The late Mesoproterozoic – early Neoproterozoic tectonostratigraphic evolution of northwest Scotland: the Torridonian revisited.

T.C. Kinnaird[1], A.R. Prave[2], C.L. Kirkland[3], M. Horstwood[4], R. Parrish[4,5] and R.A. Batchelor[2]

[1]School of Geosciences, University of Edinburgh, Edinburgh, EH9 3JW, UK
[2]School of Geography and Geosciences, University of St Andrews, Fife, KY16 9AL, UK
[3]Swedish Museum of Natural History, 104 05 Stockholm, Sweden
[4]NERC Isotope Geosciences Laboratory, Keyworth, Nottingham, NG12 5GG, UK
[5]Department of Geology, Leicester University, Leicester, LE1 7RH, UK

ABSTRACT

The Torridonian succession of northwest Scotland comprises three groups, deposited during late Mesoproterozoic to early Neoproterozoic time, the Stoer, Sleat and Torridon. Previous workers have inferred that each was formed in a series of (how can 'each' (singular) be deposited in a series (plural) of basins?) sequential ('sequential'?? see comments on next page) rift basins and is internally conformable. New fieldwork and detrital zircon age data indicate that this model is incorrect and should be abandoned. Our main findings are as follows: (1) the facies characteristics and detrital zircon data for the Sleat Group indicate that it is genetically unrelated to the Torridon Group; (2) the Sleat and Stoer Groups contain features suggestive of deposition in extension-related basins that predate the c. 1.0 Ga Grenville Orogeny; (3) the base of the Applecross – Aultbea succession of the Torridon Group is an unconformity, and (4) the Applecross – Aultbea succession is most objectively interpreted as a non-marine molasse. The significance of this data is that it can be used as a constraint to test and define tectonic models for the deposition of the Torridonian succession and geological evolution of the Scottish Highlands. This will facilitate comparison of Torridonian rocks with successions elsewhere and thereby enable better integration of the Scottish Highlands into Mesoproterozoic – Neoproterozoic Earth history. (The last two sentences sound impressive but what do they actually mean? How has this been demonstrated in the paper? Perhaps best to replace with the last sentence of the conclusions which makes a clear positive statement)

The later Proterozoic tectonic evolution of the British Isles is based largely on the geological framework of the Scottish Highlands in which three major stratigraphic units are recognised, the Torridonian, Moine and Dalradian. Of these, the Torridonian is the least deformed and metamorphosed and as such provides the best opportunity to assess palaeoenvironmental settings and reconstruct palaeogeographies. The term 'Torridonian' refers collectively to the entire

Precambrian sedimentary succession exposed along the northwest coast and islands of Scotland (Fig. 1a). This succession is divided into three groups, the Stoer, Sleat and Torridon (each with its respective formations and members; Fig. 1b). The generally accepted interpretation of these groups is that they record sedimentation in a series of sequential (what do you mean by 'sequential'? it sort of implies to me that you are suggesting a continuous history of rifting, whereas it has been known for a long time that the Stoer is ~200 myr older than the Torridon and different geotectonic scenarios have been suggested for these basins) rift basins (*e.g*. Stewart 1982, 2002; Beacom *et al*. 1999; Jonk *et al*., 2004 (do all these workers refer specifically to 'sequential' rift basins?). This interpretation has been exported to other Neoproterozoic successions located around the present-day North Atlantic region and figures prominently in Proterozoic plate tectonic reconstructions (*e.g*., Soper and England 1995; Dalziel 1997). In this paper we present new stratigraphic observations and U-Pb age data for detrital zircons from various parts of the Torridonian succession to build upon existing work and further refine understanding of its geological development. We conclude that several of the long held inferences regarding the Torridonian are dubious and offer an alternative model for the tectonostratigraphic framework of this part of the Scottish Highlands. This has important implications for understanding not only the Proterozoic geological evolution of Britain but also that of the North Atlantic region as a whole.

Regional setting

The Torridonian succession has been a subject of study for many decades (e.g. Lawson 1965; Jonk *et al*. 2004; Peach *et al*. 1907; Phemister 1948; Nicholson 1993; Rainbird *et al*. 2001; Rodd and Stewart 1992; Stewart 2002; Stewart and Donnellan

1992; Turnbull *et al*. 1996; Van de Kamp and Leake 1997; Williams 2001; Young 2002 references should be in order of age not alphabetical). Stewart (2002) has compiled an exhaustive synthesis of previous work on the Torridonian rocks, including detailed descriptions of many field locations. Like many late Precambrian successions worldwide, this succession is poorly dated. However, field relationships enable a relative stratigraphy to be constructed, though only broad absolute age brackets have been established. Palaeomagnetic data for parts of the succession imply a later (meaning what? be precise!) Proterozoic age for deposition (**Stewart & Irving 1974; Smith et al. 1983;** these are seminal references - this has been known for a lot longer than since 1997! Williams and Schmidt 1997; Darabi and Piper 2004) and detrital zircon studies have provided maximum depositional ages (*e.g*. Rainbird *et al*. 2001).

Of the three Groups, the Stoer is considered the oldest. Exposures of the Stoer rocks are limited to a discontinuous belt from Stoer in the north to Loch Maree in the south (Fig. 1a). They rest nonconformably on Archaean – Palaeoproterozoic Lewisian basement and their upper contact is marked by an angular unconformity with the overlying Torridon Group rocks (Lawson 1965; Stewart 1969). The succession can be as much as *c*. 2 km thick (Stewart 2002). It is comprised of fluvial-alluvial sandstones and sedimentary breccias, with minor lacustrine mudstones and rare carbonates (Stewart 2002). A thin volcanogenic deposit (Stac Fada Member; *e.g.* Lawson 1972*;* Young 2002) makes a good marker unit for correlation. A maximum age for the Stoer Group is provided by a Rb-Sr age of 1187 $\pm$ 35 Ma on chloritised biotite from a gneissic boulder in the lowermost Stoer beds (Moorbath *et al*. 1967) and a Pb-Pb 'depositional' age of 1199 ± 70 Ma on a thin stromatolitic bed low in the group (Turnbull *et al*. 1996). The Stoer's detrital zircon age profile (Rogers *et al*. 1990; Rainbird *et al*. 2001) and composition (Stewart 2002; Young 1999) indicate that sediment was sourced from the underlying Lewisian basement. Thus, given existing data, the depositional age of the Stoer Group is *ca*. 1200 Ma.

The type area of the Sleat Group is the eponymous peninsula of eastern Skye. Outcrops are limited to this island and to two narrow north-trending belts on the adjacent Scottish mainland (Fig. 1a). It is as much as *ca*. 3 km in thickness and consists of fine to locally coarse feldspathic and quartzitic sandstones with varying proportions of shale. The overall vertical facies trend defines a fining-upward succession and the rocks have been interpreted as recording non-marine depositional settings (Stewart 2002). No radiometric ages have been obtained for these rocks. The Sleat and Stoer rocks do not occur in outcrop together, thus their exact stratigraphic relationship is not known. However, because the Sleat Group is assumed to be conformable beneath Torridon rocks (Applecross Formation) on Skye, its depositional age is generally regarded to be similar to that of the Torridon (see below) and thus younger than the Stoer Group (Stewart 2002).

The Torridon Group, the collective term for the Diabaig, Applecross, Aultbea and Cailleach Head Formations, has a combined thickness of 6 - 7 km. The basal Diabaig Formation is only preserved locally within palaeo-topographic lows developed in Lewisian basement. The Applecross and Aultbea Formations are more widespread whilst the Cailleach Head Formation is primarily limited to a single, fault-bounded exposure at the western tip of the eponymous peninsula (Fig. 1a). These units were deposited in a variety of alluvial-fluvial-lacustrine settings with the bulk of the Group consisting of trough and planar cross-bedded, medium to pebbly, arkosic sandstones of the Applecross and Aultbea Formations (Selley 1965; Stewart 2002; Nicholson 1993; Williams 1966, 2001 put refs in proper order). Rocks from the

Torridon Group have yielded detrital muscovite K-Ar and diagenetic Rb-Sr ages ranging from 1168 ± 30 to 997 ± 39 Ma (Moorbath *et al*. 1967; Turnbull *et al*. 1996) and the youngest detrital zircon grain is 1060 ± 18 Ma (Rainbird *et al.* 2001). Diagenetic phosphate concretions in the Diabaig Formation yield a whole rock Rb-Sr isochron age of 994 ± 48 Ma and a Pb-Pb isochron age of 951 ± 120 Ma (Turnbull *et al*. 1996). Hence, the depositional age of the Torridon is most likely earliest Neoproterozoic. In addition, provenances other than the Scottish foreland basement rocks are required to explain the presence of clasts composed of lithologies not found in the Scottish Highlands (such as?) and the diverse detrital zircon age population.

New field observations

Two aspects of Torridonian geology are striking. The first is the lithological monotony of the Applecross – Aultbea Formations, essentially cross-bedded arkosic sandstone and locally pebbly sandstone preserved along 150 km of strike exposure and up to several kilometres in stratigraphic thickness. Detailed facies and palaeocurrent studies (*e.g*. Williams, 2001) have shown diverging sediment transport paths locally, but this is only a moderate variant on the overall sedimentological theme, namely, broadly E-SE-directed sediment transport recording fluvial – alluvial deposition over the entire outcrop belt. The second aspect, in contrast to above, is the lithological diversity exhibited by the other Torridonian units, particularly the Sleat Group and the Diabaig Formation, which are all marked by lateral and/or vertical facies changes (the Cailleach Head Formation is also distinctive but is not discussed here and will be the subject of a forthcoming paper). It is these first-order observations that have driven our curiosity to re-examine these rocks and the nature of the contacts between them.

The contact between the Diabaig and Applecross formations is interpreted to be transitional and thus conformable (Stewart 2002). However, some rather pronounced lithological changes occur across this contact indicating it may not be conformable. The contact between the Diabaig and Applecross formations is well exposed on the shore of the eponymous type area (Figs. 1a & 2). There, the Diabaig displays an overall coarsening- and thickening-upward trend from dark-grey mudstone exhibiting rhythmically alternating and commonly desiccation-cracked laminae into interbedded mudstone and sub-greywacke sandstone. Thin, discontinuous beds of coarser-grained sandstones and carbonate rocks occur locally. In places phosphate nodules are developed and these contain acritarchs (*e.g*. Downie 1962; *Leiosphaerid* forms were identified by A. Knoll, pers. comm., 2002). The upper part of the succession is marked by an increase in the proportion of sandstone beds that are of metre-scale thicknesses, have sharp bases, define tabular to broadly lenticular geometries (over tens of metres) and commonly display ripple-drift cross-lamination. Palaeocurrent data from the rippled linsen- and flaser-bedded units indicate that the main flow component was towards the southwest (Fig. 2). In many places, the Diabaig exhibits an interesting lateral sedimentological changeability, which is well expressed at the type locality (Fig. 2, see also Stewart 2002). There, the basal unit is a variably developed sedimentary breccia shed off palaeo-highs of the Lewisian basement. The breccia beds grade into tabular, red sandstone and these in turn pass laterally and upward into micaceous siltstone and fine sandstone. At Lower Diabaig, all these facies are sharply overlain by the Applecross Formation. It consists of red-grey medium to pebbly arkosic sandstone (the Allt na Bieste member of Stewart 2002) that erodes into the underlying Diabaig rocks; sandstones above this contact contain abundant, irregularly shaped (‘rip-up’) clasts derived from the Diabaig units. Interestingly, pebbles (e.g. types?) in the Diabaig rocks can be attributed to mostly local sources whereas numerous varieties in the Applecross sandstones (e.g. types?) were derived from provenances not known within the foreland area of the Scottish Highlands (Selley 1965; Rodd and Stewart 1992; Stewart 2002). Thus, this contact marks a sharp change in facies and in clast provenance compositions. Additionally, the contact also defines a difference in petrography and diagenetic histories. Rodd and Stewart (1992) and Van de Kamp and Leake (1997) documented differences in the relative abundances of plagioclase (2:1 Diabaig:Applecross), K-feldspar (1:4 – 1:3) and mica (8:1). Our observations (from samples collected in the vicinity of Loch Torridon) indicate very similar findings with relative abundances of plagioclase (4:1), K-feldspar (1:3) and mica (10:1). At Lower Diabaig, the pore-fill cement is comprised predominantly of illite and sericite, with authigenic chlorite (developed partly by the alteration of plagioclase, as indicated by relict feldspar) and as interstitial matrix between framework grains. In contrast, the Applecross sandstone cement consists mainly of syntaxial overgrowths of quartz and K-feldspar, with minor albite. Diagenetic chlorite and limonitic oxide are present in the Diabaig whereas these minerals are absent in the adjacent Applecross sandstone, despite it containing the correct mineral constituents for such a reaction. Applecross samples within 30 stratigraphic metres of the Diabaig – Applecross boundary have undergone weak pressure dissolution, which has sutured the quartz grain contacts. This fabric is absent from the Diabaig Formation.(So, what does this mean and why?? This needs spelling out clearly – at present you have just reported some observations but not drawn any conclusions. What contrasting diagenetic temperatures are implied?)

As well as the dissimilarity of facies and composition between the Applecross and Diabaig units, the contact between these two formations commonly displays erosive channelling, marks a sharp increase in grain size, and in many places a slight angular discordance between the two formations can be discerned. For example, at the Diabaig type locality, and at Inveralligin, the discordance is 4°-7° across the contact (Fig. 2). One could argue that this may reflect a difference in the initial dip of the Diabaig and Applecross rocks and/or differential compaction. However the fact that the basal Applecross sandstones typically rest sharply and erosively across all facies of the Diabaig Formation, in combination with the differences noted above, questions the assumption of a conformable, transitional contact between these formations.

The Sleat Group is best developed on Skye (Fig. 1a) where it consists of four formations; in ascending order, the Rubha Gail, Loch na Dal, Beinn na Seamraig and Kinloch Formations (Fig. 1b; Stewart 1988b, 1991, 2002; Sutton and Watson 1964 order of refs!). The basal 'Torridon' unit on Skye is the Applecross Formation. The contact between the Sleat and Torridon rocks is nowhere well exposed but has nevertheless been assumed to be conformable (Stewart 1988b, 2002). This is questionable for a number of reasons. The Applecross and Sleat rocks display a number of facies differences (*e.g.*, coarser vs. finer grained, thicker, lenticular beds vs. thinner, more tabular beds, absence vs. presence of interbedded shale, respectively) and the contact between the two groups is discordant, an aspect noted decades ago in that the strike of beds of the upper Sleat rocks: "…*are oblique to the general north-easterly trend of the Applecross/Kinloch boundary*" (Sutton and

Watson 1964, p. 266). These features were explained as representing a lateral facies change (*e.g*. Stewart 2002), but such an inference is unsupportable given the genuinely different lithologies, compositions and inferred palaeoenvironmental settings between the basal Applecross and upper Sleat units. Furthermore, even though the general dip of both the Sleat and Applecross units on Skye is moderately westward, there is an overall difference in attitude between these two units (Fig. 3). Consequently, like the Diabaig – Applecross boundary, the Sleat – Applecross contact is not unambiguously conformable. In fact, taken objectively, these contacts would appear to be potential candidates for unconformities.

Detrital zircon analyses

Detrital zircon age profiling has become a widely used stratigraphic tool of choice to assess not only provenance issues but also as a means of stratigraphic fingerprinting of units to independently test correlations and depositional frameworks (Rainbird *et al.* 2001; Cawood *et al*. 2003; Kirkland *et al.* 2006a; Soper *et al*. 1998 did the last paper use detrital zircon geochronology to any extent??). In order to apply this tool, we have collected samples from Torridonian rocks to compare and contrast their detrital zircon age distributions. Rogers *et al*. (1990) and Rainbird *et al*. (2001) have provided an ample dataset for the Stoer and Applecross – Aultbea units, thus we focussed our efforts on the other units.

Sample Preparation

Samples were collected from each of the major units (but you have’nt sampled the Applecross and Aultbea, have you?) defining the Torridonian succession (see Tables 1 and 2). Each sample was crushed individually and sieved using standard mineral preparation procedures. Heavy minerals were concentrated using a Wilfley table prior to settling through tetra-bromoethane for separation of the heavy mineral concentrate, which was subsequently washed in acetone and dried. Zircons were separated initially by paramagnetic behaviour using a Franz isodynamic separator and then hand-picked from the non-magnetic and least-magnetic fractions. The zircon separates were mounted in an araldite resin block, polished, and then examined using a scanning electron microprobe. Cathodluminescence (CL) images of all zircons were taken and used to target discrete domains

Analyses

Laser ablation geochronology (LA-MC-ICP-MS) was conducted at the NERC Isotope Geosciences Laboratory using procedures outlined by Horstwood *et al*. (2003) (Table 1). This included a correction for common-Pb based on the measurement of ^{204}Pb, using an electron multiplier. Analyses used a Thermo-Elemental Axiom MC-ICP-MS coupled to a New Wave Research LUV266X Nd:YAG laser ablation system. A $^{205}Tl/^{235}U$ solution was simultaneously aspirated during analysis to correct for instrumental mass bias and plasma induced inter-element fractionation using a Cetac Technologies Aridus desolvating nebuliser. On one dataset (the Rubha Guail Formation, Sleat Group; Table 2) single abraded zircons were analysed by Thermal Ionisation Mass Spectrometry (TIMS) following the procedure outlined in Parrish and Noble (2003), Parrish *et al*. (1987) and Noble *et al*. (1993) using a ^{205}Pb - ^{233}U - ^{235}U tracer.

Data were reduced and errors propagated using an in-house spreadsheet calculation package, with ages determined using the Isoplot 3 macro of Ludwig (2003). All dates quoted, unless otherwise stated, are U/Pb ages. Frequency distribution plots were constructed using the spreadsheet of Sircombe (2004). We do not switch between U/Pb and Pb/Pb ages in the frequency distribution plot e.g. at 1500Ma, as U/Pb ages are concordant and the age errors are reasonable. Data used in cumulative probability plots (Fig. 4) are presented in Tables 1 and 2. Only data less than 10% discordant are used in placing age constraints.

Stoer Group

U-Pb LA-MC-ICP-MS ages were obtained from 23 analyses on detrital zircons from sandstones of the Stoer Group (Fig. 4; Table 1). Of these, 16 were concordant. The age distribution profile of detrital zircons is largely bimodal and dominated by Archean ages with a main peak at *c*. 2.8 Ga. A smaller cluster occurs at *c.* 1.9 Ga. We acknowledge that this is a small data set, but as Andersen (2005) has shown, small datasets can still yield important information. For 16 measured ages, only detrital populations more abundant than c. 15% will exceed the detection limit at the 0.95 confidence level (Andersen 2005). Hence, each zircon population recognized in our dataset by one or more grains is likely to be an important constituent of the sediment. The peaks we identified at *c*. 2.8 and 1.9 Ga, correlate with the zircon distribution documented by Rainbird *et al*. (2001) (Fig. 4).

Sleat Group

U-Pb LA-MC-ICP-MS ages were obtained from 20 different single zircon grains from sandstones of the basal Rubha Guail Formation (Table 1). A further 14 U-Pb ages were obtained using TIMS (Table 2). Of these, 28 were concordant and define two main clusters of ages (Fig. 4). The dominant zircon population yields Archaean ages between *c*. 2.8 – 2.5 Ga and a second subpopulation of grains yields ages between *c*. 2.0 – 1.7 Ga.

In contrast, the detrital zircon age distribution for the combined Loch na Dal and Kinloch Formations is quite different. This distribution is based on 30 concordant analyses (out of 54) obtained using LA-MC-ICP-MS. The profile exhibits a broad, multi-peaked spectra spanning *c*. 2.0 – 1.2 Ga. A single detrital zircon is discordant but has a $^{207}Pb/^{206}Pb$ age of 2823 ± 51 Ma which represents a minimum age for the grain. The youngest concordant grain is 1247 ± 17 Ma from the Kinloch Formation. The Kinloch Formation zircon crystals have a diversity of shapes, internal structures and surface textures ranging from prismatic crystals to sub-rounded stubby grains. Both oscillatory and radial zoning is present and several grains have inclusions, but distinguishing Palaeoproterozoic from Mesoproterozoic grains is ambiguous.

Torridon Group: Diabaig Formation

U-Pb LA-MC-ICP-MS ages were obtained from 16 zircon grains from micaceous siltstones and fine sandstones of the Diabaig Formation (Fig. 4). Of these, 10 were concordant. This is a very small sample size and we acknowledge its statistical limitations. However if the method of Andersen (2005) is applied again, we would expect clusters at *c*. 2.8, 1.8, 1.6 and 1.1 Ga to be important constituents of a larger detrital zircon profile and one that is similar to the Applecross – Aultbea profile but much different to the Sleat rocks. Detrital zircons in this sample have a diversity of shape. The Archaean 'subset' includes fragments of prismatic grains and sub-rounded equant grains. CL imaging also shows a variety of growth characteristics, from oscillatory zoning to un-zoned. Surface textures vary from clear to strongly pitted (the latter is more prevalent in the older grains). The youngest grain is of late

Mesoproterozoic age (1092 ± 17 Ma). It is a pale brown, sub-rounded fragment that in the dated part of the crystal exhibits magmatic idiomorphic zoning. It is overgrown by a CL dark rim that may be metamorphic in origin.

Torridon Group: Applecross – Aultbea Formations

U-Pb ages on detrital zircons for these formations have been provided by Rainbird *et al*. (2001) and we reproduce those data here (Fig. 4). It is an extensive dataset, in total 82 analyses were taken, and all are within 10% concordance. Three clusters are indicated: Archaean ages between *c*. 3.1 – 2.7 Ga; late Palaeoproterozoic to earliest Mesoproterozoic ages grouped between *c*. 2.0 – 1.6 Ga; and late Mesoproterozoic ages between *c*. 1.3 – 1.1 Ga. The Archaean 'subset' of grains range in shape, from sub-rounded stubby prisms to well-rounded equivalents. CL imagining reveals two distinct morphologies ~ flat, dark cores and oscillatory zoned cores (Rainbird et al 2001). The late Palaeoproterozoic to earliest Mesoproterozoic grains have a diversity of shapes, from sub-rounded to rounded stubby prisms to sub-rounded irregular grains to rarer, sharply facetted squat prisms. Surface textures also vary from clear to strongly pitted. CL imaging, though, illustrates that all have similar growth characteristics (*e.g*. Rainbird *et al*. 2001). Late Mesoproterozoic grains are rounded, brown to buff coloured and several show diffuse zoning in CL (Rainbird et al 2001).

Discussion

The Sleat Group rocks yield two dissimilar detrital zircon profiles. The lower Sleat profile (Rubha Guail Formation) displays distinct Archaean and late Palaeoproterozoic clusters; in many respects it is similar to the Stoer Group profile.

In contrast, the upper Sleat profile (Loch na Dal through Kinloch Formations) is characterised by a dominance of late Palaeoproterozoic and early Mesoproterozoic zircons. Archaean detrital grains are either absent (the Kinloch sample) or constitute only a small percent of the final spectrum (the Loch na Dal sample). It is not surprising that the 'lower' Sleat profile is dominated by Lewisian-aged zircons given its 'local' derivation from Lewisian basement. What is interesting, though, is that the 'upper Sleat' zircons are strongly dominated by late Palaeoproterozoic ages with the youngest grain being of mid-Mesoproterozoic age, 1247 ±17 Ma. This is not the case for the overlying Torridon rocks in which grains younger than *c*. 1.2 Ga are present. Thus, the age distribution of detrital zircons from the Sleat Group is substantially different to the Applecross Formation, implying that the two units were derived from different source areas. Furthermore, there is a *c*. 200 Ma age difference between the youngest detrital grains in the Sleat rocks (1247 ±17 Ma) and the Applecross Formation (1060 ± 18 Ma). Although this is not an absolute reflection in difference of depositional ages (especially considering the low number of the Sleat analyses), when combined with the discordant attitudes and facies differences between the two formations, it is consistent with our interpretation that the base of the Applecross Formation is an unconformity.

The Diabaig detrital zircons yield Archaean (2.9 - 2.7 Ga) and Palaeoproterozoic (1.9 - 1.6 Ga) clusters. The youngest grain has an age of *c*. 1090 Ma. Given the small sample size for the Diabaig, we are cautious in drawing strong conclusions. Nevertheless, unlike the Sleat profile, the Diabaig's is similar to the Applecross Formation profile. The Diabaig is generally inferred to be a 'distal' portion of the Applecross depositional system thus it follows logically that the age profiles should be similar. However, as noted previously the base of the Applecross marks a surface of erosion which emplaces relatively coarse, braided fluvial rocks onto much finer-grained lacustrine and lacustrine-margin Diabaig strata. Thus, this contact is a prime candidate for being a major sequence boundary and suggests that the Applecross depositional system was most likely genetically distinct from that of the Diabaig.

Rift basin settings for each of the Torridonian Groups have been championed for the past two decades (*e.g*. Stewart 2002 Pavlovski 1958 was the first to suggest this – see reference in 'Geology of Scotland'). It is noteworthy, though, that not a single basin-bounding extensional fault has been identified in outcrop, all such faults are purely hypothetical or inferred to be hidden beneath the Minch seaway between the Scottish mainland and Outer Hebrides. Seismic lines have been suggested to image potential candidates (*e.g*. Smythe *et al*. 1982; Blundell *et al*. 1985; Stein and Blundell, 1990) but it is interesting to note that these inferred basin-bounding faults are shown cutting the entire Torridon succession, thus, for the most part they must post-date those rocks. Nevertheless, focussing on what can be observed, two aspects are noteworthy: (i) with the exception of the thin Stac Fada Member of the Stoer Group, no rift-related volcanism or significant volcaniclastic detritus is known within the Torridonian; and (ii) the main part of the Torridon exhibits a remarkable consistency of facies character along its +150 km of strike length and +4 km of stratigraphic thickness. With respect to the former, in the mid-continent Mesoproterozoic rift system exposed in the Lake Superior Region, USA, volcanic rocks are as much as *c*. 20km thick (Ojakangas *et al*. 2001). Hence, it is justified to critically re-evaluate the evidence upon which interpretations for rifting are based.

The Stoer Group is interpreted as recording sedimentation in a rift graben with intermittently active margin faults (Stewart 1988a; Van de Kamp and Leake 1997).

Beacom *et al*. (1999) proposed a variant to this by suggesting that rifting (and the subsequent deposition of the Stoer) occurred under broadly north-south oriented dextral transtension. Whichever is more correct, what is immediately obvious is that the facies characteristics of the Stoer rocks support an interpretation for sedimentation during extensional tectonism; laterally and vertically variable coarse- to fine-grained facies, clasts mostly locally derived, palaeocurrent indicators displaying reversals and local variability, interfingering between alluvial-fluvial and lacustrine units and, albeit thin, the presence of a mafic volcanogenic unit. These features are similar to those documented in many sedimentary basins elsewhere that formed in continental extensional settings (*e.g.* Friedmann and Burbank 1995; Leeder and Gawthorpe 1987; Schlische 1991 order of refs). In that the Stoer basin(s) was developed on Lewisian basement, the detrital zircon data yield a profile reflecting characteristic Archaean and Palaeoproterozoic clusters. These data are consistent with previously obtained geochemical data indicating that sediment was derived from local provenances (Stewart 2002, and references therein).

The Sleat Group rocks similarly have facies characteristics typical of sedimentary successions formed in continental extensional basins, namely, rather rapid lateral and vertical changes between coarser and finer grained lithologies representing various components of alluvial-fluvial-lacustrine systems (*e.g*. Stewart 2002). The detrital zircon profile of the lower Sleat rocks fits a Lewisian derivation but the late Palaeoproteorozoic – early Mesoproterozoic ages that dominate the upper Sleat profile show that source areas outside the Scottish foreland were contributing detritus during the later stages of basinal evolution. This supports the inference of previous workers who suggested that basinal overstepping occurred following an initial phase of Sleat ‘rifting’ (e.g. Nicholson 1993).

In striking contrast is the Torridon Group, in particular the Applecross-Autlbea rocks. These rocks do not display features typical of deposits in active rift basins developed in continental crust, a fact pointed out over a decade ago by Nicholson (1993). Their stratigraphic monotony of kilometre after kilometre of cross-bedded arkoses and pebbly arkoses with relatively low palaeocurrent variance for thousands of metres of vertical section is not a facies feature readily attributable to active continental rifting and half-graben basins. Thus, the puzzling observation is that, even though all of the Torridonian Groups were purportedly deposited in similar rift basin settings (*e.g*. Stewart 1982, 1988a,b, 2002), the Torridon is unlike the Sleat and Stoer. Jonk et al. (2004) in a study of Lewisian- and Torridonian-hosted clastic dykes at Gairloch, speculated that the dykes formed under ESE-WNW directed extension and that they developed during deposition of the upper Torridon Group, This evidence was used to promote the idea of north to NE trending faults in the area, not only during the onset of Torridonian sedimentation (Soper and England 1995; Beacon *et al*. 1999 but how can a paper written in 2004 influence ideas in papers that preceded it?), but throughout Torridonian times. However, no evidence of significant extensional faulting is recorded in the Applecross Formations. Thus, our conclusion, like that of Nicholson (1993) and Rainbird *et al*. (2001), is that there is no objective evidence to support the Applecross – Aultbea sequence being a rift basin fill. Instead, the facies characteristics of these rocks are better interpreted as a fluvial-alluvial apron whose genesis can be attributed to the erosional denudation of the Grenville orogenic highlands, *i.e.* a non-marine molasse. Such an interpretation is also consistent with the detrital zircon profile.

Advocates of a rift setting for the Torridonian are rather dismissive of a molasse interpretation (*e.g*. Stewart 2002). However, as discussed above many of the arguments for a solely rift-related genesis are equivocal and criticisms against a molasse-style setting are not convincing. For example, the most common criticism is that, given that the Grenville orogenic belt lay southwest of the Torridonian outcrop, the southeast-directed palaeocurrent trends of the Applecross – Aultbea rocks are incompatible as a molasse (refs?). This is readily dismissed. Many fluvial systems (modern and ancient) flow initially orthogonal to the orogenic front and then veer towards basin axial (or orogenic-front-parallel) directions. For the Torridon example, the SE-directed Applecross – Aultbea system would represent the axial component. At this point it is worth noting that the preserved width of the Torridon outcrop belt (a few 10's of kilometres) is miniscule compared to the scale of the depositional systems that the Applecross – Autlbea rocks are inferred to represent, thus palaeogeographic reconstructions are inescapably speculative. The inferred timing of deposition also casts doubt on the interpretation of a rift-dominated tectonic setting for those rocks. Although a direct depositional age is lacking, given the bracketing age constraints provided by detrital zircon and diagenetic ages, the Torridon was likely deposited *c*. 1000 Ma. Global tectonic reconstructions show that this was a time near the zenith to waning phases of supercontinental amalgamation (Grenville Orogeny) and that break-up did not begin until later (*e.g*. Cawood 2005; Dalziel 1997). Consequently, the interpretation that most objectively fits the available evidence is that the Applecross – Aultbea rocks are a remnant of what would have been a much larger, non-marine molasse shed off the rising eroding Grenville highlands.

Like better-dated and constrained successions of largely non-marine strata elsewhere (both Phanerozoic and Proterozoic examples), the Torridonian successions can now be examined in light of realistic depositional frameworks in which hiatal surfaces are a common component punctuating sequences thousands of metres thick. Our data show that the base of the Applecross is best viewed as a compound surface that defines a major unconformity where it rests on the Lewisian, Stoer and Sleat rocks and a less significant hiatal surface (sequence boundary) where it rests on the Diabaig Formation. This indicates that, rather than being a conformable succession, the Torridonian is actually a composite sequence of temporally unrelated and genetically distinct units.

Thus, we need to re-evaluate how the units fit within the framework of the late Mesoproterozoic Grenville orogenesis, which is known to have affected the length of eastern Laurentia (Gower 1996; Dalziel 1997; Strachan and Holdsworth 2000; Rivers and Corrigan 2000; Dalziel and Soper 2001; Kirkland *et al*. 2006a,b are these references all the most appropriate?). The Stoer, Sleat and Diabaig rocks record deposition that is genetically unrelated to the Applecross – Aultbea succession. Considering our data in context of known global tectonic events, then the Stoer and Sleat rocks are reasonably interpreted as recording a phase of crustal extension perhaps driven by far-field stresses associated with the *c*. 1.23 – 1.18 Elzevirian Orogeny (Gower 1996; Rivers and Corrigan 2000; Gower and Krough 2002). As argued above, the Applecross - Aultbea rocks are best interpreted as the deposits of a late- to post-Grenvillian foreland trunk river system that flowed axially with respect to the orogenic belt (Rainbird *et al*. 2001). Young (1999) suggested that the deposition of the Applecross – Aultbea rocks might be associated with the collapse of the Grenville orogen. Syn- to post-orogenic extension is inferred to have followed the Grenville orogeny through a combination of orogenic collapse and/or mantle delamination (Streepy *et al*. 2000), but it remains to be established if the depositional age of the preserved Torridon units is coeval with orogenic collapse.

Conclusion

Our data have shown that the existing stratigraphic framework and the inferred basinal evolution of the Torridonian succession needs to be revised to account for the presence of previously unrecognised and/or under-appreciated unconformities within what have been generally considered to be conformable successions. The most significant of these is the base of the Applecross – Aultbea succession, which is everywhere an unconformity. We propose that a more correct and insightful late Mesoproterozoic through early Neoproterozoic tectonostratigraphic framework of the Highlands is: (1) deposition of the Stoer and Sleat Groups in extension-related sedimentary basins: existing age constraints and the detrital zircon age spectra of these rocks imply derivation from Archaean through early Mesoproterozoic sources with no input from late Mesoproterozoic ('Grenvillian') components and it is likely that both Groups are pre-1200 Ma in age; (2) deposition of the Diabaig rocks during the latest Mesoproterozoic and/or earliest Neoproterozoic, in lacustrine and lacustrine-margin settings after *c*. 1090 Ma, and (3) deposition of the Applecross – Aultbea succession as a late- to post-Grenville Orogeny non-marine molasse that accumulated after *c*. 1060 Ma. Consequently, each of the major Proterozoic sedimentary successions in the foreland of the Scottish Highlands, the Stoer, Sleat and Torridon, can now be viewed as being bounded by unconformities and temporally and genetically unrelated to each other. In that the detrital zircon profiles do not provide depositional ages it is difficult to estimate the temporal magnitude, but it is plausible that the hiatus along the Sleat – Applecross contact may be of the order of many 10^6 years or more and that of the Diabaig – Applecross as much as a couple of 10^6 years. Consequently, the view that the Torridonian rocks record deposition in a suite?? of long-lived sequential ?? rifts, whilst the rest of the consanguineous Laurentian margin experienced collisional and orogenic episodes (*e.g*. Rivers and Corrigan 1999), becomes equivocal and in need of reassessment, if not outright abandonment.

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References:

ANDERSEN, T. 2005. Detrital zircons as tracers of sedimentary provenance: limiting conditions from statistics and numerical simulation. *Chemical Geology,* **216**, 249-270.

BEACOM, L.E., ANDERSON, T.B. and HOLDSWORTH, R.E. 1999. Using basement-hosted clastic dykes as syn-rifting palaeostress indicators: an example from the basal Stoer Group, northwest Scotland. *Geological Magazine*, **136**, 301-310.

BLUNDELL, D.J., HURICH, C.A. and SMITHSON, S.B. 1985. A model for the MOIST seismic reflection profile, N. Scotland. *Journal of the Geological Society, London,* **142**, 245-258.

CAWOOD, P.A., NEMCHIN, A.A., SMITH, M. and LOEWY, S. 2003. Source of the Dalradian Supergroup constrained by U-Pb dating of detrital zircons and implications for the East Laurentian margin. *Journal of the Geological Society, London.* **160**, 231-246.

CAWOOD, P.A. 2005. Terra Australis Orogen: Rodinia breakup and development of the Pacific and Iapetus margins of Gondwana during the Neoproterozoic and Palaeozoic. *Earth Science Reviews*, **69**, 249-279.

DALZIEL, I.W.D. 1997. Overview: Neoproterozoic – Palaeozoic geography and tectonics: review, hypothesis, environmental speculation. *Geological Society of America Bulletin,* **109**, 16-42.

DALZIEL, I.W.D. and SOPER, N.J. 2001. Neoproterozoic extension on the Scottish promontory of Laurentia: paleogeographic and tectonic implications. *Journal of Geology*, **109**, 299-317.

DARABI, M.H. and PIPER, J.D. 2004. Palaeomagnetism of the (Late Mesoproterozoic) Stoer Group, northwest Scotland: implications for diagenesis, age and relationship to the Grenville Orogeny. *Geological Magazine*, **141**, 15-39.

DOWNIE, C. 1962. So-called spores from the Torridonian. *Proceedings of the Geological Society, London*, **1600**, 127-128.

FRIEDMANN, S.J. and BURBANK, D.W. 1995. Rift basins and supradetachment basins: intracontinental extensional end members. *Basin Research*, **7**, 109-127.

GOWER, C.F. 1996. The evolution of the Grenville Province in eastern Labrador, Canada. In *Precambrian crustal evolution in the North Atlantic region, Geological Society.* Eds. Brewer, T.S. *Special Publication,* **112**, 197-218.

GOWER, C.F. and KROGH, T.E. 2002. A U-Pb geochronological review of the Proterozoic history of the eastern Grenville Province. *Canadian Journal of Earth Science*, **39**, 795-829.

HORSTWOOD, M.S.A., FOSTER, G.L., PARRISH, R.R., NOBLE, S.R. and NOWELL, G.M. 2003. Common-Pb corrected *in-situ* U-Pb accessory mineral geochronology by LA-MC-ICP-MS. *Journal of Analytical Atomic Spectrom*, **18**, 837-846.

JONK, R., KELLY, J. and PARNELL, J. 2004. The origin and tectonic significance of Lewisian- and Torridonian-hosted clastic dykes near Gairloch, NW Scotland. *Scottish Journal of Geology*, **40**, 123-130.

KIRKLAND, C.L., DALY, J.S., and WHITEHOUSE, M.J. 2006a. Provenance and terrane evolution of the Kalak Nappe Complex, Norwegian Caledonides: implications for Neoproterozoic palaeogeography and tectonics. *Journal of Geology*. In press.

KIRKLAND, C.L., DALY, J.S., and WHITEHOUSE, M.J. 2006b. Granitic magmatism of Grenvillian age in Finnmark: Constraining pre-Scandian deformation in the Kalak Nappe Complex. *Precambrian Research.* ***145**, 24-52.*

LAWSON, D.E. 1965. Lithofacies and correlation within the lower Torridonian. *Nature,* **207**, 462-465.

LAWSON, D.E. 1972. Torridonian volcanic sediments. *Scottish Journal of Geology,* **8**, 345-362.

LEEDER, M.R. and GAWTHORPE, R.I. 1987. Sedimentary models for extensional tilt-block/half-graben basins, in Coward, M.P., Dewey, J.F. and Hancock, P.L., eds., Continental extensional tectonics. *Journal of the Geological Society, London, Special Publication,* **28**, 139-152.

LUDWIG, K.R. 2003. Isoplot 3, A Geochronological toolkit for Microsoft Excel. Berkeley Geochronology Centre Special Publication No.**1a**.

MOORBATH, S., STEWART, A.D., LAWSON, D.E. and WILLIAMS, G.E. 1967. Geochronological studies on the Torridonian sediments of northwest Scotland. *Scottish Journal of Geology,* **3**, 389-412.

NICHOLSON, P.G. 1993. A basin reappraisal of the Proterozoic Torridon Group, northwest Scotland. *Special Publication of the International Association Sedimentologists,* **20**, 183-202.

NOBLE, S.R., TUCKER, T.C. and PHARAOH, T.C. 1993. Lower Palaeozoic and Precambrian igneous rocks from eastern England, and their bearing on late

Ordovician closure of the Tornquist Sea: constraints from U-Pb and Nd isotopes. *Geological Magazine*, **130**, 835-846.

OJAKANGAS, R.W., MOREY, G.B. and GREEN, J.C. 2001. The Mesoproterozoic Midcontinent Rift System, Lake Superior Region, USA. *Sedimentary Geology*, **141-142**, 421-442.

PARRISH, R.R. and NOBLE, S.R. 2003. Zircon U-Pb geochronology by isotope dilution-thermal ionisation mass spectrometry (IDTIMS). In: HANCHAR, J.M. and HOSKIN, P.W.O. (eds) Zircon. *Reviews in Mineralogy and Geochemistry, Mineralogical Society of America and Geochemial* Society, **53**, 183-213.

PARRISH, R.R., RODDICK, J.C., LOVERIDGE, W.D. and SULLIVAN, R.W. 1987. Uranium-lead analytical techniques at the geochronology laboratory. *Special paper – Geological Association of Canada*, **87-2**, 3-7.

PEACH, B.N., HORNE, J., GUNN, W., CLOUGH, C.T. and HINXMAN, L.W. 1907. The geological structure of the Northwest Highlands of Scotland. *Memoirs of the Geological Survey of Great Britain.*

PHEMISTER, J. 1948. British Regional Geology: Scotland. The Northern Highlands. *Department of Scientific and Industrial Research. Geological Survey and Museum.*

RAINBIRD, R.H., HAMILITON, M.A. and YOUNG, G.M. 2001. Detrital zircon geochronology and provenance of the Torridonian, NW Scotland. *Journal of the Geological Society, London*, **158**, 15-27.

RODD, J.A. and STEWART, A.D. 1992. Geochemistry, weathering and diagenesis of the Diabaig formation (Torridon group) in NW Scotland. *Scottish Journal of Geology,* **28**, 27-35.

ROGERS, G., KROGH, T.E., BLUCK, B.J. and KWOK, Y.Y. 1990. Provenance of the Torridonian sandstone of NW Scotland using single grain U-Pb analysis. *Geological Society of Australia, Abstracts*, **27**, 84.

RIVERS, T. and CORRIGAN, D. 2000. Convergent margin on southeastern Laurentia during the Mesoproterozoic: tectonic implications. *Canadian Journal of Earth Science*, **37**, 359-383.

SCHLISCHE, R.W. 1991. Half-graben filling models: Implications for the evolution of continental extensional basins. *Basin Research*, **3**, 123-141.

SELLEY, R.C. 1965. Diagenetic characteristics of fluviatile sediments of the Torridonian Formation (Precambrian) of northwest Scotland. *Journal of Sedimentary Petrology,* **35**, 366-380.

SIRCOMBE, K.N. 2004. Age display: and EXCEL workbook to evaluate and display univariate geochronological data using binned frequency histograms and probability density distributions. *Computers & Geosciences,* **30**, 21-31.

SMYTHE, D.K., ROBINSON, A., MCQUILLAN, R., BREWER, J.A., MATTHEWS, D.H., BLUNDELL, D.J. and KELK, B. 1982. Deep structure of the Scottish Caledonides revealed by the MOIST reflection profile. *Nature*, **299**, 383-340.

SOPER, N.J. and ENGLAND, R.W. 1995. Vendian and Riphean Rifting in NW Scotland. *Journal of the Geological Society, London*, **152**, 11-14.

SOPER, N.J., HARRIS, A.L. and STRACHAN, R.A. 1998. Tectonostratigraphy of the Moine Supergroup: a synthesis. *Journal of the Geological Society, London,* **155**, 13-24.

STEIGER, R.H. and JÄGER, E. 1977. Subcommission on geochronology: convention on the use of decay constants in geo- and cosmo-chronology. *Earth and Planetary Science Letters*, **1977**, 359-262.

STEIN, A.M. and BLUNDELL, D.J. 1990. Geological inheritance and crustal dynamics of the northwest Scottish continental shelf. *Tectonophysics*, **173**, 455-467.

STEWART, A.D. 1966. An unconformity in the Torridonian. *Geological Magazine,* **103**, 462-465.

STEWART, A.D. 1969. Torridonian rocks of northwest Scotland reviewed. In: *North Atlantic: Geology and Continental Drift.* Edited by Kay, M. *American Association of Petroleum Geologists,* **12**, 595-606.

STEWART, A.D. 1982. Late Proterozoic rifting in NW Scotland: the genesis of the Torridonian. *Journal of the Geological Society, London*, **139**, 413-420.

STEWART, A.D. 1988a. The Stoer Group, Scotland. In: *Later Proterozoic stratigraphy of the northern Atlantic region.* Edited by Winchester, J. A. *Blackie*, 97-103.

STEWART, A.D. 1988b. The Sleat and Torridon Groups. In: *Later Proterozoic stratigraphy of the northern Atlantic region.* Edited by Winchester, J. A. *Blackie*, 104-112.

STEWART, A.D. 1991. Geochemistry, provenance and palaeoclimate of the Sleat and Torridon groups in Skye. *Scottish Journal of Geology*, **27**, 81-95.

STEWART, A.D. 2002. The later Proterozoic Torridonian rocks of Scotland; their sedimentology, geochemistry and origin. *Geological Society Memoirs*, **24**. London, Bath: Geological Society of London.

STEWART, A.D. and DONNELAN, N.C.B. 1992. Geochemistry and provenance of red sandstones in the Upper Proterozoic Torridon Group in Scotland. *Scottish Journal of Geology*, **28**, 143-153.

STRACHAN, R.A. and HOLDSWORTH, R.E. 2000. Proterozoic sedimentation, orogenesis and magmatism on the Laurentian craton (2500-750Ma). *In:* 'Geological

History of Britain and Ireland'. Eds. Woodcock, N. and Strachan, R. *Blackwell Science.*

STREEPY, M.M., VAN DER PLUIJM, B.A., ESSENE, E.J., HALL, C.M. and MAGLOUGHLIN, J.F. 2000. Later Proterozoic (ca. 930 Ma) extension in eastern Laurentia. *Geological Society of America Bulletin*, **112**, 1522-1530.

SUTTON, J, and WATSON, J.V. 1964. Some aspects of Torridonian stratigraphy in Skye. *Proceedings of the Geologists Association,* **75**, 251-289.

TURNBULL, M.J.M., WHITEHOUSE, M.J. and MOORBATH, S. 1996. New isotopic age determinations for the Torridonian, NW Scotland. *Journal of the Geological Society, London*, **153**, 955-964.

VAN DE KAMP, P.C. and LEAKE, B.E. 1997. Mineralogy, geochemistry and sodium metasomatism of Torridonian rift basin clastic rocks, NW Scotland. *Scottish Journal of Geology,* **33**, 103-124.

WILLIAMS, G.E. 1966. Palaeogeography of the Torridonian Applecross Group. *Nature,* **209**, 1303-1306.

WILLIAMS, G.E. 1968. Torridonian weathering, and its bearing on Torridonian palaeoclimate and source. *Scottish Journal of Geology,* **4**, 164-168.

WILLIAMS, G.E. 1969. Characteristics and origin of a Precambrian pediment. *Journal of Geology*, **77**, 183-207.

WILLIAMS, G.E. 2001. Neoproterozoic (Torridonian) alluvial fan succession, northwest Scotland, and its tectonic setting and provenance. *Geological Magazine,* **138**, 471-494.

WILLIAMS, G.E. and SCHMIDT, P.W. 1997. Palaeomagnetic dating of the sub-Torridon Group weathering profiles, NW Scotland: verification of Neoproterozoic palaeosols. *Journal of the Geological Society, London,* **154**, 987-997.

YOUNG, G.M. 1999. Some aspects of the geochemistry, provenance and palaeoclimatology of the Torridonian of NW Scotland. *Journal of the Geological Society, London,* **156**, 1097-1111.

YOUNG, G.M. 2002. Stratigraphy and geochemistry of volcanic mass flows in the Stac Fada Member of the Stoer Group, Torridonian, NW Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences,* **93**, 1-16.

Figure captions:

Figure 1: (a) Generalised geological map of northwest Scotland showing the distribution of the Torridonian units. (b) Stratigraphy of the Torridonian succession (after Stewart 1966, 2002; Lawson 1965; Williams 1966). In A, you identify figs X and Y – relabel as 1 & 2 presumably

Figure 2: (a) Geological map of the Diabaig area (see Fig. 1a for location). Palaeocurrent directions of the various mapped units are shown and include: (i) trough cross-stratified sandstone; (ii) nested trough cross-bedded sandstone; and (iii) ripple-drift cross lamination. (b) Stratigraphic section across the upper Diabaig – lower Applecross formational contact. The log on the left is modified from Rodd and Stewart (1992).

Figure 3: Simplified geological map of the Sleat Group, Sleat Peninsula, Skye (see Fig. 1a for location). See text for discussion.

Figure 4: Detrital zircon cumulative probability diagrams for the analysed samples (see Tables 1 and 2). Approximate age boundaries for the major tectonothermal events in Laurentia – Baltica cratons are shown as shaded boxes. Vertical lines represent the Period boundaries of the Proterozoic at 2500 Ma, 1600 Ma and 1000 Ma. Light grey distribution plots include data with > 10 % discordance. The number of grains < 10% discordant and the total number of analysed grains is indicated. The Stoer probability diagram shows the data of Rainbird *et al*. (2001) with data from this paper overlain (black).

Table Captions:

Table 1 LA-MC-ICP-MS data. % Disc. is the age discordance. Positive numbers are reverse discordant. Ratio errors are at the 1σ level, age errors at 2 σ. Age calculations use the routines of Ludwig (2003) and follow the decay constant recommendations of Steiger and Jäger (1977).

Table 2 TIMS data. U–Pb isotopic data for analysed zircon grains; [a]Z, zircon; all analyses are of single abraded grains; [b]Total common Pb in analysis, corrected for spike and Pb fractionation; [c]Corrected for spike contribution and instrumental bias; [d]Atomic ratio of Th to U, calculated from radiogenic $^{208}Pb/^{206}Pb$ and; [e]Corrected for blank Pb and U, and common Pb (Stacey-Kramers model Pb equivalent to interpreted age of mineral).

Figure 1:

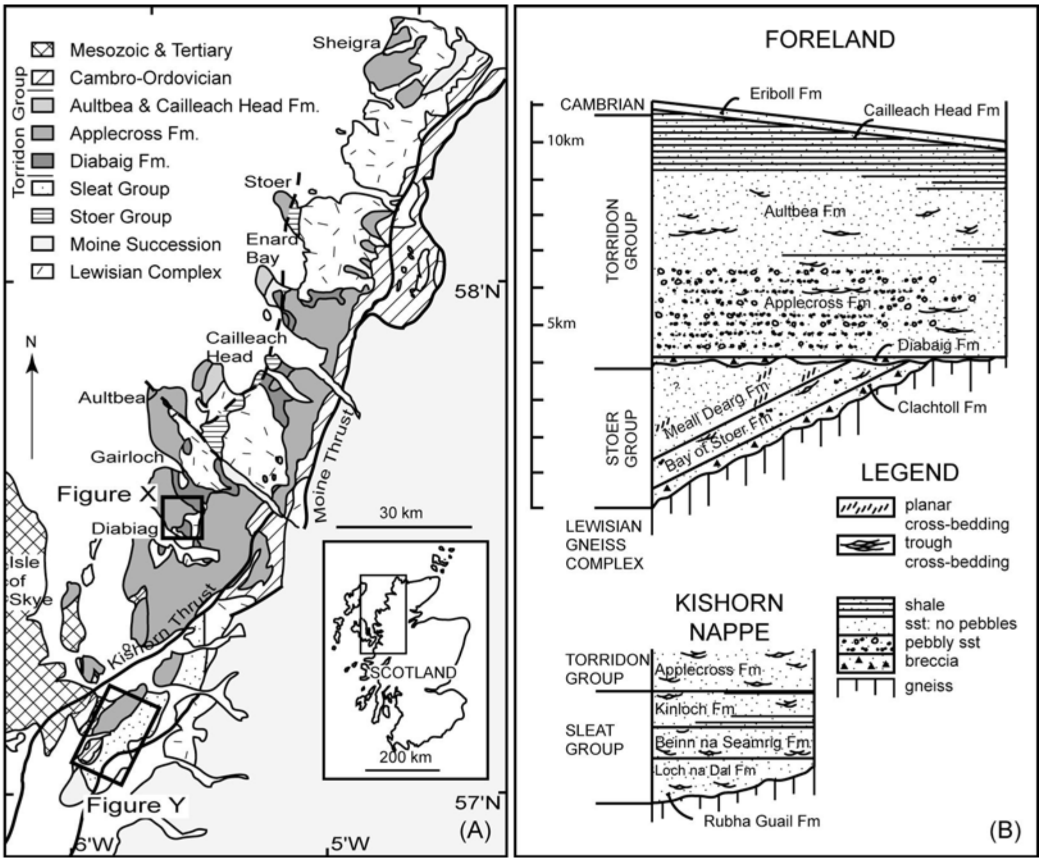
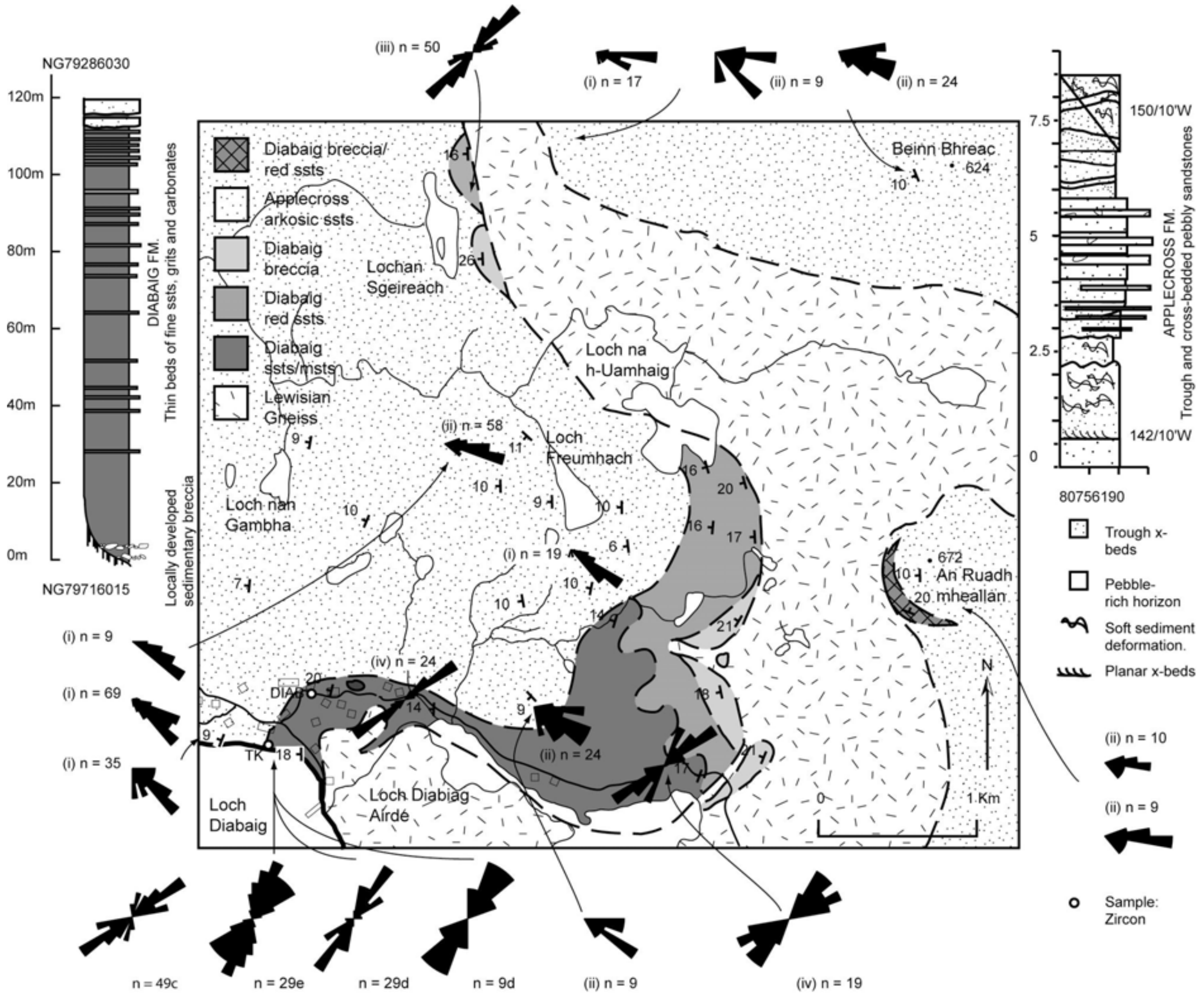
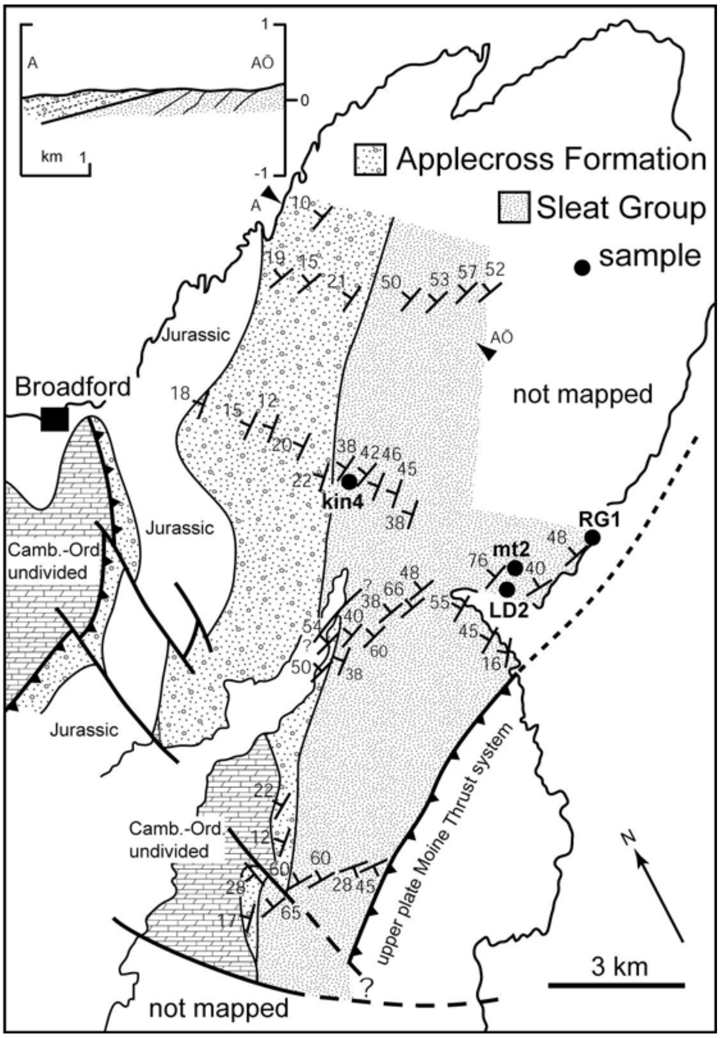

Mesozoic & Tertiary
Cambro-Ordovician
Torridon Group
Aultbea & Cailleach Head Fm.
Applecross Fm.
Diabaig Fm.
Sleat Group
Stoer Group
Moine Succession
Lewisian Complex
Sheigra
Stoer
Enard Bay
58'N
Cailleach Head
Aultbea
Gairloch
Figure X
Diabaig
Isle of Skye
Kishorn Thrust
Moine Thrust
30 km
SCOTLAND
200 km
Figure Y
57'N
6'W
5'W
(A)
FORELAND
CAMBRIAN
Eriboll Fm
Cailleach Head Fm
10km
TORRIDON GROUP
Aultbea Fm
Applecross Fm
5km
Diabaig Fm
STOER GROUP
Meall Dearg Fm
Bay of Stoer Fm
Clachtoll Fm
LEWISIAN GNEISS COMPLEX
LEGEND
planar cross-bedding
trough cross-bedding
shale
sst: no pebbles
pebbly sst
breccia
gneiss
KISHORN NAPPE
TORRIDON GROUP
Applecross Fm
Kinloch Fm
SLEAT GROUP
Beinn na Seamrig Fm
Loch na Dal Fm
Rubha Guail Fm
(B)

Figure 2:

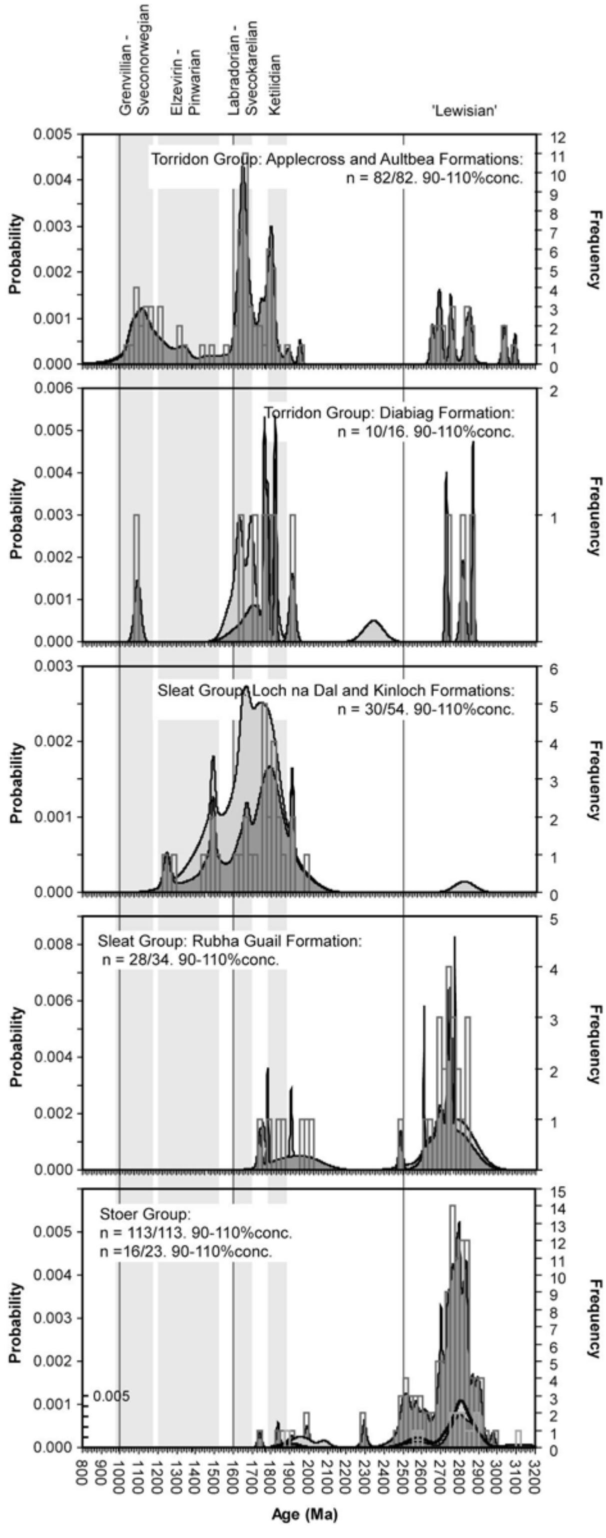


NG79286030
120m
100m
80m
60m
40m
20m
0m
NG79716015
DIABAIG FM.
Thin beds of fine ssts, grits and carbonates
Locally developed sedimentary breccia
Diabaig breccia/ red ssts
Applecross arkosic ssts
Diabaig breccia
Diabaig red ssts
Diabaig ssts/msts
Lewisian Gneiss
(iii) n = 50
(i) n = 17
(ii) n = 9
(ii) n = 24
Beinn Bhreac
624
Lochan Sgeireach
Loch na h-Uamhaig
Loch Freumhach
Loch nan Gambha
(ii) n = 58
(i) n = 19
(iv) n = 24
(ii) n = 24
(i) n = 9
(i) n = 69
(i) n = 35
DIAB
TK
Loch Diabaig
Loch Diabiag Airde
672
An Ruadh mheallan
N
0
1 Km
(ii) n = 10
(ii) n = 9
n = 49c
n = 29e
n = 29d
n = 9d
(ii) n = 9
(iv) n = 19
150/10'W
142/10'W
7.5
5
2.5
0
APPLECROSS FM.
Trough and cross-bedded pebbly sandstones
80756190
Trough x-beds
Pebble-rich horizon
Soft sediment deformation.
Planar x-beds
Sample: Zircon

808



A
AÖ
1
0
-1
km 1
Applecross Formation
Sleat Group
sample
not mapped
Jurassic
Broadford
Jurassic
Camb.-Ord undivided
Jurassic
Camb.-Ord. undivided
kin4
RG1
mt2
LD2
upper plate Moine Thrust system
N
3 km
not mapped


Grenvillian - Sveconorwegian
Elzevirin - Pinwarian
Labradorian - Svecokarelian
Ketilidian
'Lewisian'
Torridon Group: Applecross and Aultbea Formations:
n = 82/82. 90-110%conc.
Torridon Group: Diabiag Formation:
n = 10/16. 90-110%conc.
Sleat Group: Loch na Dal and Kinloch Formations:
n = 30/54. 90-110%conc.
Sleat Group: Rubha Guail Formation:
n = 28/34. 90-110%conc.
Stoer Group:
n = 113/113. 90-110%conc.
n =16/23. 90-110%conc.
Probability
Frequency
Age (Ma)