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Timing of deposition, orogenesis and glaciation within the Dalradian rocks of Scotland: constraints from U–Pb zircon ages

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Abstract: The stratigraphical and structural continuity of the Late Proterozoic Dalradian rocks of the Scottish Highlands is re-examined in the light of new U–Pb zircon ages on the tuffs belonging to the Tayvallich Volcanic Formation (601 ± 4 Ma), and on the late Grampian 'Newer Gabbros' (470 ± 9 Ma) of Insch and Morven–Cabrach in Aberdeenshire. These age data, together with the existing 590 ± 2 Ma age for the Ben Vuirich Granite, provide key radiometric constraints on the evolution of the Dalradian block, and the implications arising from these ages are critically assessed. Three main conclusions are drawn.

(1) The entire Caledonian orogeny, although short-lived, is unlikely to have affected sediments of Arenig age and a break probably occurs between those Dalradian sediments of late Proterozoic (<600 Ma) age and the Ordovician rocks of the Highland Border Complex.

(2) A period of crustal thickening probably affected some Dalradian rocks prior to 590 Ma. Such an event is indicated by both the polymetamorphic histories of the lower parts of the Dalradian pile and the contact metamorphic assemblages within the aureole of the Ben Vuirich Granite, which are incompatible with sedimentary thicknesses.

(3) Age constraints on global Late Proterozoic glacial activity also suggest that the Dalradian stratigraphy is broken into discrete smaller units. Models involving continuous deposition of Dalradian sediments from pre-750 Ma to 470 Ma are rejected.

Keywords: Dalradian Orogeny, Neoproterozoic, glaciation, U–Pb, zircons.

Understanding the evolution of orogenic belts critically depends upon having reliable geochronological constraints. This is particularly important in Precambrian orogenic belts, which lack fossiliferous successions, and in which interpretations rely only on isotopic ages and correlations with global events. The dating of late orogenic events is relatively straightforward, using Rb–Sr, ^{39}Ar–^{40}Ar or K–Ar techniques on micas (e.g. Cliff 1985). However, such systems typically only record cooling after the last thermal pulse, and the dating of peak metamorphic and prograde events directly is more difficult (e.g. Vance *et al.* 1999). An alternative way of constraining the timing of both deposition, and the early parts of orogenic history is to date igneous bodies whose emplacement relative to tectonothermal events can be established (e.g. Long 1964; Pidgeon & Johnson 1974; Rogers & Dunning 1991). In these cases, geochronological systems with high closure temperatures, such as U–Pb on zircon, must be used in order to minimize effects of resetting by later events.

There is considerable uncertainty in both the age of deposition of the Dalradian sediments in the Scottish Highlands and their subsequent metamorphism (Tanner & Bluck 1999; Soper *et al.* 1999; Prave 1999). The accepted stratigraphy of the Dalradian block is presented in Figure 1. Although there is evidence that the Central Highland Division rocks are not part of the 'Dalradian Supergroup' and have experienced a *c.* 800 Ma orogenic event (Piasecki & van Breemen 1983; Noble *et al.* 1996; Highton *et al.* 1999), the extent to which Precambrian tectonothermal events have affected the 'higher' stratigraphic levels is uncertain (e.g. Phillips *et al.* 1999). The uppermost boundary of the Dalradian is similarly controversial (e.g. Tanner 1995, Bluck & Ingham 1997). A single Early Ordovician microfossil specimen is reported to be from the Macduff Slate (Downie *et al.* 1971; re-examined by Molyneux 1998) but no fossils have been found in these rocks by any later study (Bliss 1977). Some workers use this unconfirmed palaeontological evidence to argue that Southern Highland Group deposition continued through to the Arenig and that the Dalradian rocks were affected by a single short-lived Caledonian orogeny soon afterwards (Soper *et al.* 1999; Dewey & Mange 1999). Continued Dalradian deposition into

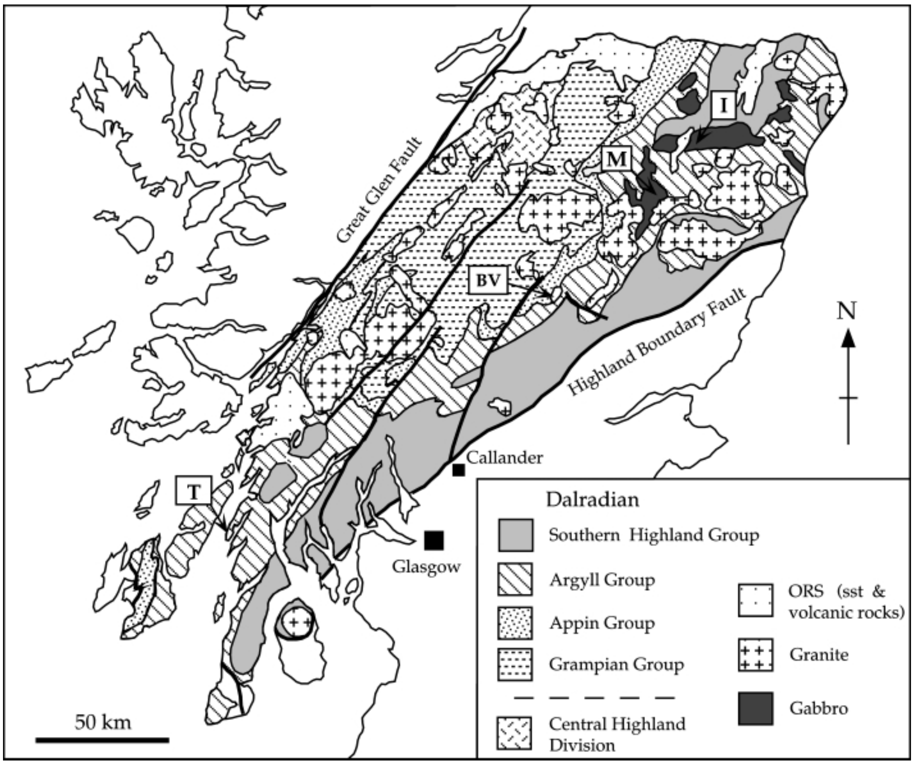

Fig. 1. Map showing the distribution of the main geological units of the Scottish Highlands between the Great Glen and Highland Boundary faults. I, M and T represent sample locations for the Insch Gabbro, Morven Cabrach Gabbro and Tayvallich Tuff respectively. BV represents the Ben Vuirich Granite.

the Lower Palaeozoic is also suggested by apparent structural and stratigraphical continuity between Southern Highland Group Dalradian rocks and the Cambrian Leny Limestone from the Callander area (Harris 1962; Tanner 1995) close to the Highland Boundary Fault. These findings do appear to be at-odds with the pre-Ordovician isotopic ages from Southern Highland Group rocks (Harper 1967; Dempster 1985; Dempster *et al.* 1995), although, as pointed out by Tanner & Pringle (1999), there are likely to be inherited components to some of the white-mica ages in the low grade rocks at the Highland Border.

In the absence of recognized stratigraphical breaks anywhere within the Highland sequence these data sets and the views generated from them require a re-appraisal of some of the key age constraints on the Dalradian rocks of the Scottish Highlands (see also Prave 1999). We present new U–Pb age data for both the 'Newer Gabbros' of the NE Highlands, whose emplacement is considered to have been close in time to that of peak metamorphism, and for the age of the Tayvallich Volcanics in the SW Highlands, which provides a minimum age for the deposition of the Upper Dalradian sediments.

General geology

Gabbros of NE Highlands

The 'Younger basic' or 'Newer Gabbro' rocks (Read 1919) represent a major phase of magma emplaced into the Dalradian metasediments (Fig. 1). They comprise at least six large bodies which range in composition from peridotite cumulates through gabbros and norites to syenites, although the full compositional spectrum is not present in each intrusion. The petrology of the intrusions has been summarized by Wadsworth (1982) and Kneller (1987), and diverse aspects of their geology have been presented in a dedicated volume of the *Scottish Journal of Geology* (1970). The intrusions were thought by Stewart & Johnson (1960) to represent a single sheet folded by the Boyndie syncline, but subsequent reinterpretation of this structure (Treagus & Roberts 1981) has led to a rejection of this hypothesis. Nonetheless, the various 'Newer Gabbros' are still considered to have been emplaced during a single event (e.g. Ashcroft *et al.* 1984).

The relationship between the 'Newer Gabbros' and the deformation and metamorphism in the Buchan area has been the subject of several studies (e.g. Fettes 1970; Ashcroft *et al.* 1984; Ashworth 1985). Although contacts are occasionally complicated by the presence of later shearing (Ashcroft *et al.* 1984) the gabbros do contact metamorphose the Dalradian Macduff Slates. Porphyroblast–matrix textural relationships indicate that the development of Buchan-style regional metamorphic assemblages was associated with local D_2 structures (Treagus & Roberts 1981). This regional metamorphism predated the emplacement of the gabbros (Fettes 1970; Leslie 1987). Harte & Hudson (1979), however, suggested that the high-*T*– low-*P* Buchan metamorphism could have been produced within the same high heat flow regime which culminated with the intrusion of the gabbros. Dempster *et al.* (1995) have argued that the kyanite-bearing Barrovian metamorphic assemblages which overprint regional metamorphic andalusite-bearing assemblages to the west of the Portsoy–Duchray Hill lineament (Chinner 1980; Treagus & Roberts 1981; Goodman 1994) could have been caused by magmatic loading producing a pressure increase of up to 2 kbar (Baker 1985; Beddoe-Stephens 1990). This kyanite growth appears to be associated with the late stages of local D_2 (Treagus & Roberts 1981; Beddoe-Stephens 1990). Hence the final stages of the D_2 deformation, the Buchan metamorphism, the higher pressure Barrovian overprint, and the crystallization of the gabbros may have been approximately contemporaneous (Fettes 1970). However, the gabbros post-date D_1 deformation, and most of the D_2-related events, which through much of the Highlands are associated with crustal thickening and Barrovian metamorphism (e.g. Fettes *et al.* 1986; Harte 1988).

Tayvallich Volcanic Formation of SW Highlands

The 'Tayvallich Volcanics' belong to the Tayvallich Subgroup and form the uppermost part of the Argyll Group of the Dalradian Supergroup. The voluminous basic magmatism, which includes a variety of pyroclastic lithologies, including tuffs and hyaloclastite rocks, pillow lavas and associated sills (Graham 1986), has been linked to the initial stages of Iapetus opening (Anderton 1985) after what is considered by some as a prolonged history of rifting (e.g. Soper *et al.* 1999; cf. Prave 1999). On the basis of their geochemistry, which is atypical of mid-ocean ridge basalts, other workers have suggested an origin within a transtensional basin (Graham 1986). The succession has experienced both a low temperature, but relatively high-pressure, regional metamorphism (Graham *et al.* 1983; Skelton *et al.* 1995) (up to garnet zone) and a phase of earlier hydrothermal metamorphism.

Previous geochronology

The earliest attempts to date the 'Newer Gabbros' were made by Brown *et al.* (1965) and Bell (1968) who obtained a variety of K–Ar and Rb–Sr biotite ages from the intrusions, typically between 444 and 479 Ma. (All ages quoted have been recalculated using the decay constants recommended by Steiger & Jäger (1977).) Pankhurst (1970) determined K–Ar biotite and muscovite ages for the Arnage, Haddo House and Insch intrusions that were relatively uniform, all but one being between 465 and 473 Ma. Pankhurst (1970) also obtained an imprecise Rb–Sr whole-rock age of 492 ± 26 Ma for the upper zone rocks from the Insch intrusion, this being the most evolved part of the basic bodies and apparently not influenced by crustal contamination. A similar Rb–Sr whole-rock age of 489 ± 23 Ma from schists and gneisses from the thermal aureole of the Haddo House mass was also determined, which Pankhurst (1970) argued represented the age of emplacement of the gabbro. Van Breemen & Boyd (1972) published a Rb–Sr muscovite–K-feldspar–whole-rock age of 467 ± 5 Ma from a pegmatite that cuts sheared gabbro at Belhelvie Quarry. Similar late-orogenic gabbros are emplaced into Dalradian metasediments of western Ireland (Tanner 1990); these share a broadly similar history to the gabbros of NE Scotland. The Irish gabbros have recently been dated by high precision U–Pb determinations on zircon and yield ages of *c.* 470 and 475 Ma (Friedrich *et al.* 1999*a*).

The Tayvallich Volcanics were dated by Halliday *et al.* (1989), who analysed a felsic 'keratophyre' from the Tayvallich Peninsula and obtained a conventional multi-grain U–Pb zircon age of 595 ± 4 Ma, the date defining a simple discordia line. Although the keratophyre was interpreted by these authors as dating the volcanic succession, the field description given by Gower (1977) suggested an intrusive cross-cutting relationship with adjacent rocks, and hence there is some uncertainty about its relationship to the Dalradian sequence. An examination of the zircon separate used in the study of Halliday *et al.* (1989) using both cathodoluminescence and back-scattered electron imaging revealed that many of the individual grains contain evidence of cores which were surrounded by euhedral magmatic growth zones (Fig. 2). This may point to an inherited component within the 595 ± 4 Ma age of Halliday *et al.* (1989).

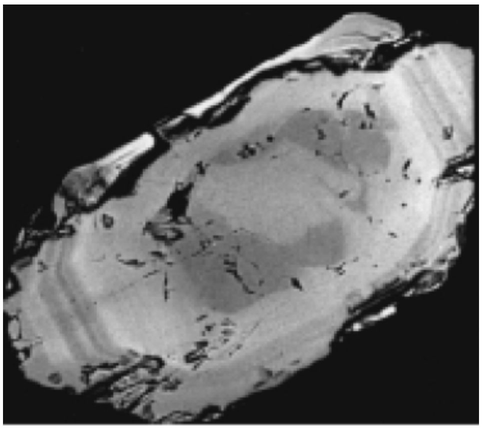

Fig. 2. Back-scattered electron image of zircon from keratophyre dated by Halliday *et al.* (1989). Field of view 150 μm.

Given the importance of reliable ages from the Dalradian metasediments, both the 'Newer Gabbros' and the Tayvallich Volcanics were targeted for further geochronological investigation.

Analytical techniques

Zircons were separated using a jaw crusher, disc grinder and Wilfley Table, followed by heavy liquids and a Frantz LB-1 magnetic separator.

The zircons from the 'Newer Gabbros' were analysed by thermal ionization mass spectrometry at SUERC. The zircons were subdivided on the basis of magnetic susceptibility and grain size. Analysed fractions were handpicked under alcohol, abraded (Krogh 1982), and then washed sequentially in hot 3M HNO_3, distilled water and distilled acetone. They were weighed into Savillex® PFA microcapsules (Parrish 1987) along with a mixed ^{205}Pb–^{235}U spike (Parrish & Krogh 1987) and 0.15 ml 48% HF and 0.015 ml 7M HNO_3. The microcapsules were placed in a steel-jacketed, 125 ml PTFE Parr® bomb to which 6 ml 48% HF were added. The bomb was heated in an oven for *c.* 30–48 hours at 240 °C, and then the solution in the microcapsules was evaporated. To ensure dissolution of the resultant fluoride salts, 0.2 ml 3.1 M HCl were added to the samples; they were put back into the Parr® bomb containing 5 ml 3.1 M HCl, and reheated in an oven at 210 °C for *c.* 14 hours. Separation and purification of U and Pb followed the method of Krogh (1973). Pb and U were loaded separately on single Re filaments using H_3PO_4 and silica gel. Analyses were performed on a VG Sector 54–30 thermal ionization mass spectrometer. The analytical data reported here were collected using an ion-counting Daly detector. All Pb analyses were performed at 1340 ± 30 °C and U at 1670 ± 30 °C in order to minimize intersample mass fractionation. Ratios were corrected for Pb mass fractionation of 0.086 ± 0.051 $\%\text{amu}^{-1}$, and U mass fractionation of 0.102 ± 0.047 $\%\text{amu}^{-1}$ based on multiple analyses of NBS981 and U500. Data reduction, error propagation and plotting were performed using the ISOPLOT and PBDAT programs (Ludwig 1993*a*, *b*). Ages were calculated using the decay constants of Jaffey *et al.* (1971). All errors are quoted at the 2σ level. Analytical data are presented in Table 1. The zircons from the Tayvallich Volcanics were analysed on the SHRIMP RG at the Stanford University–USGS microisotopic analytical centre (SUMAC). Procedures followed standard SHRIMP operating conditions (Muir *et al.* 1996). A 7 nA primary O_2-beam was used to erode a pit of 30 μm diameter with positive secondary ions extracted. Individual masses were analysed at a mass resolution of 7000 R (10% full-width base height definition). U and Th

Table 1. . *U–Pb data for 'Newer' basic intrusions*

Fractions	Measured						Atomic ratios§			Ages (Ma)			
Fraction number and description*	Wt [µg]†	U (ppm)	Pb rad. (ppm)	Total common Pb (pg)	^{206}Pb/^{204}Pb‡	^{208}Pb/^{206}Pb	^{206}Pb/^{238}U	^{207}Pb/^{235}U	^{207}Pb/^{206}Pb	^{206}Pb/^{238}U	^{207}Pb/^{235}U	^{207}Pb/^{206}Pb	ρ‖
Insch (RC 2168)													
1 NM0, +100, cl, eu, prisms	108	41.1	3.50	220	109.8	0.2866	0.07368 ± 136	0.5746 ± 116	0.05655 ± 45	458	461	474	0.921
2 NM0, +100, cl, needles	222	39.2	3.24	46	841.9	0.3233	0.06967 ± 82	0.5418 ± 68	0.05640 ± 24	434	440	468	0.942
Morvern–Cabrach (RC 2165)													
3 NM0, +100, cl, eu, prisms	306	–	1.93	130	244.3	0.3812	–	–	0.05650 ± 46	–	–	472	–

[*] NM0, fractions are non-magnetic at 1.5A, 0° tilt on Frantz isodynamic magnetic separator; + 100, grain size microns; cl, clear; eu, euhedral.

† Uncertainty in weight ± 6 µg (2σ).

‡ Corrected for fractionation and spike, 50 pg Pb blank (isotopic composition ^{208}Pb: ^{207}Pb: ^{206}Pb: ^{204}Pb = 36.88: 15.49: 17.35: 1), and 10 pg U blank.

§ Corrected for fractionation, spike, blank and initial common Pb calculated from the model of Stacey & Kramers (1975).

‖ $\rho = {}^{207}\mathrm{Pb}/{}^{235}\mathrm{U} - {}^{206}\mathrm{Pb}/{}^{238}\mathrm{U}$ error correlation coefficient (Ludwig 1993*b*).

Table 2. *U–Pb isotope data for zircons from the Tayvallich tuffs*

	U (ppm)	Th (ppm)	Th/U	f206 (%)	^{204}Pb/^{206}Pb ($\times 10^{-5}$)	^{207}Pb/^{206}Pb	^{238}U/^{206}Pb	Age (Ma)
1.1	201	209	1.040	−0.04 ± 0.10	6 ± 8	0.0593 ± 0.0008	10.43 ± 0.16	590.5 ± 8.6
2.1	583	343	0.588	0.07 ± 0.07	2 ± 2	0.0605 ± 0.0006	10.25 ± 0.08	599.9 ± 4.5
3.1	1263	971	0.769	0.10 ± 0.05	5 ± 2	0.0608 ± 0.0004	10.19 ± 0.07	602.7 ± 4.1
4.1	194	155	0.800	0.10 ± 0.15	5 ± 12	0.0607 ± 0.0012	10.25 ± 0.13	599.5 ± 7.3
5.1	119	73	0.614	0.23 ± 0.21	17 ± 13	0.0613 ± 0.0017	10.57 ± 0.19	581.5 ± 9.9
6.1	1192	845	0.709	0.00 ± 0.04	1 ± 1	0.0600 ± 0.0003	10.22 ± 0.07	601.7 ± 3.8
7.1	694	572	0.824	0.04 ± 0.06	1 ± 2	0.0603 ± 0.0005	10.21 ± 0.08	602.2 ± 4.4
8.1	2742	3964	1.445	−0.07 ± 0.04	0 ± 1	0.0598 ± 0.0003	9.92 ± 0.06	619.4 ± 3.5
9.1	228	178	0.781	0.06 ± 0.13	11 ± 8	0.0607 ± 0.0010	10.07 ± 0.10	610.2 ± 6.0
10.1	397	297	0.748	0.02 ± 0.07	1 ± 4	0.0601 ± 0.0006	10.22 ± 0.08	601.9 ± 4.8
11.1	492	478	0.972	0.02 ± 0.07	0 ± 3	0.0600 ± 0.0006	10.30 ± 0.08	597.1 ± 4.6
12.1	1256	930	0.741	−0.07 ± 0.06	1 ± 2	0.0594 ± 0.0005	10.24 ± 0.07	601.0 ± 3.8
13.1	1345	1007	0.749	0.01 ± 0.06	0 ± 2	0.0601 ± 0.0005	10.18 ± 0.07	603.8 ± 3.7
14.1	1270	918	0.723	0.02 ± 0.06	3 ± 1	0.0602 ± 0.0005	10.18 ± 0.08	604.1 ± 4.4

Errors are 1σ. U/Pb normalized to 1099 Ma AS57 standard. Ten samples give 1099.4 ± 2.4 (1σ) with MSWD = 0.63 (0.5% uncertainty summed in quadrature for standard and unknown analyses). Comments: Analysis 8.1 is a high U grain. Older apparent age may be due to inappropriate calibration for high U grains. All remaining analyses give a satisfactory mean 601.4 ± 1.3 Ma (1σ). Summing in the final error of the standard gives 601.4 ± 3.7 Ma ($2\sigma_m$) or 601 ± 4 Ma.

concentrations were normalized to the Australian National University standard SL13 (238 ppm U; 21 ppm Th). Pb/U ratios were calibrated with UO/U and normalized to AS57 from the 1099 Ma Duluth Anorthosite Complex. Analytical data are presented in Table 2. Ten standards were analysed during the course of the analytical session and all were within error to give a mean ^{206}Pb/^{238}U ratio of 1099 ± 2.4 Ma ($1\sigma_m$, MSWD = 0.63); equating to a relative uncertainty of 0.5% to be added as a systematic error to the normalized age determination.

Sampling, zircon morphology and results

Insch

A sample (RC 2168) of an upper zone 'b' syenogabbro of the Insch intrusion (Wadsworth 1970) from the disused quarry near Mill of Johnston [Grid Reference NJ 571 247] yielded a zircon population of needles, euhedral prisms and sub-rounded grains. The sample is a medium-grained, clinopyroxene–orthopyroxene monzonite with minor marginal amphibolitization of the mafic minerals. Orthoclase is more abundant than plagioclase feldspar. Apatite, zircon and opaques are common accessory phases. Typically the zircons display no zoning when examined using back-scattered electron images and only weak oscillatory and sector zoning under cathodoluminescence. Non-magnetic, clear, crack- and inclusion-free needle and prism fractions were picked and strongly abraded. The prisms (fraction #1) are slightly discordant (3.4%) with a ^{207}Pb/^{206}Pb age of 474 Ma; the needles are a little more discordant with a ^{207}Pb/^{206}Pb age of 468 Ma (Table 1, Fig. 3). The U contents of both fractions are extremely low at *c.* 40 ppm, comparable with those of some granulite facies gneisses (e.g. Corfu *et al.* 1994). Regression of the data with a fixed lower intercept of 0 ± 50 Ma (Dunning & Krogh 1985) yields an age of 470 ± 9 Ma that is considered to be the crystallization age of the Insch gabbro.

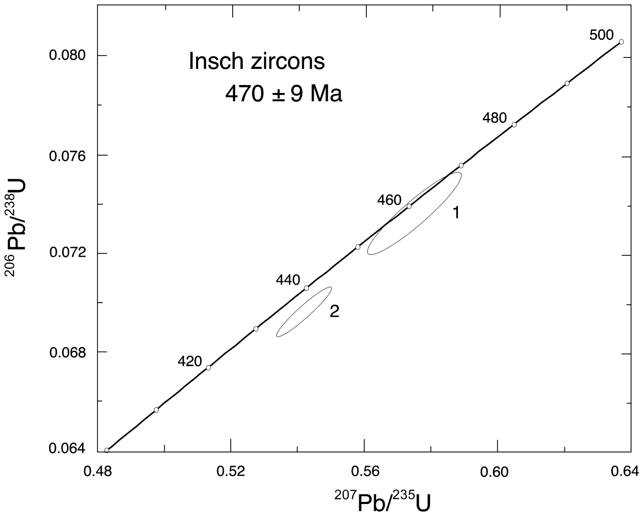

Fig. 3. U–Pb concordia plot showing analyses of zircons from the Insch gabbro (1, prisms; 2, needles).

Morven Cabrach

Zircons from a sample (RC 2165) of medium-grained clinopyroxene-bearing monzonite from Craig of Bunzeach within the Morven Cabrach intrusion [NJ 370 094] contain ubiquitous inclusions of apatite and opaque oxides. Orthoclase is somewhat less abundant in this sample than in the monzonite from Insch, coarse biotite is present and amphibolitization of pyroxene and biotite is pervasive with only rare relicts of clinopyroxene preserved. Occasional small euhedral cores are recognized within a few of the zircon prisms (Fig. 4) which contain concentric oscillatory zoning parallel to the outer edges of the grains. These cores probably represent an earlier phase of magmatic growth. However typically the zircons are unzoned. A needle fraction contained about half of the radiogenic Pb of the Insch samples, and yielded a ^{207}Pb/^{206}Pb age of 472 Ma (Table 1), similar to the age obtained from Insch. The low concentration of radiogenic Pb implies that there is only about half the U content of the zircons at Insch, assuming that the intrusions are the same age. Because of such low U contents we were unable to analyse successfully the U content of these needles. Nonetheless, the similarity of the ^{207}Pb/^{206}Pb ages, coupled with the needle morphology, lead us to conclude that the Morven Cabrach intrusion is also the same age (*c.* 470 Ma) as Insch.

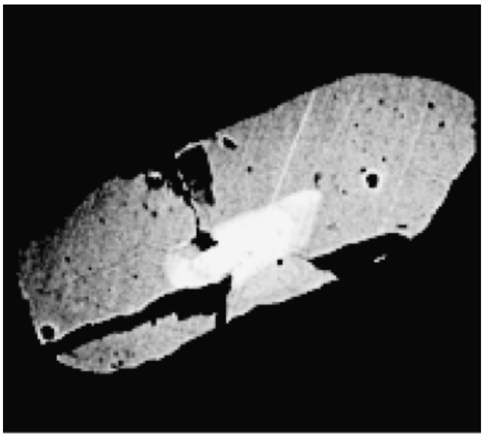

Fig. 4. Back-scattered electron image of zircon separated from the Morven Cabrach gabbro. Field of view 150 μm.

Tayvallich Volcanics

A sample of tuff was collected from the western coast of the Tayvallich Peninsula at Port a' Bhuailteir [NR 688 810]. Here a series of felsic tuff bands are interstratified with typical dark green fine-grained mafic tuffs and breccias contained within the more massive pillowed and non-pillowed mafic lava sequences (Gower 1977). The thickest of these felsic tuff bands was sampled; it forms a narrow (*c.* 0.4 m) pale pink band interbedded within the main lava sequence which consists of stratified dark green amphibolites. This tuff band can be traced along strike parallel to the coast for *c.* 60 m. Within this sequence, coarse breccias occur that contain large clasts of 'keratophyre', similar in hand specimen to the intrusion dated by Halliday *et al.* (1989). The tuff is composed predominantly of fine-grained (*c.* 25 μm) quartz and albite, with small white micas defining a penetrative cleavage, rare biotite and calcite, and opaques. Locally the band contains coarser-grained (1 mm) white feldspars. Zircon separates were examined for signs of inheritance using a combination of back-scattered electron imaging, and cathodoluminescence and unlike those from the Halliday *et al.* (1989) study, the zircons contain no obvious cores. Zircons from the Tayvallich volcanics show a wide range in trace element chemistry with U variation from 120 to 2700 ppm, and Th from 73 to 4000 ppm, and Th/U ranging from 0.59 to 1.45. Analyses show very low levels of common Pb with estimations based on ^{204}Pb being within error of zero. This is also apparent on the conventional Tera-Wasserburg concordia diagram (uncorrected common Pb plotted) with all data plotting within error of the concordia (Fig. 5). Thirteen of the fourteen zircon analyses lie within error of their mean ^{206}Pb/^{238}U age of 601.4 ± 1.3 Ma ($1\sigma_m$, MSWD = 0.82). One analysis lies to the older side of the main cluster. It may be xenocrystic, but this grain has extremely high U and Th concentrations and it is more likely that this is an artifact of the U–Pb calibration procedure. The zircons from this rock therefore appear to show only a single population with a calculated age of 601 ± 4 Ma ($2\sigma_m$) that is within error of the age determined by Halliday *et al.* (1989). This date confirms a late Precambrian age for the start of Southern Highland Group deposition. The 'inherited' cores of zircon identified within the 'keratophyre' seem likely to represent an early magmatic pulse within the same igneous system.

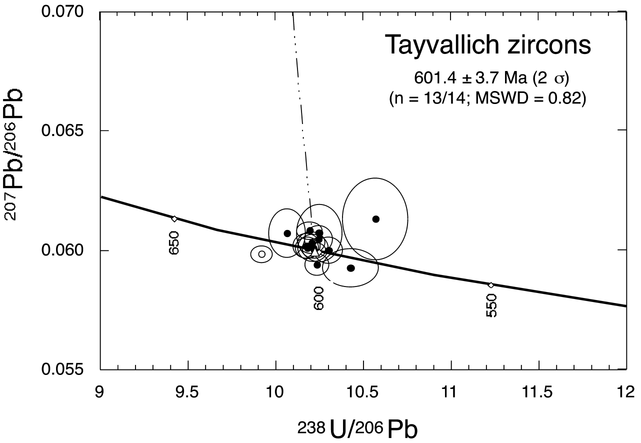

Fig. 5. Tera–Wasserburg concordia plot showing U–Pb SHRIMP analyses of the zircons from the Tayvallich Tuff.

Implications for the age of orogenesis and deposition of the Dalradian rocks.

Stratigraphical continuity at the top of the Dalradian pile and the timing of Palaeozoic orogenesis

Deposition of all of the Dalradian sediments, nappe formation, thickening and the early parts of the regional metamorphic history, must have occurred before 470 ± 9 Ma, the age of the 'Newer gabbros' (Fettes 1970). This situation appears to be strikingly similar to that reported by Friedrich *et al.* (1999*a*, *b*) who obtained ages of *c.* 470–475 Ma for the gabbros, emplaced in previously metamorphosed Dalradian rocks (Yardley *et al.* 1987; Tanner 1990) from Connemara, Ireland. Friedrich *et al.* (1999*a*, *b*) concluded that the syn-D_2 intrusion of these gabbros (Wellings 1998) at *c.* 475 Ma coincided with the end of sedimentation on the Laurentian passive margin (which was interpreted to include the Dalradian sediments) and hence dates the *onset* of the Grampian orogeny. On this basis they concluded that the Grampian orogeny was very short-lived. Although a tempting correlation to make (Dewey & Mange 1999), this assumes a close proximity at this time between Laurentia and the Dalradian blocks that may not be justified (e.g. Bluck *et al.* 1997), and a more cautious approach may be warranted.

The 'Newer Gabbro' U–Pb zircon ages, in combination with mica cooling ages from much of the Highlands (Dewey & Pankhurst 1970; Dempster 1985) do point to a fairly rapid *end* to the Caledonian orogeny, especially within the southern parts of the belt. The age of peak Barrovian metamorphic garnet growth in the Scottish Dalradian, 467 ± 3 Ma (Oliver *et al.* 2000) is very similar to that of the gabbros. However, there are few age constraints on the *start* of orogenesis. Heating associated with thickening-related metamorphism of the sort preceding the gabbro emplacement is typically slow (England & Richardson 1977), *much* slower than thermal changes driven by rapid unroofing (e.g. Baldwin *et al.* 1993; Crowhurst *et al.* 1996). Hence the 470 ± 9 Ma age of the *late* orogenic Scottish gabbros is difficult to reconcile with both continued Dalradian deposition into the Tremadoc/Arenig (Tanner 1995, Molyneux 1998), and an *entirely* post-Arenig (< *c.* 466 Ma; Tucker & McKerrow 1995) orogeny (Soper *et al.* 1999). Therefore the crustal thickening that affects the Southern Highland Group rocks (deposited post-600 Ma) most likely represents a pre-Arenig Caledonian event (Dempster *et al.* 1995).

If deposition of the Southern Highland Group did indeed continue into the Ordovician (Soper *et al.* 1999), then not only is rapid prograde metamorphism required but also *exceptionally* slow deposition is needed. In this model, typically about 2–3 km of Southern Highland Group sediments (Harris *et al.* 1994) must have accumulated in *c.* 130 Ma (i.e. roughly equivalent to the total Ordovician–Devonian time span). However, thickly bedded turbidite successions are not typical of slow deposition! Continuous deposition within the Highland Border Complex also appears to be ruled out by the presence of ophiolitic units such as the *amphibolite-facies* metabasic rocks of the ophiolite sole (Henderson & Robertson 1982; Dempster & Bluck 1991), found adjacent to the low-grade greenschist-facies Dalradian rocks. This juxtaposition, the presence of exotic clasts in boulder-bearing conglomerates (Dempster & Bluck 1989), and the thick mylonite, found locally in the Highland Border Complex (Henderson & Robertson 1982), is incompatible with models of continuous deposition at the southern margin of the Dalradian. Such evidence of a faulted (terrane) boundary with considerable displacement along the edge of the Highlands suggests that models relying on compatible geological histories across the fault-bounded blocks of Scotland face problems.

We conclude that continuous deposition for 130 Ma is unlikely to have occurred, and there must be breaks and omissions from the sequence between the reliably dated Arenig (*c.* 470 Ma) rocks (Curry *et al.* 1984) at the Highland Border and the reliably dated late Precambrian (Tayvallich) 600 Ma Dalradian rocks. With respect to the Ordovician Highland Border Complex rocks, apparent structural continuity (Johnson & Harris 1967) within a complex fault zone is an unreliable indicator of stratigraphical continuity (Tobisch & Fiske 1982; Tavarnelli & Holdsworth 1999).

Stratigraphical continuity in the middle of the Dalradian pile

Whilst it is difficult to understand how a Barrovian metamorphism could have been generated in the Dalradian rocks during a short-lived Arenig orogeny, it is especially difficult to see how *two* separate regional metamorphic events (e.g. Dempster & Harte 1986) could be squeezed into the same time gap between proposed Arenig (*c.* 470 Ma) deposition of the uppermost Dalradian and the regional cooling event at *c.* 460 Ma. Although distinguishing separate regional metamorphic events from stages in a single prograde cycle is difficult, prograde Barrovian metamorphism is not typically associated with increasing pressures as found in areas of the Dalradian (Dempster & Harte 1986). Given the relatively rapid end to the 470 Ma event (e.g. Dempster 1985) the presence of polymetamorphic assemblages suggest that the earliest phase of regional metamorphism significantly predates a widespread *c.* 470 Ma overprint (Oliver *et al.* 2000). Such evidence of an early metamorphism is mostly restricted to the Argyll Group rocks and apparently 'deeper' stratigraphic levels (Chinner & Heseltine 1979; Beddoe-Stephens 1990; Dempster & Harte 1986). In addition, rare pre-470 Ma isotopic dates are found within the older parts of the Dalradian pile (e.g. Argyll Group, Dempster 1985; Dempster *et al.* 1995) and the Central Highlands area (Noble *et al.* 1996; Highton *et al.* 1999). Although the timing of an early event is reasonably well known as Neoproterozoic in the Central Highlands area (Noble *et al.* 1996; Highton *et al.* 1999), its nature, timing or even presence, is not well constrained in the Argyll and Appin Group rocks. The emplacement of the Ben Vuirich Granite at 590 ± 2 Ma (Rogers *et al.* 1989) does provide some indications of the thermal state of these rocks during the Late Proterozoic. The structural age of this intrusion depends on correlations of structures from the southern boundary of the Highlands and has been the subject of many publications (Bradbury *et al.* 1976; Rogers *et al.* 1989; Tanner & Leslie 1994; Tanner 1996). Structural arguments in favour of either pre-D_1 or post-D_1 emplacement, and on the nature of pre-hornfels fabric, are presented elsewhere (Tanner 1996), however, the interpretation of these relationships is such a key factor that a few aspects that are independent of structural considerations are highlighted below.

(1) High- and moderate-temperature metamorphic aureoles around granites are not typically developed in rocks that have not previously experienced regional metamorphism (see Kerrick 1991).

(2) The Ben Vuirich Granite was emplaced into crust that locally preserves evidence of an 'early' phase of regional metamorphism (Dempster & Harte 1986).

(3) Pressures within the aureole defined on the basis of the reported contact metamorphic assemblages indicate conditions of between 2 and 4 kbar (Tanner 1996).

The pressures of the contact metamorphic rocks have perhaps the most significant implications for the timing of the intrusion relative to the tectonothermal evolution of the Dalradian. These pressure estimates have been revised by Ahmed-Said & Tanner (2000) on the basis of the composition of the granite. However, their revised lower pressure estimate of ≤ 2 kbar fails to incorporate the effects of the anorthite component in plagioclase on melt composition (see Thompson 1981; Johannes 1984), a factor, which if ignored, will *significantly* underestimate pressures. On an Ab–Or–Qz phase diagram the position of the granite minimum is shifted directly away from albite, by the effects of both low pressure and increased Ca in plagioclase (James & Hamilton 1969). The contact metamorphic assemblages of andalusite–cordierite–biotite–muscovite–quartz (Tanner 1996; Ahmed-Said & Tanner 2000) are compatible with peak temperatures in the range 550–600 °C (Pattison & Tracy 1991). This estimate used in combination with the temperature estimate of the granite magma of ≤ 700 °C (Ahmed-Said & Tanner 2000) suggests that original country rock temperatures may have been of the order of 400–500 °C (Jaeger 1968) (i.e. well into greenschist-facies conditions at the time of emplacement). Even assuming an unrealistically high geothermal gradient (cf. Ahmed-Said & Tanner 2000) a *minimum* depth of emplacement of 8–10 km is required.

Tanner's (1996) pressure estimate, based on the equilibrium cordierite–andalusite–muscovite–biotite–quartz assemblage (see Pattison & Tracy 1991) in the aureole, yields a similar depth of emplacement for the 590 Ma granite of *at least 7 km and up to 14 km*. Recent work has suggested that the granite was emplaced into the relatively thin sequence of strata of the upper part of the Appin Group (A. G. Leslie pers. comm. but see Bradbury *et al.* 1979). Quoting a *maximum* thickness of 9 km for the whole of the Argyll Group determined in Harris *et al.* (1994), Tanner (1996) suggested this would be consistent with pre-tectonic emplacement of the granite. However, crucially the maximum sedimentary thickness takes no account of tectonic thickening or lateral sedimentary thickness variations (Harris *et al.* 1994). It is notable that the similarly derived estimate of >25 km for thickness for the whole Dalradian sedimentary pile, is greater than the thickest passive margin sequence (Miall 1990), or indeed any sedimentary thickness in present day basin settings. This would place the base of the Dalradian basin within a few kilometres of the base of the continental crust! Even the estimated 9 km for the Argyll Group *alone* is well in excess of maximum basin thickness in most tectonic settings. Where the post-deformational thicknesses of the Argyll Group rocks are constrained close to the Central Perthshire area (Harris *et al.* 1994, fig. 14, S8-10), values of *c.* 3–5 km are reported. Such thicknesses are not only far more realistic but crucially would be inadequate to generate the pressures of metamorphism experienced in the aureole rocks of the Ben Vuirich Granite, even allowing for large errors in geobarometry.

The possibility that these rocks were thickened during the 870–780 Ma orogeny that affected Moine and Central Highland Division rocks to the north can not be entirely discounted. However, the presence of glacial deposits at deeper levels within the apparent stratigraphy argues for a thickening event between 720 and 590 Ma ago (see next section).

Consequently we conclude that an *orogenic* break may be present in the middle of the Dalradian succession somewhere stratigraphically above the Appin Group and below the Tayvallich Volcanics.

Global events and Dalradian stratigraphy.

The late Proterozoic Dalradian rocks of Scotland and Ireland appear to contain abundant evidence of glacial activity, notably the Port Askaig Boulder Bed, which occurs at the base of the Argyll Group (Spencer 1971). This is not surprising given that Late Proterozoic glacial deposits are known throughout the globe (Hambrey 1983; Kaufman *et al.* 1997; Shields 1999; Evans 2000). Their presence at low- and mid-palaeolatitudes, together with associated excursions in the carbon isotope signature, has led to recent speculation of the existence of a Precambrian 'snowball' Earth (Hoffman *et al.* 1998). Glacial activity is recognized within two main pulses at *c.* 720 Ma (Sturtian) and 580 Ma (Marinoan) (e.g. Brasier *et al.* 2000) although there may be multiple events within each pulse (Kennedy *et al.* 1998).

The confirmation of a 600 Ma age for the Tayvallich Volcanics and the characteristic signature of diamictites and carbonates seen with some of the tillites (e.g. Port Askaig Boulder Bed) places further constraints on the stratigraphy of the Dalradian (e.g. Prave 1999; Brasier & Shields 2000). The apparently close stratigraphical association of the Tayvallich Volcanics with the Loch na Cille Boulder Bed (Elles 1935) suggests that if this is a tillite, it is probably the product of Marinoan glacial activity (Condon & Prave 2000). The occurrence of at least *two* other tillites apparently at stratigraphic levels significantly below the 600 Ma Tayvallich Volcanics suggests that these are most likely to be associated with the Sturtian event (*c.* 720 Ma). In this regard the Kinlochlaggan Boulder Bed (Treagus 1997) and the Port Askaig Boulder Bed may represent different pulses of this event, albeit apparently separated by significant stratigraphic thickness, or alternatively they may represent the same Sturtian (or a later) glacial horizon duplicated tectonically (see Evans & Tanner 1996; Treagus 1997; Evans & Tanner 1997; Robertson & Smith 1999).

We conclude that *either* significant parts of the Dalradian stratigraphy (and the possible faunas in some of these sediments (Brasier & McIlroy 1998, but see Brasier & Shields 2000)) are of Sturtian age (*c.* 720 Ma), *or* major tectonic breaks occur within the Dalradian stratigraphy to allow the Port Askaig Boulder Bed to be linked to the Marinoan event. However, if a Sturtian age for the Port Askaig Boulder Bed, and a model involving continuous Dalradian sedimentation to Arenig time, are *both* accepted then the Argyll and Southern Highland group sediments alone represent a highly improbable 250 Ma of uninterrupted deposition (Fig. 6). An alternative model (Fig. 6) is clearly more realistic and involves one or more orogenic breaks within the Dalradian stratigraphy.

Implications of a broken stratigraphy

Some of the implications of the presence of orogenic breaks, separating smaller packages of rock, within the 'Dalradian' are as follows.

(1) Stratigraphic continuity within the Dalradian block (cf. Harris & Pitcher 1975; Anderton 1985; Harris *et al.* 1994) would be destroyed. Models of Dalradian history built on this basis, such as the evolution from extensional basins to passive margin drape (e.g. Anderton 1985) would also be rejected.

(2) A corollary of this is that the Dalradian Supergroup is not an ideal sequence to use for constructing a Neoproterozoic chemostratigraphy (cf. Brasier & Shields 2000).

(3) The unified structural interpretation of the Dalradian block would no longer be tenable as there can not be complete structural continuity between the units. Generations of structural geologists have correlated structures from Southern Highland Group to Appin Group rocks and even from the Central Highland Division (with reliable metamorphic ages of 800 Ma, e.g. Noble *et al.* 1996) all the way through to the undisputed Ordovician rocks (Curry *et al.* 1982) at the Highland Border. Thus, throughout this crustal block, structures seem to follow a consistent sequence of deformation phases with consistent orientations and fabrics (Harris *et al.* 1976; Harte *et al.* 1984; Lindsay *et al.* 1989). Although the progressive evolution of styles may simply be a function of changing rheology, consistent orientations may be difficult to produce during a sequence of unrelated orogenic events (but see Tavarnelli & Holdsworth 1999).

(4) The way would be open for models that involve tectonic duplication and disruption of the overall chronostratigraphy. For example, rock units from the traditional stratigraphy could conceivably represent crustal terranes of identical age. Until reliable geochronological constraints are available for the rocks of the existing Argyll, Appin and Grampian groups, models involving significant repetitions within the sequence are plausible.

(5) The metamorphism of the Scottish Highlands would be seen as representing a variable Ordovician overprint on blocks with disparate thermal and tectonic histories.

Models invoking Precambrian orogenesis through much of the Dalradian pile are faced with the *enormous problem* that they require the presence of an orogenic break which has proved to be very elusive. Despite the recognition of some discontinuities (Gregory 1931; Garson & Plant 1973; Fettes *et al.* 1991; Goodman 1994; Robertson & Smith 1999), including possible periods of local non-deposition, the absence of obvious orogenic unconformities makes models invoking Late Precambrian, Cambrian and Early Ordovician crustal

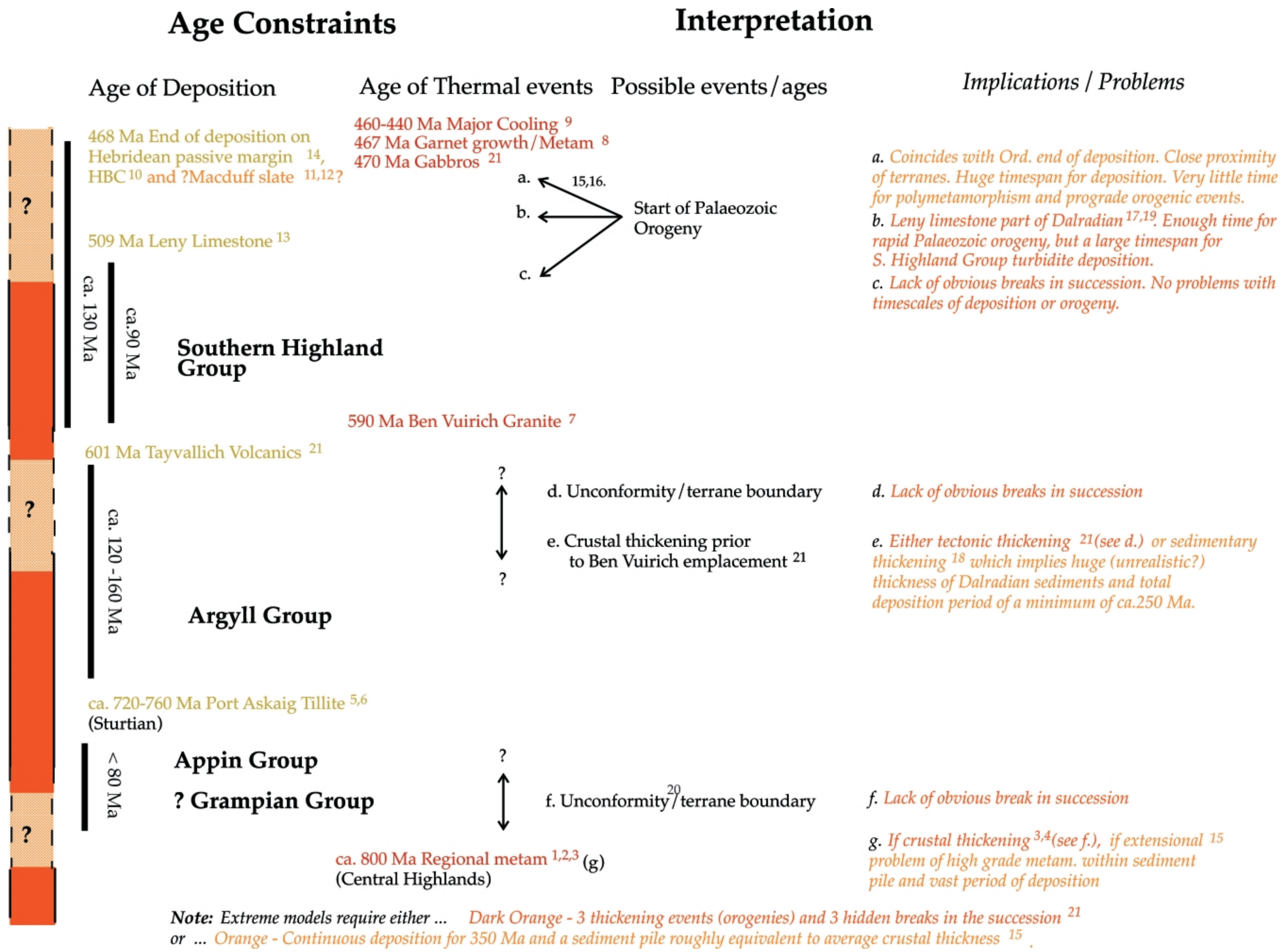

Fig. 6. Age constraints on Dalradian stratigraphy and tectonothermal events compared to models of Dalradian evolution. Major problems associated with models incorporating breaks in the succession (highlighted in dark orange) or no breaks in the succession (highlighted in pale orange) are emphasized. Uncertainties regarding the timing and presence of orogenic activity are illustrated in the stratigraphic column. Evidence for a break in the succession associated with the *c.* 800 Ma event is discussed in Tanner & Bluck (1999). Sources: 1, Noble *et al.* (1996); 2, Highton *et al.* (1999); 3,Vance et al. (1999); 4, Phillips *et al.* (1999); 5, Prave (1999); 6, Condon & Prave (2000); 7, Rogers *et al.* (1989); 8, Oliver *et al.* (2000); 9, Dempster (1985); 10, Curry *et al.* (1984); 11,. Downie *et al.* (1971); 12, Molyneux (1998); 13, Pringle (1939); 14, Bergstrom & Orchard (1985); 15, Soper *et al.* (1999); 16, Friedrich *et al.* (1999*a*); 17, Tanner (1995); 18, Tanner (1996); 19, Harris (1962); 20, Robertson & Smith (1999); 21, This study.

thickening very difficult to sustain. However, the lack of reliable age constraints throughout the Dalradian pile makes it difficult to know where to look for the evidence of breaks in the sequence. In part this problem may be because boundaries are represented by tectonic slides (e.g. Bailey 1922), and in part it may have resulted from an understandable desire to look for unity in mapping of both structures and stratigraphy. It seems most likely that the suggested crustal blocks are separated by tectonic boundaries, as orogenic unconformities would be easier to identify and also imply an intact chronostratigraphy, which seems improbable.

At present our preferred model (Fig. 6) would incorporate the following terrane boundaries, although we must emphasize that their locations are *very* poorly constrained and we would not wish to exclude the possibility of other equally well hidden breaks within the Dalradian stratigraphy.

(i) A Caledonian (pre-470 Ma) orogenic break between the Dalradian and the Ordovician rocks of the Highland Border Complex. Many have attributed a break at the Highland Border to the presence of the Highland Boundary Fault (e.g. Bluck 1984), whereas others have argued for structural continuity. Tanner & Pringle (1999) argued for overall continuity up to the early Cambrian at Callander, although significant changes in provenance and rock chemistry were identified. Doing away with the need for continuous (600–470 Ma) deposition allows both a more reasonable timescale for Dalradian deposition and provides a little more time for the early stages of Caledonian orogenesis.

(ii) A late Precambrian (pre-590 Ma) orogenic break near the top of the Argyll Group. This thickening event would have produced relatively low-grade (greenschist-facies) regional metamorphism reaching a maximum grade in the Appin and Argyll group rocks of Central Perthshire (i.e. the earliest phase of the polymetamorphism in these areas). Higher-grade *c.* 800 Ma assemblages of the Central Highlands are typically not significantly overprinted, but generally elsewhere Caledonian (470 Ma) metamorphic overprinting is very common.

Discussion

The deposition of Dalradian sediments in part coincides with an extreme global environment, possibly involving long-lived 'snowball' conditions (Hoffman *et al.* 1998; Prave 1999). Such an environment would be expected to have a profound influence on the depositional record within sediments formed at the time, and would create breaks in deposition within basins as precipitation ceased during which there may not even have been production of glacial tills (see Christie-Blick *et al.* 1999; Hoffman & Schrag 1999). Whereas tills could conceivably mark the beginning and end of such 'snowball' periods, prolonged breaks in deposition may occur during these events and significant fractions of Dalradian history may be hidden here. This may be relevant to arguments about the apparently prolonged nature of deposition within, for example, the Southern Highland Group (i.e. post-Tayvallich volcanics (600 Ma) through to Leny Limestone at *c.* 508 Ma). Such conditions could also influence the nature of orogeny and cause difficulty in recognizing breaks within the Dalradian sequence. The absence of precipitation and erosion for a considerable period of time would mean that major unconformities could not be generated. Although crustal thickening could occur, subsequent thinning during continued 'snowball' conditions must occur by extension rather than erosion. The longer these global glaciations lasted, the greater chance there would be of orogens thinning without either a sedimentary record or major unconformities being produced. Perhaps the unusual nature of this period in Earth's history provides clues as to why the stratigraphic record within the Dalradian is so difficult to decipher.

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