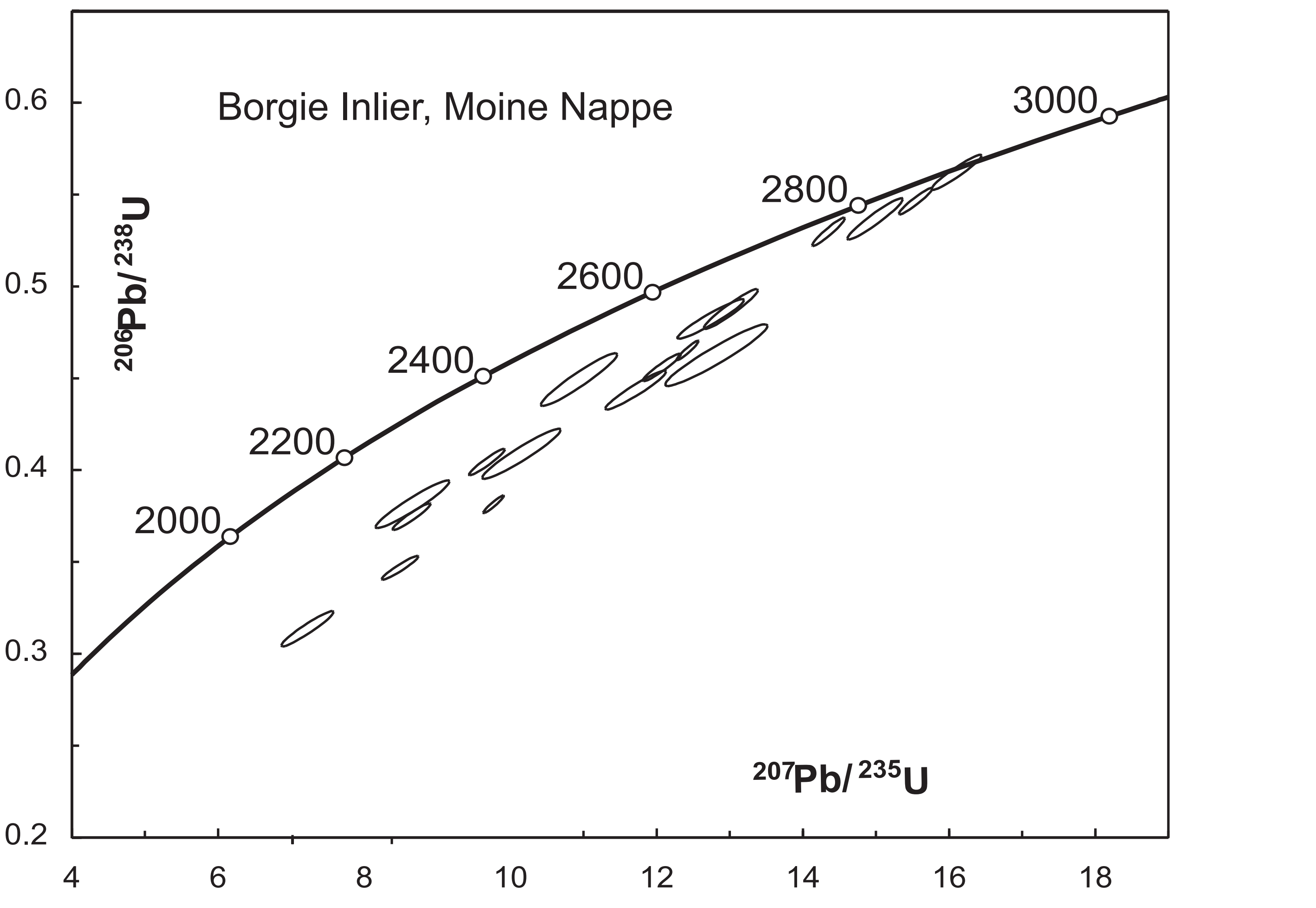
Figure 5. Concordia plot for sample S96/41 Western Glenelg inlier, including cathodoluminescence images of representative grains. Identified grain numbers are listed in Table 1, with the approximate locations of SHRIMP analytical spots indicated by white circles.

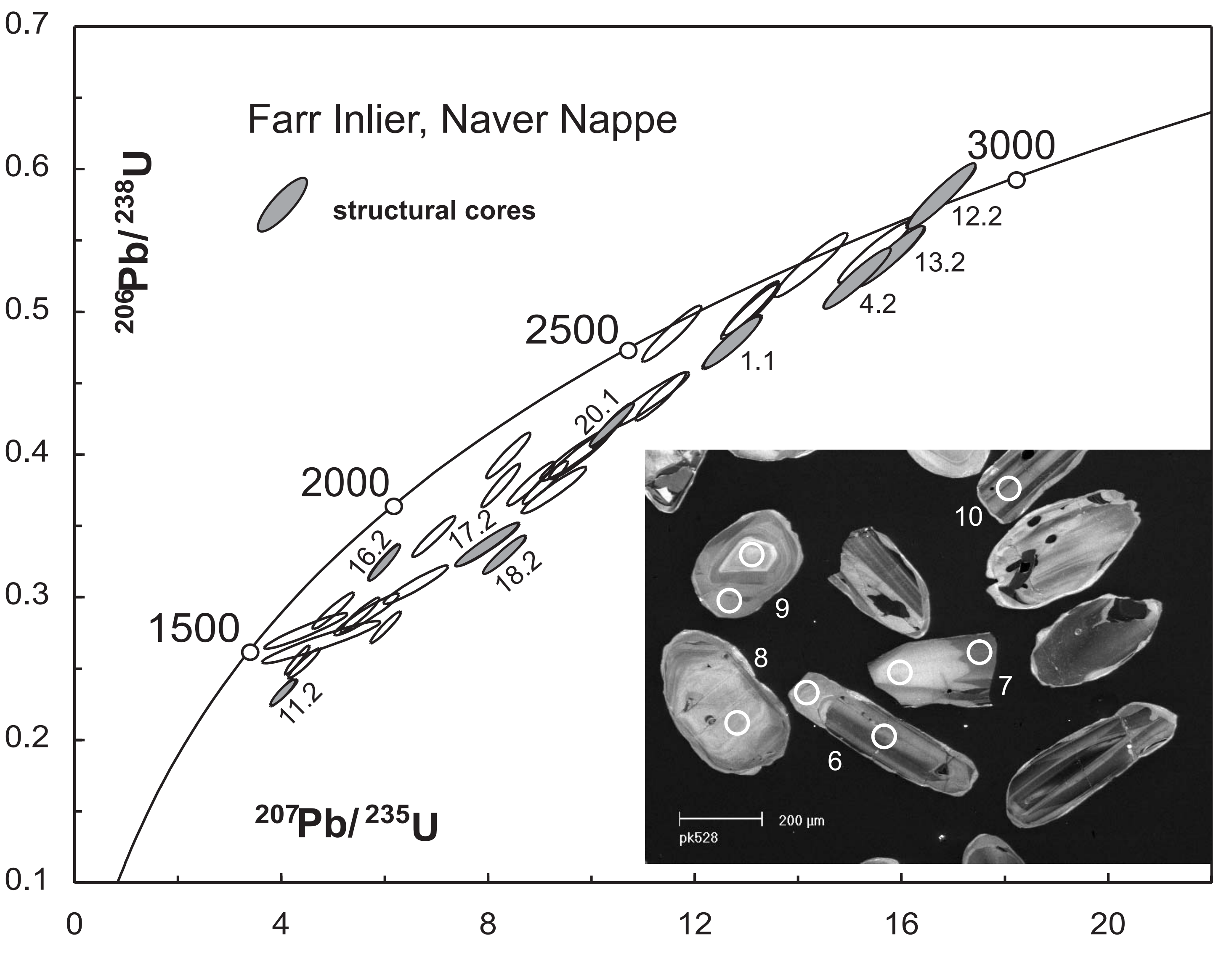
Friend et al. Fig. 1 07/01/2008



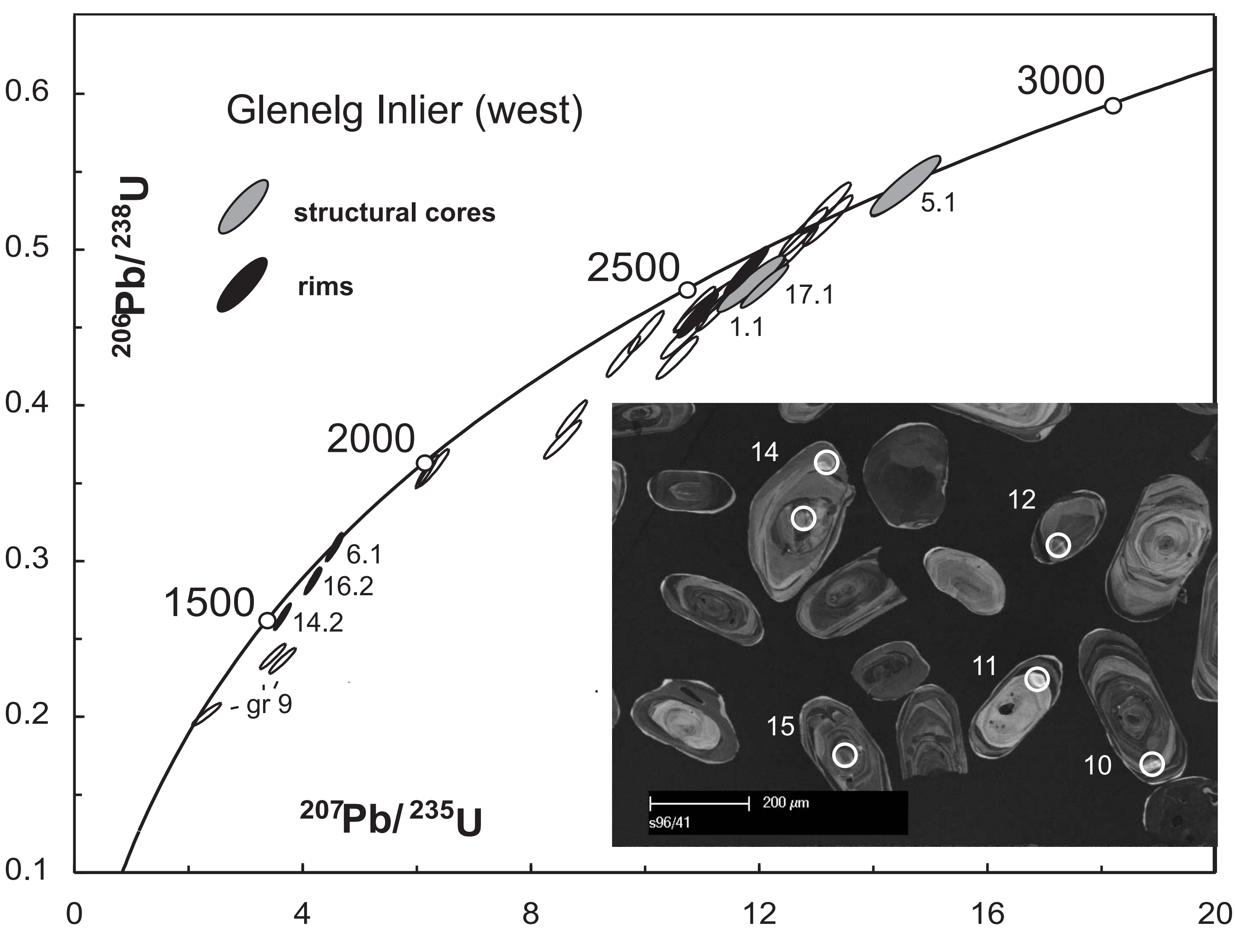


Ribigill Inlier, Moine Nappe
structural cores
rims
$^{206}Pb/^{238}U$
$^{207}Pb/^{235}U$
0.6
0.5
0.4
0.3
0.2
0
4
8
12
16
20
1800
2600
3000
5.1
2.3
3.2
6.1
4.1
1.1
6
8
5
7
200 µm
pk517


Borgie Inlier, Moine Nappe
2000
2200
2400
2600
2800
3000
^{206}Pb/^{238}U
^{207}Pb/^{235}U
0.2
0.3
0.4
0.5
0.6
4
6
8
10
12
14
16
18



Farr Inlier, Naver Nappe
structural cores
$^{206}Pb/^{238}U$
$^{207}Pb/^{235}U$
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
4
8
12
16
20
1500
2000
2500
3000
12.2
13.2
4.2
1.1
20.1
17.2
18.2
16.2
11.2
10
9
8
7
6
200 µm
pk528



Glenelg Inlier (west)
structural cores
rims
3000
2500
2000
1500
5.1
17.1
1.1
6.1
16.2
14.2
gr 9
0.6
0.5
0.4
0.3
0.2
0.1
$^{206}Pb/^{238}U$
$^{207}Pb/^{235}U$
0
4
8
12
16
20
14
12
11
15
10
200 μm
s96/41

Grain. Spot	Position	U ppm	Th ppm	Th/U	%com ^{206}Pb	^{207}Pb/^{206}Pb ± 1σ		^{206}Pb/^{238}U ± 1σ		^{207}Pb/^{235}U ± 1σ		^{206}Pb/^{238}U Age ± 1σ		^{207}Pb/^{206}Pb Age ± 1σ	
Ribigill inlier s99/2															
1.1	core	142	108	0.76	0.17	0.2005	0.0012	0.5469	0.0135	15.12	0.39	2812	56	2830	10
8.1	centre	91	51	0.55	0.34	0.1989	0.0015	0.5041	0.0126	13.82	0.37	2632	54	2817	12
4.1	core	79	30	0.39	0.14	0.1985	0.0017	0.5220	0.0132	14.28	0.39	2708	56	2814	14
6.1	core	57	20	0.36	0.56	0.1928	0.0023	0.4812	0.0124	12.79	0.38	2533	54	2766	19
3.1	centre	182	81	0.44	0.17	0.1917	0.0012	0.5403	0.0133	14.28	0.37	2785	56	2757	10
2.1	centre	541	44	0.08	0.06	0.1875	0.0005	0.5118	0.0123	13.23	0.32	2664	53	2721	4
1.2	outer	125	97	0.78	0.18	0.1867	0.0011	0.5340	0.0132	13.75	0.36	2758	55	2714	10
6.2	outer	86	86	1.00	0.48	0.1865	0.0016	0.4973	0.0126	12.79	0.36	2602	54	2711	14
7.1	centre	197	79	0.40	0.40	0.1842	0.0018	0.4420	0.0110	11.22	0.31	2360	49	2691	16
4.2	outer	130	95	0.73	0.25	0.1833	0.0013	0.5131	0.0127	12.97	0.34	2670	54	2683	11
2.2	outer	90	84	0.94	0.24	0.1808	0.0015	0.5179	0.0130	12.91	0.35	2690	55	2660	14
5.2	outer	90	69	0.77	0.35	0.1796	0.0018	0.4489	0.0113	11.12	0.31	2390	50	2649	16
3.2	tip	332	9	0.03	0.06	0.1699	0.0007	0.4677	0.0114	10.96	0.28	2474	50	2556	6
2.3	tip	375	49	0.13	0.06	0.1518	0.0006	0.4388	0.0106	9.19	0.23	2345	48	2366	7
5.1	dark rim	1145	96	0.08	0.07	0.1057	0.0003	0.2836	0.0068	4.13	0.10	1609	34	1726	6
Borgie inlier s96/12															
94.1		44	20	0.47	0.13	0.2078	0.0015	0.5620	0.0063	16.10	0.22	2875	26	2888	12
75.1		133	70	0.52	0	0.2063	0.0007	0.5463	0.0048	15.54	0.15	2810	20	2877	6
9.1		90	28	0.31	0	0.2026	0.0016	0.5367	0.0074	14.99	0.25	2770	31	2847	13
10.1		21	6	0.30	0.15	0.2010	0.0049	0.4625	0.0111	12.82	0.46	2451	49	2834	39
28.1		732	62	0.09	0	0.1965	0.0005	0.5297	0.0051	14.35	0.15	2740	22	2797	4

87.1		617	73	0.12	0.03	0.1937	0.0004	0.4652	0.0035	12.42	0.10	2462	15	2774	3
13.1		82	16	0.20	0.11	0.1936	0.0020	0.4876	0.0071	13.01	0.24	2560	31	2773	17
68.1		51	11	0.22	0.15	0.1920	0.0015	0.4559	0.0049	12.07	0.17	2422	22	2759	13
6.2		18	16	0.89	0.26	0.1916	0.0030	0.4436	0.0070	11.72	0.27	2367	31	2756	26
10.2		21	19	0.91	0.31	0.1916	0.0032	0.4822	0.0071	12.74	0.30	2537	31	2756	27
85.1		197	34	0.17	0.05	0.1857	0.0007	0.3814	0.0032	9.77	0.09	2083	15	2705	6
38.1		29	8	0.28	0.10	0.1801	0.0044	0.4089	0.0090	10.15	0.35	2210	41	2653	40
9.2		33	18	0.54	0.49	0.1775	0.0024	0.3469	0.0043	8.49	0.17	1920	21	2630	23
17.1		30	10	0.32	0.28	0.1766	0.0037	0.4493	0.0095	10.94	0.34	2392	42	2621	35
17.2		43	40	0.92	0.31	0.1736	0.0018	0.4044	0.0047	9.68	0.16	2189	22	2593	17
88.1		31	28	0.91	0.38	0.1674	0.0023	0.3747	0.0048	8.65	0.17	2052	22	2532	23
11.1		37	8	0.22	0.17	0.1670	0.0039	0.3136	0.0063	7.22	0.24	1758	31	2528	39
6.1		27	8	0.29	0.60	0.1647	0.0047	0.3814	0.0086	8.66	0.33	2083	40	2504	48

Farr inlier s99/1

13.2	core	72	34	0.48	0.06	0.2126	0.0018	0.5388	0.0138	15.79	0.44	2778	58	2925	14
4.2	core	56	59	1.05	0.18	0.2100	0.0020	0.5233	0.0137	15.15	0.44	2713	58	2906	16
12.2	core	100	100	0.99	0.10	0.2094	0.0013	0.5807	0.0145	16.76	0.45	2952	59	2901	10
7.2	patchy	44	43	0.97	0.55	0.2072	0.0024	0.5420	0.0142	15.48	0.46	2792	59	2884	19
9.2	outer	32	14	0.43	0.12	0.1939	0.0028	0.5329	0.0148	14.25	0.47	2754	62	2776	24
1.1	core	45	31	0.69	0.10	0.1927	0.0023	0.4789	0.0125	12.72	0.38	2522	55	2765	20
13.1	rim	75	60	0.81	0.37	0.1896	0.0020	0.5004	0.0128	13.08	0.38	2615	55	2738	17
20.2	outer	100	58	0.58	0.08	0.1890	0.0015	0.5025	0.0125	13.09	0.35	2624	54	2733	13
2.1	centre	73	79	1.08	0.34	0.1867	0.0019	0.4407	0.0112	11.34	0.32	2354	50	2713	16
7.1	patchy	17	11	0.66	1.17	0.1838	0.0061	0.4377	0.0133	11.09	0.53	2340	60	2688	55
18.2	core	58	40	0.69	0.29	0.1830	0.0030	0.3301	0.0086	8.33	0.27	1839	42	2681	27
20.1	core	199	272	1.36	0.09	0.1794	0.0011	0.4206	0.0103	10.40	0.27	2263	47	2647	11
16.1	rim	25	9	0.34	0.58	0.1794	0.0055	0.3751	0.0108	9.28	0.41	2053	50	2647	51
3.1	centre	20	10	0.52	0.39	0.1773	0.0046	0.4003	0.0116	9.79	0.40	2170	53	2628	43

9.1	centre	20	23	1.12	1.44	0.1760	0.0059	0.4002	0.0123	9.71	0.47	2170	56	2616	55
14.1	centre	54	52	0.97	0.51	0.1737	0.0026	0.3804	0.0099	9.11	0.29	2078	46	2593	25
12.1	rim	42	19	0.46	0.03	0.1729	0.0027	0.4847	0.0130	11.56	0.38	2548	56	2586	26
17.2	core	23	11	0.48	0.82	0.1723	0.0063	0.3371	0.0100	8.01	0.40	1873	48	2580	61
5.1	centre	85	63	0.74	0.40	0.1687	0.0032	0.3795	0.0101	8.83	0.30	2074	47	2545	32
4.1	rim	42	29	0.69	0.00	0.1581	0.0017	0.3783	0.0100	8.25	0.25	2068	47	2435	18
19.2	centre	71	58	0.82	0.38	0.1565	0.0026	0.2790	0.0074	6.02	0.20	1586	37	2418	28
19.1	rim	33	21	0.63	6.37	0.1552	0.0080	0.3087	0.0089	6.60	0.41	1734	44	2404	88
10.1	centre	57	37	0.66	0.41	0.1524	0.0027	0.3994	0.0105	8.39	0.28	2166	48	2373	31
17.1	rim	44	29	0.66	0.98	0.1471	0.0037	0.3426	0.0095	6.95	0.28	1899	46	2313	43
18.1	rim	12	4	0.32	1.53	0.1424	0.0087	0.2879	0.0097	5.65	0.42	1631	48	2256	106
6.1	rim	33	20	0.60	0.89	0.1393	0.0045	0.2876	0.0080	5.52	0.25	1629	40	2218	56
16.2	core	68	29	0.42	0.55	0.1336	0.0024	0.3245	0.0084	5.98	0.20	1812	41	2145	32
8.1	centre	15	7	0.50	7.10	0.1289	0.0193	0.2685	0.0098	4.77	0.76	1533	50	2083	267
15.1	centre	52	54	1.03	0.99	0.1270	0.0043	0.2537	0.0069	4.44	0.20	1458	36	2057	60
6.2	centre	60	46	0.77	1.00	0.1260	0.0039	0.2330	0.0062	4.05	0.18	1350	33	2043	55
11.2	core	114	27	0.24	0.46	0.1251	0.0023	0.2338	0.0060	4.03	0.13	1354	31	2030	32
11.1	rim	30	15	0.51	0.84	0.1250	0.0051	0.2905	0.0084	5.01	0.26	1644	42	2028	72
1.2	rim	44	24	0.54	0.29	0.1221	0.0027	0.2559	0.0068	4.31	0.16	1469	35	1987	40
3.2	tip	48	22	0.46	4.55	0.1175	0.0131	0.2764	0.0083	4.48	0.53	1573	42	1918	201

Glenelg inlier s96/41

5.1	core	45	21	0.47	0.63	0.1957	0.0024	0.5401	0.0124	14.57	0.40	2784	52	2790	20
12.1		185	238	1.29	0.19	0.1846	0.0009	0.5186	0.0107	13.20	0.29	2693	45	2695	8
17.1	core	138	81	0.59	0.37	0.1834	0.0012	0.4783	0.0099	12.10	0.27	2520	43	2684	10
15.1		189	209	1.11	0.09	0.1828	0.0008	0.5005	0.0103	12.61	0.27	2616	44	2678	8
10.1		182	60	0.33	0.22	0.1814	0.0009	0.5267	0.0108	13.17	0.29	2728	46	2665	8
11.1		182	22	0.12	0.25	0.1814	0.0009	0.5110	0.0106	12.78	0.28	2661	45	2665	9
1.1	core	32	20	0.61	1.26	0.1802	0.0034	0.4779	0.0116	11.87	0.39	2518	51	2654	31

19.1		147	31	0.21	0.17	0.1780	0.0012	0.4306	0.0090	10.56	0.24	2308	40	2634	11
4.1		348	476	1.37	0.11	0.1767	0.0006	0.4619	0.0093	11.25	0.24	2448	41	2622	6
1.2	rim	1457	463	0.32	0.03	0.1756	0.0003	0.4868	0.0096	11.79	0.24	2557	42	2612	3
16.1		77	86	1.11	0.73	0.1744	0.0019	0.4446	0.0097	10.69	0.27	2371	43	2600	18
1.3	rim	1261	252	0.20	0.05	0.1743	0.0003	0.4653	0.0092	11.18	0.23	2463	41	2599	3
18.1		25	36	1.45	0.92	0.1736	0.0041	0.4648	0.0118	11.12	0.41	2461	52	2592	39
8.1		593	235	0.40	0.09	0.1731	0.0005	0.4577	0.0091	10.93	0.22	2429	40	2588	4
2.1		358	149	0.42	0.15	0.1709	0.0007	0.4619	0.0094	10.88	0.23	2448	41	2566	7
5.2	outer	99	31	0.31	0.51	0.1641	0.0017	0.3781	0.0081	8.56	0.21	2067	38	2499	18
17.2	outer	525	189	0.36	0.05	0.1625	0.0005	0.4470	0.0089	10.01	0.21	2382	40	2482	5
6.2		953	179	0.19	0.06	0.1617	0.0004	0.4313	0.0086	9.62	0.20	2312	39	2474	4
3.1		924	790	0.86	0.08	0.1615	0.0004	0.3914	0.0078	8.71	0.18	2129	36	2471	4
14.1		85	37	0.43	0.77	0.1268	0.0019	0.3600	0.0078	6.30	0.17	1982	37	2055	26
7.1		738	90	0.12	0.13	0.1252	0.0004	0.3575	0.0071	6.17	0.13	1971	34	2032	6
9.1		53	21	0.40	1.29	0.1120	0.0036	0.2360	0.0055	3.64	0.15	1366	28	1832	59
6.1	rim	904	159	0.18	0.10	0.1069	0.0004	0.3089	0.0061	4.55	0.09	1735	30	1747	6
9.2		63	35	0.55	1.57	0.1055	0.0036	0.2388	0.0054	3.48	0.15	1381	28	1724	63
16.2	rim	325	80	0.25	0.15	0.1053	0.0007	0.2873	0.0058	4.17	0.09	1628	29	1720	12
14.2	rim	152	110	0.73	0.47	0.1000	0.0013	0.2641	0.0055	3.64	0.09	1511	28	1624	24
9.3		44	19	0.44	1.68	0.0833	0.0055	0.2016	0.0049	2.32	0.17	1184	26	1277	129

~~Key to spot positions: Unless otherwise stated, analytical spots were centrally located. ‘core’ implies a visible structural core, and ‘rim’ i~~mplies a distinct overgrowth. Otherwise, the terms ‘centre’ and ‘outer’ and/or ‘tip’ are used. ‘patchy’ indicates a domain lacking in concentric growth zonation. Detailed spot locations are unfortunately not available for the Borgie sample.