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DISCUSSION

Discussion of 'Metamorphic *P*–*T* and retrograde path of high-pressure Barrovian metamorphic zones near Cairn Leuchan, Caledonian orogen, Scotland'

D. R. Viete, G. J. H. Oliver and S. A. Wilde comment: First, we would like to commend Aoki *et al.* (2013) on a careful study and thought-provoking manuscript. Their interpretation of the Barrovian metamorphism as a fundamentally retrograde feature offers a refreshing alternative to the more conventional 'peak-metamorphic' models.

Aoki *et al.* (2013) suggested that high-grade rocks from the eastern Grampian Terrane, Scotland, signify high-pressure/high-temperature (1.2–1.4 GPa, ≥770–800 °C) metamorphism during the early stages of the Grampian Orogeny. These granulite-facies rocks were overprinted during the Grampian Orogeny by the amphibolite-facies Barrovian metamorphism. Here, with consideration of time scales and heat sources available for metamorphism during the Grampian Orogeny, we argue that an early Grampian high-temperature metamorphism is highly implausible. The results of structural and geochronological work from the literature provide support for another interpretation of the origins of the Aoki *et al.* (2013) gneisses: rather than forming during the Grampian Orogeny, they represent Precambrian basement to the Dalradian Supergroup. We present a new latest Mesoproterozoic (1003 ± 6 Ma) U–Pb age for migmatization of the Cowhythe Gneiss, which corroborates the Precambrian basement model for some high-grade metamorphic rocks of the eastern Grampian Terrane.

1. Results and interpretations of Aoki *et al.* (2013) and background information

The study of Aoki *et al.* (2013) focused on garnetite lenses within garnet amphibolites from the region of Cairn Leuchan, above Glen Muick, in the Grampian Highlands of Scotland (location shown on Fig. 1). These rocks experienced a high-pressure granulite-facies (HGR) metamorphism and later amphibolite-facies (AM) metamorphism (Aoki *et al.* 2013).

The early HGR metamorphism produced mineral assemblages of grt + amp + qtz + pl + cpx ± ep in the Cairn Leuchan garnetites and garnet amphibolites (Aoki *et al.* 2013). Thermodynamic modelling of metamorphic phase equilibria and the composition of garnet (X_{alm}, X_{gr}), clinopyroxene (X_{aug}) and amphibole ($X_{Ca\text{-}amph}$) – using PERPLEX v. 6.6.6 (Connolly, 2005) and an update of the thermodynamic dataset of Holland & Powell (1998) – yielded pressure–temperature (*P*–*T*) estimates for the HGR metamorphism in the range 1.2–1.4 GPa and 770–800 °C (Aoki *et al.* 2013). Additional thermodynamic modelling using THERMOCALC v. 3.33 (Powell & Holland, 1988) and the same thermodynamic dataset gave higher estimates of *T* to *c.* 900 °C (Aoki *et al.* 2013). Thus, the HGR metamorphism of Aoki *et al.* (2013) involved conditions approaching those for ultrahigh-temperature metamorphism (i.e. >900 °C at 0.7–1.3 GPa; Harley, 1998).

The late AM metamorphism produced mineral assemblages of grt + amp + qtz + pl ± ep in the garnetites and garnet amphibolites (Aoki *et al.* 2013). Absence of cpx from the AM metamorphic assemblage is suggestive of *P*–*T* conditions for the metamorphic overprint in the range 0.5–0.8 GPa and 580–700 °C (Aoki *et al.* 2013).

Aoki *et al.* (2013) published ^{206}Pb/^{238}U ages obtained from laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) analysis of metamorphic zircons from the Tomatin eclogitic amphibolite of the central Grampian Highlands (location shown on Fig. 1a). The Tomatin eclogitic amphibolite has typical mineralogy for a garnet amphibolite (grt + hbl + qtz + pl), but also contains symplectic intergrowths of cpx and pl (Baker, 1986). Baker (1986) considered the cpx within the cpx-pl symplectites as a remnant of a previously more widespread grt-cpx-qtz assemblage, which formed during an early (probably Precambrian in Baker's view) high-*P* metamorphic episode.

The ^{206}Pb/^{238}U analyses of Aoki *et al.* (2013) produced ages of 446 ± 32 Ma and 485 ± 37 Ma, which overlap with the Grampian Orogeny. They took these ages to date a late AM (Barrovian-type) overprint in the Tomatin rocks. Supposing that the HGR metamorphism at Cairn Leuchan represented early-stage retrogression of eclogite-facies assemblages similar to those preserved at Tomatin – and with reference to the many global examples of Barrovian-type metamorphic overprinting of high-*P* (eclogite- and blueschist-facies) metamorphism – Aoki *et al.* (2013) assumed that the HGR and AM metamorphisms at Cairn Leuchan represented two metamorphic episodes along a single Grampian-age retrogression path.

Aoki *et al.* (2013) related the late AM metamorphism to the Barrovian metamorphism (Barrow, 1893, 1912), a brief thermal event that occurred at *c.* 475–465 Ma (Oliver *et al.* 2000; Baxter, Ague & DePaolo, 2002; Viete *et al.* 2013; Vorhies, Ague & Schmitt, 2013) during the Grampian Orogeny. If the earlier HGR metamorphism at Cairn Leuchan was also Grampian – as Aoki *et al.* (2013) assert – it occurred after initial Grampian collision and crustal thickening at *c.* 488 Ma (Chew, Graham & Whitehouse, 2007; Viete *et al.* 2013), but before the Barrovian metamorphism.

Thermodynamic modelling of phase equilibria and mineral geochemistry for blueschist rocks from South Achill, western Ireland, has yielded *P*–*T* estimates of 0.9–1.2 GPa and 415–505 °C for Grampian blueschist-facies (BS) metamorphism (Chew *et al.* 2003). These *P* estimates are similar to those for the HGR metamorphism at Cairn Leuchan. However, *T* for the Irish BS metamorphism was 300–400 °C cooler. Temperatures of >650–700 °C are sufficient to cause partial melting of metasedimentary rocks, which form the majority of rock outcrop in the Glen Muick region (Baker, 1985). Such partial melting processes are strongly endothermic, meaning that *T* of 770–800 °C (and possibly 900 °C) for the HGR metamorphism would have required substantially greater heat input when compared to the BS metamorphism of Chew *et al.* (2003).

So, how did the HGR gneisses of the Glen Muick region get so hot? Within the context of the Grampian Orogeny, any

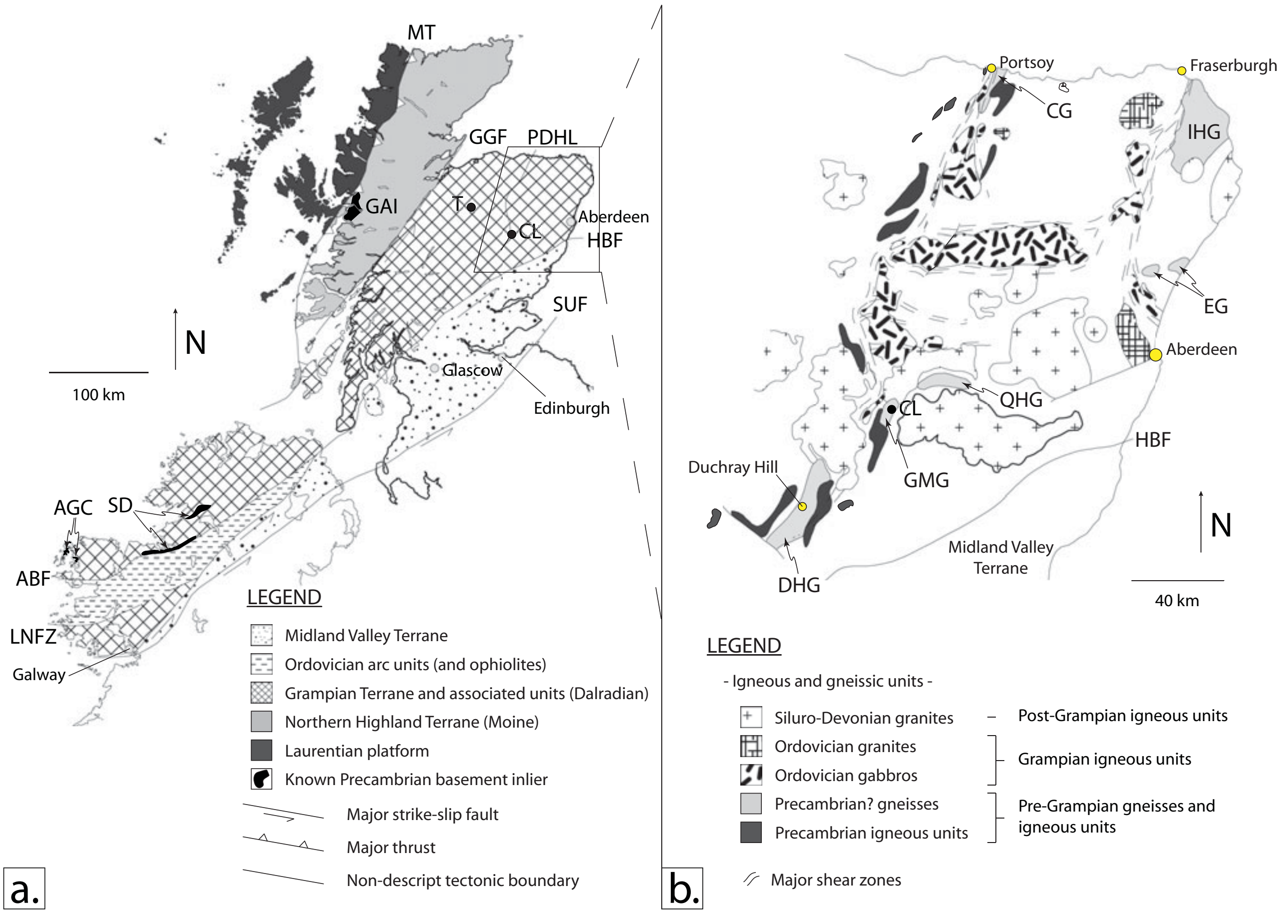

Figure 1. (Colour online) Map of northern United Kingdom and Ireland showing (a) distribution of major tectonic boundaries and terranes, known Precambrian basement inliers and locations of interest; and (b) distribution of the major shear zones and magmatic and gneissic bodies of the eastern Grampian Terrane, Scotland. Shear zones and faults after Ashcroft *et al.* (1984), Fettes *et al.* (1986), Goodman (1994) and Dewey (2005). Magmatic and gneissic bodies after Read (1955), Goodman (1994), Brewer *et al.* (2003), Flowerdew & Daly (2005) and MacAteer *et al.* (2010). ABF – Achill Beg Fault; AGC – Annagh Gneiss Complex; CG – Cowhythe Gneiss; CL – Cairn Leuchan; DHG – Duchray Hill Gneiss; EG – Ellon Gneiss; GAI – Glenelg–Attadale Inlier; GGF – Great Glen Fault; GMG – Glen Muick Gneiss; HBF – Highland Boundary Fault; IHG – Inzie Head Gneiss; LNFZ – Lough Nafooey Fault Zone; MT – Moine Thrust; PDHL – Portsoy–Duchray Hill Lineament; QHG – Queen's Hill Gneiss; SD – Slishwood Division; SUF – Southern Uplands Fault; T – Tomatin.

valid explanation must involve rapid heating following initial Grampian collision, perhaps with some heat inherited from a pre-Grampian thermal history. Below, we discuss the validity of this metamorphic heating scenario in light of time scales and heat sources available during the Grampian Orogeny. Following that, we propose what we believe to be a more plausible explanation for the HGR metamorphism: that it is much older than Aoki *et al.* (2013) have supposed. We refer to the geological literature on the Grampian Highlands and provide geochronological evidence in support of this alternative hypothesis.

2. Could rapid, early Grampian heating have produced the HGR gneisses?

A summary of all known ages for Grampian magmatism is provided by Viete *et al.* (2013, section 4.1.2, appendix B supplementary file). Magmatism during the Grampian Orogeny began with the emplacement of both mafic and felsic magmas from *c.* 475 Ma. Bimodal magmatism continued until *c.* 470 Ma. Exclusively felsic magmatism persisted from *c.* 470 Ma until *c.* 465 Ma. There is no evidence for any igneous activity during the earliest phase of the Grampian Orogeny (*c.* 488–475 Ma) prior to the Barrovian metamorphism. Grampian-age advection of mantle heat can therefore be rejected as a heat source for the early HGR metamorphism of Aoki *et al.* (2013).

Fettes *et al.* (1986) and Goodman (1994) mapped a wide zone of highly sheared rocks and thinly sliced tectonostratigraphy through the region of Glen Muick, which they considered a continuation of the Portsoy Shear Zone of Read (1955) and more extensive shear zone network of Ashcroft *et al.* (1984). The highly deformed nature of the rock in the region of Glen Muick raises the prospect of mechanical heating. Mechanical heating within rocks undergoing pure or simple shear is calculated as the product of shear stress and strain rate, for which typical maximum values for highly deformed gneisses might approach 50 MPa (Yuen *et al.* 1978) and 10^{-13} s^{-1} (Pfiffner & Ramsay, 1982), respectively. This could produce significant heating rates of the order 5 μW m^{-3}. However, mechanical heating rates can only be maintained for temperatures at which the shear strength of rock is significant; mechanical heating to beyond 500–700 °C is self-limiting due to the onset of partial melting and/or emergence of ductile deformation processes and associated rock strength decrease (Toksöz & Bird, 1977; Yuen *et al.* 1978). Considering the high values of T (770–800 °C and possibly 900 °C) for the HGR metamorphism (Aoki *et al.* 2013), mechanical heating cannot have been significant.

Radioactive heating rates for high-grade granulites take a mean value of 1.5 μW m^{-3}, but can be as high as 10 μW m^{-3} for some examples (Vilà, Fernández & Jiménez-Munt, 2010). Despite the close attention paid to the Highlands of Scotland by the geological community, there is no published evidence for rocks within the Grampian Terrane that are particularly enriched in heat-producing elements. For radiogenic heating rates of 1.5 μW m^{-3} and instantaneous doubling of crustal thickness, numerical modelling has shown that time scales of 30–40 Ma can only produce a T increase of the order 100 °C (Toksöz & Bird, 1977; England & Thompson, 1984; Clark *et al.* 2011). As outlined above, recent geochronological constraints on the timing of the Grampian Orogeny restrict the HGR metamorphism of Aoki *et al.* (2013) to a 13 Ma window after 488 Ma (see Viete *et al.* 2013 and references therein). This timeframe is too brief to allow significant crustal heating by heat conduction from the mantle with moderate rates of internal radioactive heating.

Johnson & Strachan (2006) suggested that much of the heat for thickening-related metamorphism may be inherited from a high heat flow setting immediately prior to the onset of orogenesis (e.g. a back-arc basin). This seems a reasonable model for deep metamorphism at modest values of T, as for the Grampian BS metamorphism of Chew *et al.* (2003). However, for the HGR metamorphism of Aoki *et al.* (2013), initial T (prior to Grampian Orogeny) would have to have been $>$700 °C and pre-Grampian partial melting and/or igneous activity would be expected. A survey of the literature shows no immediately pre-Grampian metamorphic, migmatitic or igneous ages. The ‘inherited heat’ scenario is therefore also ruled out.

With a lack of a valid source for Grampian metamorphic heating within the 13 Ma window available for the HGR metamorphism, we are not convinced that the HGR metamorphism is in fact Grampian in age.

3. Could the HGR gneisses be Precambrian?

The rich geological literature from Scotland raises the possibility of an alternative explanation for the origin of the HGR metamorphism of Aoki *et al.* (2013): that it is Precambrian in age.

In the regions of Cromar, Deeside and Glen Muick of the SE Grampian Highlands, Read (1927, 1928) mapped an extensive ‘injection complex’ he named the Queen’s Hill Group. Read (1928) considered a similar ‘injection complex’ that forms the Duchray Hill Gneiss to be a possible SW extension of the Queen’s Hill Group. The location of the Glen Muick and Queen’s Hill gneisses (which form the Queen’s Hill Group) and the Duchray Hill Gneiss is shown in Figure 1b.

The Queen’s Hill Group comprises intermixed micaceous schists, quartzites and feldspathic gneisses, which ‘intrude’ hornblende basic igneous rocks (Read, 1927, 1928). The lithologies studied by Aoki *et al.* (2013) are consistent with those of the Queen’s Hill Group of Read (1927, 1928) and their location (at Cairn Leuchan) corresponds precisely with the location of the Queen’s Hill Group, as mapped by Read (1928, plate II) (see Fig. 1b).

Read’s extensive mapping of the Grampian Highlands revealed a tectonic dislocation that separates high-grade gneissic packages (including the Cowhythe, Duchray Hill, Ellon, Glen Muick and Queen’s Hill Gneisses of Fig. 1b) from significantly lower-grade rocks (Read, 1955). Read (1955) proposed that this dislocation (mapped first as the Boyne Line on the E–W-trending Banffshire coast and then extended south and east) marked the tectonic removal of the upper limb of a regional structure he called the Banff Nappe. According to the model of Read (1955), the Cowhythe, Duchray Hill, Ellon, Glen Muick, Inzie Head and Queen’s Hill gneisses (Fig. 1b) are inliers: exposures of the highly metamorphosed core of the Banff Nappe from beneath low-grade upper Dalradian metasediments.

The work of Ashcroft *et al.* (1984), Fettes *et al.* (1986, 1991) and Goodman (1994) revealed a geographical association between: (1) a network of long-lived shear zones in the NE of the Grampian Terrane (including the Boyne Line and its along-strike equivalents); (2) the Cowhythe, Duchray Hill, Ellon, Glen Muick, Inzie Head and Queen’s Hill gneisses; (3) pre- and syn-Grampian igneous rocks; and (4) thinly sliced lithostratigraphy. The major branch of this network of narrow and extensive geological features (highlighted on Fig. 1b by the location of ‘major shear zones’) has come to be known as the Portsoy–Duchray Hill Lineament (PDHL). The concentration of *c.* 600 Ma ‘Dalradian’ igneous bodies along the PDHL (and associated shear zones) suggests that the history of the shear zone network pre-dates the Grampian Orogeny (see Viete *et al.* 2010). Geological mapping in the region of Portsoy (location shown on Fig. 1b) has demonstrated differing geological histories in the various lithostratigraphic units that form the PDHL there, in addition to a complex history of alternating (thrust v. normal) shear movements along the PDHL during the Grampian Orogeny (Viete *et al.* 2010). Of particular importance for this discussion is the observation that the Cowhythe Gneiss preserves a significantly more complex structural history than the lower-grade Dalradian sediments that surround it, which includes a (granulite-facies) migmatitic history that predates both Dalradian sedimentation and the Grampian Orogeny (see Ramsay & Sturt, 1979; Viete *et al.* 2010, table 1, p. 139).

Sturt *et al.* (1977) published Rb–Sr whole-rock ages of 724 ± 120 Ma and 691 ± 39 Ma for the Ellon and Inzie Head gneisses, respectively. These ages, partnered with the results of detailed structural mapping, caused Ramsay & Sturt (1979) to reinterpret the Cowhythe, Ellon, Queen’s Hill and Inzie Head gneisses (and related gneissic rocks) as basement to the Dalradian Supergroup. They proposed that a dislocation represented by the Boyne Line on the E–W-trending Banffshire coast was responsible for ‘uncoupling’ of Dalradian cover from its gneissic basement along the full extent of the shear zone network that includes the PDHL.

Various phases of shear activity within the broad zone of shear that forms the PDHL can account for isolation of thin basement gneiss bodies. Viete *et al.* (2010) argued that shear movements juxtaposed basement rocks and their Dalradian cover (as Ramsay & Sturt, 1979 envisioned), but that subsequent movements then stranded these thin slices of gneissic basement within the PDHL. According to their model, the PDHL was a ‘shuffle zone’ whose long and complex deformation history was responsible for the creation of a zone of thinly sliced lithostratigraphy containing various rock packages with markedly differing age and provenance. Aoki *et al.* (2013) state that the contacts between the amphibolitic gneisses they studied at Cairn Leuchan and the metasedimentary gneisses that enclose them are not deformed. However, this does not preclude assembly of the gneissic package during the Proterozoic, and later emplacement of the package within a ‘shuffle zone’ during the Grampian Orogeny.

Interestingly, complex structural histories and anomalously high P–T conditions (when compared to neighbouring Dalradian metasediments) are also preserved in some gneisses of the Irish Grampians (Sutton & Max, 1969; Max & Long, 1985; Sanders, Daly & Davies, 1987; Kennedy & Menuge, 1992; Flowerdew & Daly, 2005; MacAteer *et al.* 2010). These gneisses (including those of the Annagh Gneiss

Complex and Slishwood Division; Fig. 1a) have been interpreted as Precambrian basement inliers within the Irish equivalent of the Grampian Terrane, Scotland.

Below, we present previously unpublished data in support of a 1003 ± 6 Ma (latest Mesoproterozoic) age for migmitization of the Cowhythe Gneiss. These results lend support to the models of Ramsay & Sturt (1979) and Viete *et al.* (2010), which treat some gneissic units within the PDHL (and associated shear zones) as stranded slivers of Precambrian basement to the Dalradian.

4. U–Pb SHRIMP ages for migmatization of the Cowhythe Gneiss

Sample PO5, a highly strained anatectic migmatite, was sampled from the Cowhythe Gneiss on the east side of Links Bay, Portsoy [GPS NJ 59556630]. The rock comprises significant quartz-feldspar leucosomes that delineate thicker layers of biotite-rich mesosome (which themselves have thin leucosome layers) (Fig. 2a). The rock is interpreted to have formed by partial melting of a pelitic protolith, with significant deformation during and/or following migmatization.

For geochronological analysis, thick leucosome layers were removed from the bulk sample using a diamond saw to separate the dominantly leucosome material (sample PO5a) from the remaining mesosome (with some leucosome) material (sample PO5b) (Fig. 2a). Samples PO5a and PO5b were crushed separately and zircons were extracted from each using conventional Wilfley table, heavy liquid and magnetic separation techniques. The zircon grains were mounted in epoxy with Curtin University standard CZ3 (Pidgeon *et al.* 1994). The epoxy disks were ground and polished to expose the grains, then cleaned and coated in gold. Cathodoluminescence (CL) and secondary electron (SE) imaging was performed on the zircon grains to reveal internal zoning and the presence of cracks and inclusions, respectively (see example images in Fig. 2b). All isotopic analyses were performed using the SHRIMP II at Curtin University and the approach outlined in Oliver, Wilde & Wang (2008). Data reduction also followed the methodology of Oliver, Wilde & Wang (2008).

In total, 55 SHRIMP U–Pb analyses were performed on zircons from samples PO5a and PO5b. Individual concordant ages range from *c.* 3000 Ma (Archean) to *c.* 1000 Ma (latest Mesoproterozoic) (Fig. 2c). Zircon grains that yielded 3000–1300 Ma (Archean to middle Mesoproterozoic) ages were invariably well rounded and interpreted to be detrital in origin. The sedimentary protolith for the Cowhythe Gneiss was therefore deposited no earlier than 1300 Ma. The post-1300 Ma zircon population is igneous in character; grains are small and euhedral with prominent oscillatory zoning (Fig. 2b) and are more common in the leucosome material than the mesosome material, accounting for 23 of 33 analyses from PO5a but only 14 of 22 analyses from PO5b. Fifteen analyses of these small igneous grains form a discrete 1025–975 Ma (latest Mesoproterozoic – earliest Neoproterozoic) age population with a mean ^{206}Pb/^{238}U age of 1003 ± 6 Ma (2σ uncertainty, $n = 15$, MSWD = 0.99, probability of fit = 0.46) (Fig. 2c). The 1300–1025 Ma ages define an age array (see Fig. 2c) that is interpreted to signify inheritance in igneous zircon grains grown dominantly at 1003 ± 6 Ma. The 1003 ± 6 Ma age is interpreted to date partial melting (migmatization) of a metasedimentary protolith during the 1090–980 Ma Grenville Orogenic event (Rivers, 1997). The lack of any Ordovician zircons within the Cowhythe Gneiss precludes Grampian gneissification and the unit is interpreted as latest Mesoproterozoic basement to the Dalradian. A single-grain ^{206}Pb/^{238}U age of 988 ± 23 Ma (2σ), obtained for a zircon from the Inzie Head Gneiss during the same SHRIMP work that yielded the Cowhythe Gneiss ages, provides additional support for interpretation of the some of the Grampian Terrane gneisses as Precambrian basement to the Dalradian.

Latest Mesoproterozoic to earliest Neoproterozoic ages have been published for the eastern Glenelg–Attadale Inlier of the Northern Highland Terrane, NW Scotland (location on Fig. 1a). These ages include the 1082 ± 24 Ma and 1010 ± 13 Ma Sm–Nd whole-rock-garnet-clinopyroxene ages of Sanders, van Calsteren & Hawkesworth (1984), the 995 ± 8 Ma ^{206}Pb/^{238}U zircon age of Brewer *et al.* (2003) and the 971 ± 71 Ma U–Pb and 945 ± 54 Ma Pb/Pb whole-rock-titanite-feldspar ages of Brewer *et al.* (2003). Similar ages of 1070 ± 70 Ma (Rb–Sr whole rock: Max & Sonet, 1979), 995 ± 6 Ma (U–Pb zircon: Daly, 1996) and 963 ± 8 Ma (^{207}Pb/^{206}Pb titanite: Daly & Flowerdew, 2005) have been obtained for migmatization/metamorphism of the Annagh Gneiss Complex, NW Ireland (location on Fig. 1a). These ages provide robust evidence for Grenville tectonothermal activity in Scotland and Ireland and support for Grenville migmatization of the Cowhythe Gneiss. We suggest that the HGR metamorphism of Aoki *et al.* (2013) should be reinterpreted as evidence of a Precambrian pre-history for the Glen Muick Gneiss, rather than proof of high-pressure granulite-facies metamorphism during the Grampian Orogeny (for which no evidence of acceptable sources of metamorphic heat are available).

In conclusion, models for high-T metamorphism during the early stages of the Grampian Orogeny (prior to *c.* 475 Ma) cannot be supported from the available geological evidence. New U–Pb ages for Precambrian migmatization of units within the Grampian Terrane were presented. We believe the rocks studied by Aoki *et al.* (2013) are not Dalradian but Grenville basement gneisses, and that the HGR metamorphism of Aoki *et al.* (2013) occurred at 1003 ± 6 Ma. Our arguments, however, do not disqualify a significant and widespread, high-P/low-T early Grampian metamorphism (see Chew *et al.* 2003). We hope this discussion does not detract from what we see as the major contribution of the Aoki *et al.* (2013) study: the suggestion that in the case of the classic Barrovian metamorphism of Scotland, like so many other worldwide Barrovian-type metamorphic examples, metamorphism may have overprinted a higher-P (though lower-T) pre-history.

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K. Aoki, B. F. Windley, S. Maruyama & S. Omori reply: First, we thank Viete, Oliver & Wilde for their interesting and thought-provoking comments on the timing of the high-pressure granulite facies (HGR) metamorphism recorded in metamorphic rocks at Cairn Leuchan, Scotland, published by Aoki *et al.* (2013). Based on new metamorphic data of garnetites and garnet-amphibolites at Cairn Leuchan and new zircon U–Pb ages of amphibolitized eclogite at Tomatin, we suggested in our publication that the HGR metamorphism was retrograde after eclogite facies before the *c.* 470 Ma ‘Barrovian metamorphism’. Viete, Oliver & Wilde however speculate that the HGR metamorphism at Cairn Leuchan may have occurred at *c.* 1000 Ma, as a result of their new U–Pb zircon age of the Cowhythe Gneiss at Portsoy and from previous studies of the geological structure and geochronology. We are grateful for this opportunity to describe, albeit in a preliminary manner, our new understanding and tectonic model of the Caledonian orogen in Scotland and western Ireland of which the Barrovian metamorphism is a key component. A reply to a comment is not the correct place to propose an

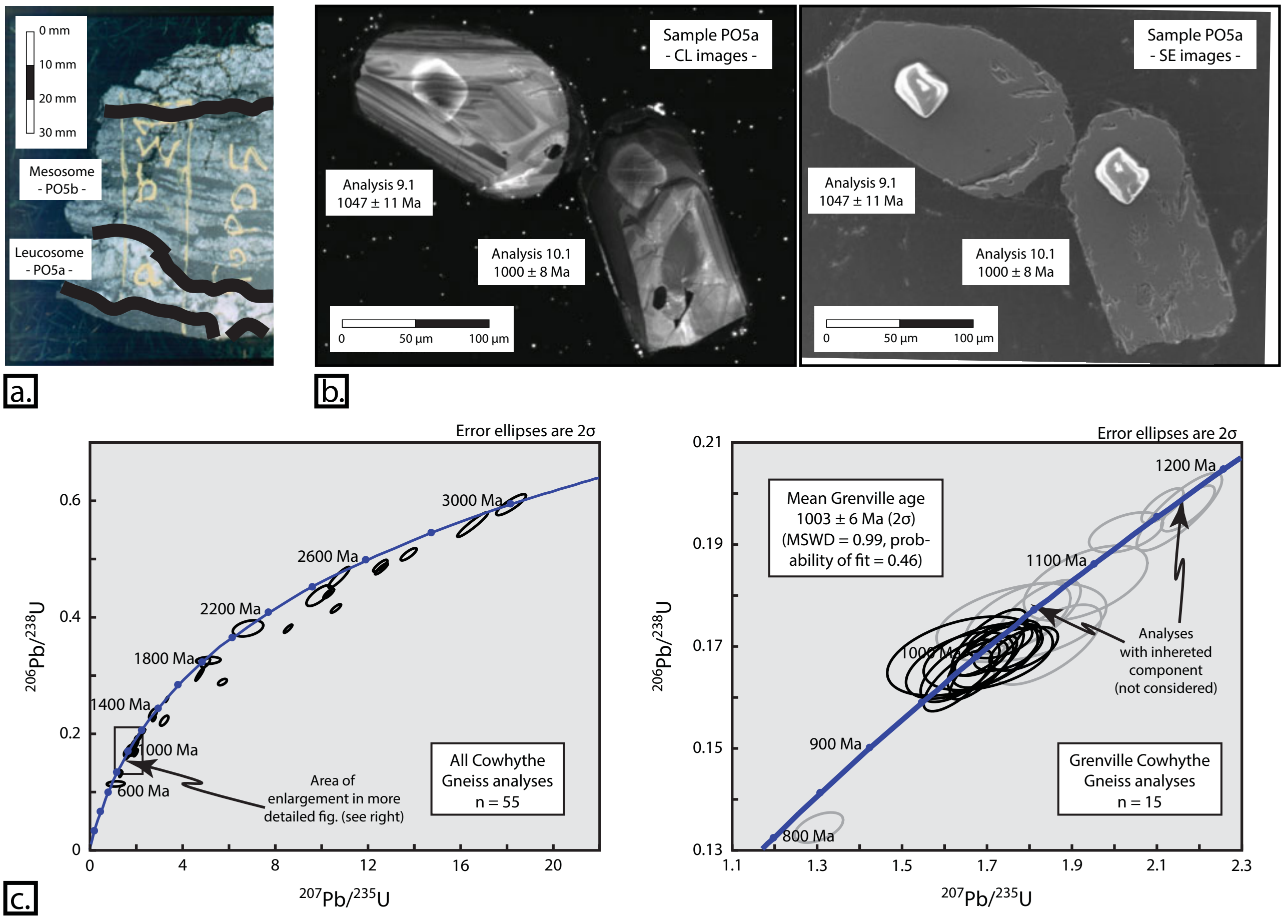

Figure 2. (Colour online) (a) Section of Cowhythe Gneiss sample PO5 [GPS: NJ 59556630] showing examples of leucosome and mesosome layers used for samples PO5a and PO5b, respectively; (b) cathodoluminescence (CL) and secondary electron (SE) images of two euhedral, zoned garnets from sample PO5a (with ages and 1σ uncertainties); and (c) ^{206}Pb/^{238}U v. ^{207}Pb/^{235}U concordia plots for all U–Pb analyses performed on sample PO5a and PO5b (black ellipses on plot on the right represent analyses used in calculation of the Cowhythe Gneiss age).

entirely new paradigm for such a classic orogen, but we will present our model more fully in a future publication.

Viete, Oliver & Wilde presented a new U–Pb age of 1003 ± 6 Ma for zircons in melt veins in the Cowhythe Gneiss near Portsoy, and suggested reasonably that this gneiss belongs to a tectonic slice of Precambrian basement which originally overlay Grampian sediments. This idea follows that of Sturt *et al.* (1977) and Ramsay & Sturt (1979). Viete, Oliver & Wilde then went on to correlate the Cowhythe Gneiss with the gneiss at Cairn Leuchan described by Aoki *et al.* (2013). The correlation of the two gneisses is weak and unacceptable, because they are completely different. The Cowhythe Gneiss is an early term for the Cowhythe Psammite Formation which is a ‘psammitic to semipeltic schist with rare limestone and pelite bands’ (Stephenson & Gould, 1995; Stephenson *et al.* 2013). In contrast, the predominant rocks at Cairn Leuchan described by Aoki *et al.* (2013) are layers of amphibolite facies (AM) metavolcanic rocks up to 1 km thick (Stephenson *et al.* 2013); they contain garnet-rich layers/pods and locally contain melt veins. The amphibolitic rocks are interbedded with subordinate metasedimentary semipelitic to pelitic schists and gneisses that contain partial melt veins and diagnostic garnet and sillimanite. Most importantly, in their latest detailed analysis and synthesis, Stephenson *et al.* (2013) concluded that the Cairn Leuchan rocks belong to the Queen’s Hill Formation of the Crinan Subgroup of the Argyll Group of the Upper Dalradian, and that ‘although these gneissic rocks were once interpreted as pre-Dalradian basement, they are now assigned to the Crinan Subgroup’. They cannot therefore be correlated with the 1.0 Ga Cowhythe gneisses.

Metamorphic zircons such as those at Cairn Leuchan, that grow during partial melting, generally show low luminescence and weak or no zoning (e.g. Oliver *et al.* 1999; Foster, Schafer & Fanning 2001; Söderlund *et al.* 2002). Viete, Oliver & Wilde however state that zircons in the Cowhythe Gneiss have prominent oscillatory zoning, but that feature is unique to igneous zircons (e.g. Corfu *et al.* 2003). Further, the analysed zircon on the left of Figure 2b appears to have an outermost low-luminescence darker rim that cuts the oscillatory zoning. In light of these relations, it is possible that the analysed domains that yielded a mean age of 1003 ± 6 Ma were not formed by metamorphism/migmatization but belong to an inherited detrital domain; they are therefore comparable with other zircons that yielded 3000–1300 Ma ages. There is therefore a possibility that the age of 1003 ± 6 Ma does not reflect the time of the metamorphism/migmatization, but that of the upper age limit of deposition of the pelitic protolith. The analysed zircons are not metamorphic formed during partial melting but are detrital; in this case the determined age does not represent the time of Grenville migmatization, but rather the upper age limit of deposition of the pelitic protolith. Also, because the nearby Inzie Head gneisses and the Ellon gneisses have a Rb–Sr isochron age of 691 ± 39 Ma and 724 ± 120 Ma, respectively (Sturt *et al.* 1977), it is more likely that the Cowhythe Gneiss was metamorphosed during Neoproterozoic time rather than with the Leuchan metavolcanic rocks during Ordovician time. More zircon dating of these pre-Dalradian gneisses is clearly needed.

Vorhies, Ague & Schmitt (2013) carefully conducted high-resolution U–Pb spot secondary ion mass spectrometry (SIMS) dating of zircons from metamorphic rocks at Cairn Leuchan, and determined that the granulite-amphibolite facies metamorphism there occurred at c. 472 ± 5 Ma. Accordingly, it seems probable that the time between the HGR and AM metamorphic events was very short; the metamorphic ages therefore become congruent within the error bars of analysis.

We now come to the perennial problem of the source of the heat for Barrovian metamorphism and crustal melting, as eloquently discussed by e.g. Jamieson *et al.* (1998), Johnson & Strachan (2006), Lyubetskaya & Ague (2010), Viete, Forster & Lister (2011) and Viete *et al.* (2011; 2013). Despite the fact that this discussion has not involved the more extreme problems of the heat source of ultrahigh-temperature metamorphism and of eclogite facies metamorphism of many other orogens, the Barrovian heat source still remains an enigma. The main model that has dominated thinking about the tectonic development of the Caledonian orogen has considered thrust-generated crustal thickening, internal radioactive heating from the base of over-thickened crust, conduction during thermal relaxation and crustal exhumation caused by erosion (e.g. England & Thompson, 1984). However, Lyubetskaya & Ague (2010) pointed out that overthrusting of continental crust with average values of basal heating and radiogenic heat production cannot produce the conductive heat exchange required for the P–T–t paths characteristic of typical Barrovian metamorphism, or the required timescale of at least 50 Ma (Viete, Forster & Lister 2011), because the short life span of the Caledonian Barrovian metamorphism of 18–12 Ma is well established (e.g. Dewey, 2005; Oliver *et al.* 2000; Lyubetskaya & Ague, 2010). We agree with Viete, Oliver & Wilde that the lack of rocks in the Grampian Terrane enriched in heat-producing elements, combined with a model of thrust-generated doubling of crustal thickness, would require a timescale of 30–40 Ma to produce the necessary temperature increase; we also agree that this is not possible given the short life span required for the Barrovian metamorphism. All these considerations lead us to agree with Viete *et al.* (2013) that the model of thrusting to create such a thickened crust, and responsive deep crustal heating and isostatic uplift and thermal relaxation, is totally untenable for the Scottish Caledonides. However, Viete *et al.* (2013) concluded that the Barrovian metamorphism formed ‘as a result of advection of heat from the lower crust and/or mantle’. Because we do not believe that the Barrovian metamorphism was a mere ‘transient phase of crustal thermal equilibrium’, we propose an alternative and more viable model to explains the whole Caledonian orogenesis: the extrusion of a major wedge of hot deep eclogite which was exhumed up a subduction channel several tens of kilometres thick, similar to that summarized by Agard *et al.* (2009) and Jamieson *et al.* (2011) for many orogens worldwide. Such a wedge extrusion model is supported by the presence of originally eclogite facies rocks at Tomatin and Cairn Leuchan, which are (as predicted) within the central highest-grade sillimanite-kyanite Barrovian zone of the extruded wedge. Further, since such a high-temperature source obviates the need to find that long-sought-for enigmatic extra heat source in the Caledonides (‘where’s the heat?’, Jamieson *et al.* 1998; ‘the missing heat problem of Barrovian metamorphism’, Lyubetskaya & Ague, 2009) which has given rise to such disparate (and in our opinion, unnecessary) proposals such as: mantle heat advection associated with gabbro intrusions (Viete *et al.* 2010); sheeted magmas concentrated on shear zones (Viete *et al.* 2011); heat dissipation from underlying mid-crustal shear zones during Grampian extension (Viete, Forster & Lister 2011); metamorphic thermal reactions (Lyubetskaya & Ague, 2010); elevated radiogenic heat production (Huerta, Royden & Hodges, 1998); back-arc setting (Johnson & Strachan, 2006; Viete, Oliver & Wilde); and large-scale contact metamorphism (Viete *et al.* 2013).

Viete *et al.* (2013) stated that there is no evidence of metamorphism and magmatism before *c.* 473 Ma in the first 15 Ma of the Grampian orogeny which could have caused the HGR metamorphism (e.g. Chew *et al.* 2003). Firstly, we do not believe that isotopic dating in the Caledonides is so abundant and tightly constrained with minuscule errors that it is possible to be so definitive in stating that HGR metamorphism could only take place during a specific 13 Ma window (Viete, Oliver & Wilde). The timing of the metamorphism in an orogen is dependent on many factors, not least the chosen tectonic model; the wrong model could yield different timing. The Grampian orogeny was caused by a brief arc–continent collision at *c.* 475–465 Ma (Friedrich *et al.* 1999*a*, *b*; Dewey, 2005), and was diachronous from *c.* 480–465 Ma in Scotland (or 488–475 Ma according to Viete, Oliver & Wilde) to 470–460 Ma in western Ireland (Oliver, 2001). At Tomatin in east Scotland retrogressed eclogites have zircon ages of 485 ± 37 Ma and 446 ± 32 Ma (Aoki *et al.* 2013). In the Naver nappe in Sutherland, almost-high-pressure sillimanite-grade metamorphism of Moine rocks took place at *c.* 470–460 Ma (Kinny *et al.* 1999) under conditions of *c.* 11–12 kbar and 650–700 ºC (Friend, Jones & Burns, 2000). On Achill, NW Ireland blueschist facies metamorphism took place at *c.* 460 Ma (Chew *et al.* 2003) and, as expected, was overprinted by medium-pressure Barrovian assemblages (Yardley, Barber & Gray, 1987). Only a model of a westwards-moving extruded wedge can account for such a diachronous westwards-younging metamorphism, which adequately includes the HP metamorphism at Tomatin and Cairn Leuchan.

Models such as crustal heating by heat conduction from the mantle, contact metamorphism or a back-arc setting are totally inadequate because they cannot explain the available geological evidence. When considering the thermal evolution of the Tauern Window, we agree with Smye *et al.* (2011) that synthrust-heating by rapid exhumation and emplacement of a hot eclogite wedge, overlooked by previous thermal models, can best resolve the Barrovian conundrum; this plausibly explains the tectono-metamorphic evolution of the Eastern Alps as well as the Grampian Caledonides. Full details and documentation of our Caledonian model will be provided in a later publication.

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