Geoscience Frontiers 8 (2017) 1469–1478

HOSTED BY
ELSEVIER

Contents lists available at ScienceDirect

China University of Geosciences (Beijing)

Geoscience Frontiers

journal homepage: www.elsevier.com/locate/gsf

Research Paper

Zircon geochronology reveals polyphase magmatism and crustal anatexis in the Buchan Block, NE Scotland: Implications for the Grampian Orogeny

T.E. Johnson [a,*], C.L. Kirkland [a], D.R. Viete [b], S. Fischer [c], S.M. Reddy [a], N.J. Evans [a], B.J. McDonald [a]

[a] *Department of Applied Geology, The Institute for Geoscience Research (TIGeR), CET-Curtin Node, John de Laeter Centre, Curtin University, Perth, WA 6102, Australia*
[b] *Morton K. Blaustein Department of Earth & Planetary Sciences, Johns Hopkins University, Olin Hall, 3400 N Charles Street, Baltimore, MD 21218, USA*
[c] *School of Earth & Environmental Science, University of St Andrews, Irvine Building, North Street, St Andrews, KY16 9AL, Scotland, UK*

ARTICLE INFO

Article history:
Received 28 December 2016
Received in revised form
3 February 2017
Accepted 9 February 2017
Available online 21 February 2017
Handling Editor: M. Santosh

Keywords:
Dalradian
Grampian Orogeny
Buchan Block
Zircon geochronology
Magmatism
Metamorphism

ABSTRACT

The type locality for high-temperature, low-pressure regional metamorphism, the Buchan Block in NE Scotland, exhibits profound differences to the rest of the Grampian Terrane. These differences have led some to regard the Buchan Block as an exotic crustal fragment comprising Precambrian basement gneisses and cover rocks thrust into their current position during Grampian orogenesis. Although rocks of the Buchan Block are now generally correlated with Dalradian strata elsewhere, the origin of the gneisses and the cause of the high heat flow and associated magmatism is debated. We report SIMS U–Pb and LA-ICPMS Hf isotopic data in zircon from high-grade rocks from the northeast (Inzie Head Gneiss) and northwest (Portsoy) corners of the Buchan Block. Around Inzie Head, upper amphibolite to granulite facies metasedimentary gneisses coexist with diorite sheets that were emplaced contemporaneously with partial melting of their host rocks, at least locally. U–Pb geochronology indicates a crystallisation age for the diorite of 486 ± 9 Ma. Highly-deformed diorites within the Portsoy Gabbro have a crystallisation age of 493 ± 8 Ma. Ages of ca. 490 Ma for magmatism and high-grade metamorphism, which are broadly contemporaneous with ophiolite obduction and the onset of orogenesis, are significantly older than the established peak of Grampian metamorphism (ca. 470 Ma). We propose a new model for the Grampian Orogeny involving punctuated tectonothermal activity due to tectonic switching during accretionary orogenesis. Rollback of a NW-dipping subduction zone at ca. 490 Ma produced a back-arc environment (the Buchan Block) with associated arc magmatism and high dT/dP metamorphism. Arrival of an outboard arc resulted in shortening (the initial phase of the Grampian Orogeny) at ca. 488 Ma. Rollback of a NW-dipping subduction zone to the SE of the ca. 488 Ma suture began at 473 Ma and led to lithospheric-scale extension, decompression melting and advective heating of the middle crust, producing the widespread ca. 470 Ma Grampian (classic Barrovian and Buchan) regional metamorphism. Resumed hinge advance and the final phase of shortening cut off the heat supply at ca. 465 Ma, marking the end of the Grampian Orogeny.

1. Introduction

Accretionary orogens record a complex interplay of subduction retreat and advance (Collins, 2002; Wallace et al., 2005; Lister and Forster, 2009; Moresi et al., 2014). Slab rollback and subduction hinge retreat induces rifting and high-grade metamorphism focused in backarcs; subduction hinge advance, triggered by the arrival of buoyant crust, results in shortening, folding of still-hot, high-grade rocks and, eventually, cooling during progressive thickening (Thompson et al., 2001; Collins, 2002; Hyndman et al., 2005; Lister and Forster, 2009). These changing tectonothermal settings are encoded in the minerals and microstructures of metamorphic rocks.

* Corresponding author.
E-mail address: tim.johnson@curtin.edu.au (T.E. Johnson).
Peer-review under responsibility of China University of Geosciences (Beijing).

http://dx.doi.org/10.1016/j.gsf.2017.02.002

The Grampian Orogeny of Scotland and Ireland (Lambert and McKerrow, 1976) records collision of island arcs with the margin of Laurentia during closure of the Iapetus Ocean in the early Palaeozoic (Dewey and Shackleton, 1984; Van Staal et al., 1998; Oliver, 2001; Tanner, 2014). Most models suggest ocean closure occurred via south or southeast dipping subduction that culminated in ophiolite obduction, arc accretion and, in the latter stages of orogeny, a reversal in subduction polarity outboard of the accreted arc (Mitchell, 1978; Dewey and Shackleton, 1984; Dewey and Mange, 1999; Dewey, 2005; cf. Tanner, 2014). Geochronological data indicate that tectonothermal events occurred over a restricted time period between 473 and 465 Ma, in which regional metamorphism peaked at ca. 470 Ma (Friedrich et al., 1999; Soper et al., 1999; Flowerdew et al., 2000; Oliver et al., 2000; Baxter et al., 2002; Carty et al., 2012; Viete et al., 2013).

Most Dalradian rocks record Barrovian metamorphism associated with moderate apparent geothermal gradients (dT/dP) and, in metapelitic rocks of suitable grade, the transition from kyanite to sillimanite (Barrow, 1893, 1912). However, in the Buchan Block of NE Scotland, the rocks record high dT/dP Buchan metamorphism, characterised by the transition of andalusite to sillimanite in metapelitic rocks, which was broadly contemporaneous with ductile deformation, emplacement of mafic magmas, crustal anatexis and generation of peraluminous granite (Ashcroft et al., 1984; Oliver et al., 2000; Johnson et al., 2001a,b, 2003, 2015; Carty et al., 2012). These differences, and sparse geochronological data, have led some to regard the Buchan Block as an allochthonous terrane comprising exotic pre-Caledonian gneisses and cover rocks thrust into their current position during Grampian orogenesis (Sturt et al., 1977; Ramsay and Sturt, 1979). Although metasedimentary rocks of the Buchan Block are now generally correlated with Dalradian strata elsewhere (Stephenson et al., 2013b), the interpretation that some of the migmatitic gneisses represent Precambrian basement persists (Viete et al., 2010, 2014).

Two such areas of gneisses are exposed on the Scottish coast, from the east side of Fraserburgh Bay to Inzie Head (Inzie Head Gneiss; Read, 1952; Fig. 2) and from the east side of Portsoy to the west side of Boyne Bay (Cowhythe Gneiss; Read, 1923, 1955; Ramsay and Sturt, 1979; Viete et al., 2010; Fig. 2). In the Inzie Head Gneiss, Argyll Group metasedimentary migmatites are intimately mingled with sheets of diorite (Johnson et al., 2001a,b). In the Cowhythe Gneiss, layers of mafic metavolcanic rock occur within migmatitic rocks (Viete et al., 2010). We report SIMS U–Pb and LA-ICPMS Hf isotopic data from zircon to constrain the timing of magmatism and high-grade metamorphism in the region of Inzie Head, and magmatism at Portsoy, with consequences for the geodynamic setting and tectonothermal evolution of the Buchan Block.

2. Geological setting

The Grampian Terrane is one of several major crustal blocks that were amalgamated to form the northern part of the British Isles. It comprises a NE–SW-trending belt of rocks that extends from the Shetland Islands through the Scottish Highlands and into northern and northwestern Ireland, and is bound to the north by the Great Glen Fault and to the south by the Highland Boundary Fault–Fair Head–Clew Bay Line (Fig. 1). The Grampian Terrane is dominated by rocks of the Dalradian Supergroup, a deformed and metamorphosed mid-Neoproterozoic to early Palaeozoic, mainly clastic sedimentary sequence, which is intruded by igneous rocks ranging from peridotite to granite. The rocks record a complex sequence of tectonomagmatic events, termed the Caledonian orogenic cycle (McKerrow et al., 2000; Chew and Strachan, 2014), related to the opening and closure of the Iapetus Ocean during supercontinent breakup and reassembly during the early Palaeozoic (Soper, 1994; Dewey and Mange, 1999; Cawood et al., 2003, 2007; Chew et al., 2009; Kirkland et al., 2013; Chew and Strachan, 2014). Recent reviews on the Caledonides of Scotland and Ireland are provided by Stephenson et al. (2013a), Chew and Strachan (2014), Tanner (2014) and Dewey et al. (2015), and of the geology of the north-east Grampian Highlands, including the Buchan Block, by Stephenson et al. (2013b).

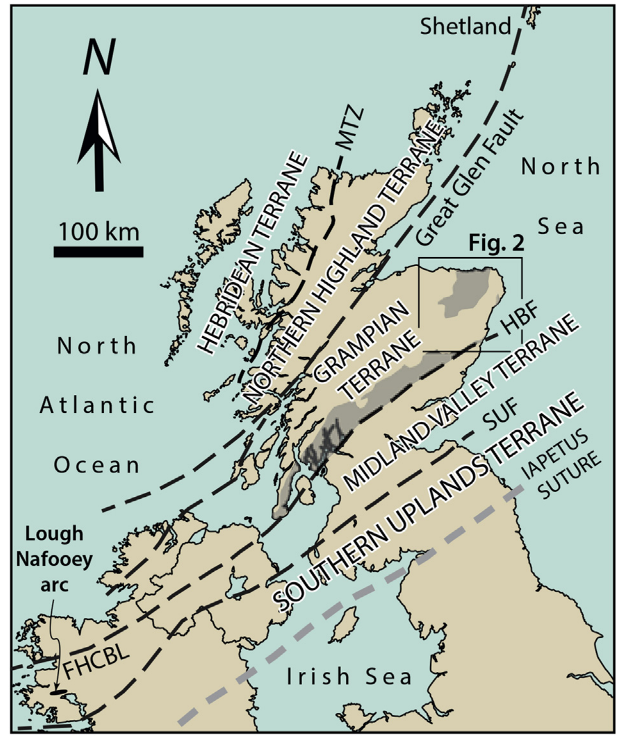

Figure 1. Terrane map of the British Isles. The Buchan Block, part of the wider Grampian Terrane, is located within the box (see Fig. 2). The darker shading shows the outcrop of Southern Highland Group rocks in Scotland. HBF = Highland Boundary Fault; FHCBL = Fair Head–Clew Bay line; SUF = Southern Uplands Fault. The location of the Lough Nafooey arc and the proposed position of the Iapetus suture are indicated.

An early phase of the Caledonian orogenic cycle, the Grampian Orogeny, records collision of oceanic arcs with the rifted Laurentian margin (e.g. Dewey and Shackleton, 1984; Van Staal et al., 1998; Oliver, 2001; Tanner, 2014; Fig. 1). A U–Pb zircon age of 493 ± 2 Ma for a subduction-related gabbro from the Tyrone Igneous Complex, Ireland, indicates subduction at or near the Laurentian margin before 490 Ma (Draut et al., 2009). U–Pb zircon ages of 490 ± 3 Ma and 488 ± 2 Ma for plagiogranite boulders from the Lough Nafooey Volcanic Arc date latest pre-Grampian subduction in the region (Chew et al., 2007). Similar $^{40}Ar/^{39}Ar$ hornblende ages of 490 ± 4 Ma and muscovite ages of 488 ± 1 Ma, from amphibolite and a metasedimentary xenolith, respectively, date ophiolite obduction in Scotland, suggesting that Grampian orogenesis had initiated by ca. 488 Ma (Chew et al., 2010). Vestiges of Grampian tectonism at ca. 488 Ma are also observed in white mica $^{40}Ar/^{39}Ar$ step-heating spectra from the low-grade zones of the Barrovian metamorphic series (Viete et al., 2013), and are interpreted to date low-temperature recrystallisation of white mica during early-Grampian folding (Viete et al., 2011). The youngest Grampian $^{40}Ar/^{39}Ar$ cooling ages (ca. 461 Ma; Dempster, 1985; Viete et al., 2013) and the oldest U–Pb zircon age from a post-tectonic granite (462.5 ± 1.2 Ma; Friedrich et al., 1999) date the end of the Grampian Orogeny. The peak of Barrovian metamorphism is constrained by Sm–Nd garnet ages between 473 ± 3 and 465 ± 3 Ma, and U–Pb metamorphic zircon ages of 472 ± 6 and

471 ± 6 Ma (Oliver et al., 2000; Baxter et al., 2002; Viete et al., 2013). Significant heat for Grampian regional metamorphism at ca. 470 Ma was supplied by several pulses of mafic magmatism (Baxter et al., 2002; Ague and Baxter, 2007; Viete et al., 2011, 2013; Vorhies and Ague, 2011).

2.1. The Buchan Block

The Buchan Block in northeast Scotland forms a broad horseshoe-shaped outcrop pattern of generally right-way-up Dalradian rocks (Stephenson et al., 2013b). In its core there is a thick sequence of metamorphosed turbidites, the Southern Highland Group, which only occurs elsewhere in the Grampian Terrane in close proximity to the Highland Boundary Fault (Fig. 1). The Buchan Block is bound to the west and south by major shear zones; the NNE–SSW-oriented Portsoy–Duchray Hill Lineament (PDHL) and E–W-trending Deeside Lineament, respectively (Ashcroft et al., 1984; Fettes et al., 1986; Fig. 2). The Buchan Block exhibits some profound differences compared to the rest of the Grampian Terrane, including (1) the presence of large layered mafic intrusions; (2) widespread development of high dT/dP regional metamorphism that, in metasedimentary rocks of suitable grade, is characterised by abundant cordierite and the transition from andalusite to sillimanite (Read, 1952; Harte and Hudson, 1979); (3) extensive exposures of metasedimentary migmatites and peraluminous granites; (4) orientation of major fold axes that are approximately N–S in the Buchan Block but NE–SW elsewhere.

Around Portsoy, the northernmost segment of the PDHL is particularly well exposed as the ~1500 m-wide, N–S-striking Portsoy Shear Zone (Fig. 2). This regionally-important long-lived structure is suggested to have controlled Neoproterozoic deposition of the Argyll Group (Fettes et al., 1986), with deformation probably spanning the entire Grampian Orogeny, with kinematic evidence for discrete episodes of both top-to-the-E and top-to-the-W shearing, as well as pure shear flattening (Carty, 2001; Viete et al., 2010; Carty et al., 2012). Rocks within the Portsoy Shear Zone are dominated by heterogeneous amphibolite-facies metagabbroic rocks that range from relatively undeformed coarse-grained variants to highly tectonised mylonites, and whose polyphase intrusion spanned the ductile (regional D2) deformation (Carty, 2001; Viete et al., 2010; Carty et al., 2012).

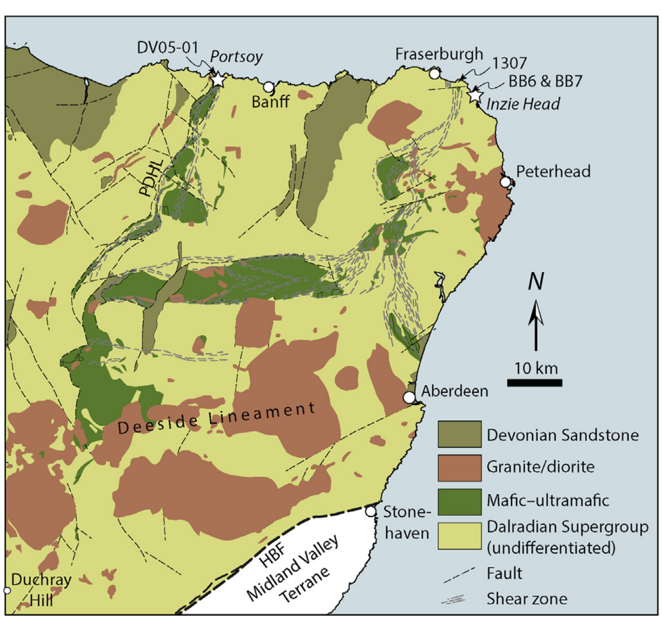

Figure 2. Geological map of the NE Grampian Highlands. The western margin of the Buchan Block is the Portsoy–Duchray Hill Lineament (PDHL); the southern margin (the Deeside Lineament) runs westwards from Aberdeen, is poorly exposed and defined by bodies of syn- to post-tectonic granite. Based upon DiGMapGB-625 bedrock data, with the permission of the British Geological Survey.

As elsewhere in the Grampian Terrane, the peak of regional metamorphism in the Buchan Block is also generally considered to have occurred at ca. 470 Ma, based on the U–Pb zircon ages of syn-metamorphic gabbro and granite (Oliver et al., 2000; Dempster et al., 2002; Carty et al., 2012). With a U–Pb zircon age of 457 ± 1 Ma, the undeformed Kennethmont granite provides a minimum age for the cessation of Grampian tectonothermal activity in the Buchan Block (Oliver et al., 2000). Similar to data from Barrovian metamorphic rocks, Stenhouse et al. (2014) found ca. 488 Ma components in white mica $^{40}Ar/^{39}Ar$ step-heating spectra from metapelites within the Portsoy Shear Zone and in staurolite zone rocks from the Buchan metamorphic series, which suggests an autochthonous relationship between it and the greater Grampian Terrane, at least since the start of the Grampian Orogeny.

Gravity and magnetic survey data emphasise many of the features of the Buchan Block described above (Fig. 3). The area is associated with a broad gravity high compared to the rest of the Grampian Terrane, consistent with relatively thin lithosphere (Fig. 3a), on which are superimposed smaller-scale positive gravity anomalies that correspond to exposed intrusions of the North-east Grampian Basic Suite (Figs. 2 and 3). The gravity data also demarcates the set of regional shear zones (Ashcroft et al., 1984) that are broadly coincident with the mafic intrusions (Figs. 2 and 3a). Although the magnetic data show far greater variability, the mafic intrusions and shear zones are similarly associated with positive anomalies (Fig. 3a). The magnetic data show positive anomalies extending offshore to the north of the western margin of the Buchan Block, and to the east of its southern margin (Fig. 3b). In both data sets, the major faults are clearly delineated. Apparent folds south of the Highland Boundary Fault defined by the magnetic data are consistent with sinistral movement on this structure (Fig. 3b).

3. Samples, methods and results

Three samples (1307, BB7 and BB6) selected for detailed study are from close to Inzie Head, and one other (DV05-01) is from Portsoy, such that the sample set spans the northern margin of the Buchan Block (Fig. 2). The rocks and field relationships around Inzie Head are described in detail by Johnson et al. (2001a,b). Sample 1307, from the foreshore at Cairnbulg, is a weakly deformed biotite-bearing granite sheet exhibiting irregular diffuse contacts with host metapelitic diatexites, from which it is interpreted to have been derived (Fig. 4a). Sample BB7 is from the more northerly of two large diorite sheets cropping out on the foreshore close to the village of St Combs. Here and elsewhere, the diorites are mingled with leucosome interpreted to have been derived from the host metapelitic migmatites (Fig. 4a–c; Johnson et al., 2001b). Sample BB6 is a coarse-grained granulite facies residual diatexite from a raft of metapelite between the two large diorite sheets at St Combs (Fig. 4d). DV05-01 is a highly deformed diorite from the package of rocks termed the Portsoy Gabbro, which occur within the Portsoy Shear Zone. The Portsoy Gabbro is a variably deformed (mylonitic in places) package of rocks and, on the basis of geochemistry, includes two mafic magma suites (Viete et al., 2010; see also Carty, 2001). Sample DV05-01 was obtained from a high-strain zone within which the degree of deformation obscures recognition of the exact (mafic igneous) lithology.

Methods of sample preparation, LA-ICPMS and SIMS analysis are given in Appendix 1. Zircon analyses are provided in Supplementary Tables 1 (U–Pb) and 2 (Lu–Hf). Exemplar cathodoluminescence and secondary electron images of selected zircon

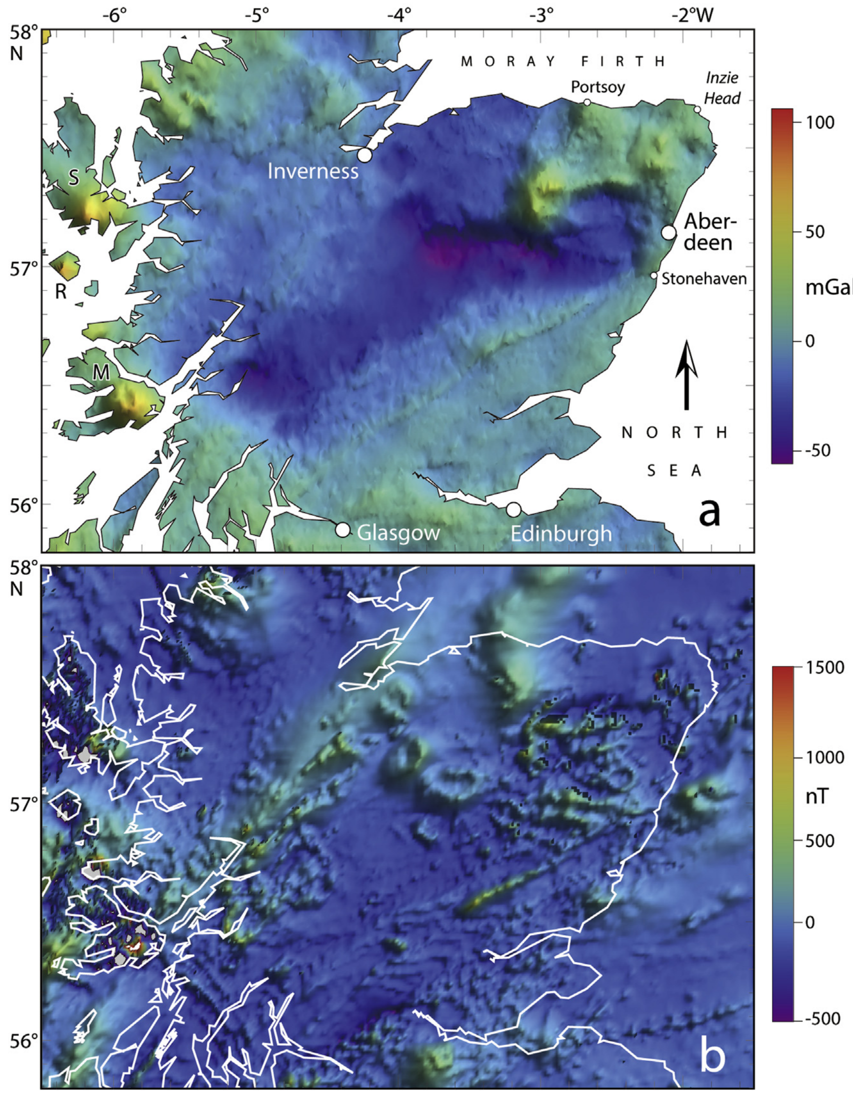

Figure 3. Geophysical data. (a) Land gravity survey data showing Bouguer gravity anomaly (in mGal) centred on the Grampian Terrane of Scotland; S = Skye, R = Rhum, M = Mull. (b) Aeromagnetic survey data for the same area showing magnetic anomalies (in nT) processed with reference to the IGRF-90 geomagnetic field model. Based upon land gravity and aeromagnetic survey data (available at: http://www.bgs.ac.uk/data/gravAndMag.html), with the permission of the British Geological Survey.

grains are shown in Figs. 5–7 (BB7, 1307 and DV05-01, respectively); images of grains from sample BB6 are shown in the supplementary material to Johnson et al. (2016). Concordia diagrams showing all data from samples 1307 and BB6 are given in Fig. S1. All ages reported in the text are at the 2σ confidence level. In the following text * is used to denote radiogenic ratios corrected for common Pb.

3.1. Sample BB7 (diorite) [NK 05556 63394]

Zircons in this sample are subhedral to euhedral ~100 μm long stubby prismatic crystals with high U contents (> or >>1000 ppm) and display homogeneous or patchy CL response (Fig. 5). U–Pb analyses are concordant to slightly discordant. However, the ^{207}Pb*/^{206}Pb* ages correlate with common Pb contents, indicating that corrections using ^{204}Pb may be inaccurate. Consequently, the age for this sample is determined from the intersection with the concordia curve of a regression through uncorrected data, anchored at contemporaneous initial Pb (^{207}Pb/^{206}Pb = 0.869 at 490 Ma; Stacey and Kramers, 1975). However, neither the form nor application of common Pb correction changes the result significantly. The analyses define a single group comprising 15 analyses of 10 zircons (Group I in Supplementary Table 1) for which the regression intersects the concordia curve at 486 ± 9 Ma (MSWD = 1.9), interpreted as the crystallisation age of the diorite (Fig. 8a). Fourteen Hf isotope measurements on 14 separate grains from sample BB7 (Supplementary Table 2) yield evolved compositions ($\varepsilon_{Hf} = -13$ to −8) indicating a significant crustal component (Supplementary Table 2). Fig. 8b presents these data converted to epsilon Nd values allowing comparison with existing regional data (Kirkland et al., 2013).

3.2. Sample 1307 (granite sheet) [NK 03251 65403]

This sample contains sub-rounded to euhedral zircons (<200 μm) with aspect ratios up to 4:1. Oscillatory-zoned cores are surrounded by homogeneous low-CL-response overgrowths up to 25 μm wide (Fig. 6). Based on CL textures and isotopic compositions, the concordant data are subdivided into four groups (S, Z, P, M) (Supplementary Table 1). Group S comprises 10 analyses from the cores of nine zircons with a maximum ^{207}Pb*/^{206}Pb* age of 2761 ± 18 Ma and a minimum ^{238}U/^{206}Pb* age of 670 ± 26 Ma, and

Figure 4. Field relations from the Inzie Head area. (a) Magma mingling textures between diorite and diatexite close to the location of sample 1307 (Fig. 2). Fifty pence coin (diameter 28 mm; circled) for scale; (b) Diorite mingled with metapelite-derived granitic leucosome within the northernmost diorite sheet at St Combs, from which sample BB7 was collected (Fig. 2); (c) Magma mingling textures between diorite and porphyritic granitic close to the contact between the large diorite sheet at St Combs and the metasedimentary migmatites. The granite can be traced into the diatexitic migmatite from which it was derived; (d) Coarse granoblastic migmatite from the area between the two diorite sheets at St Combs (Fig. 2). This lithology (sample BB6) contains partially retrogressed porphyroblasts of garnet and dark green pseudomorphs interpreted to be replacing both orthopyroxene and cordierite.

are interpreted as detrital. Group Z (six analyses from five zircons) yield $^{238}U/^{206}Pb^*$ ages from 685 ± 24 Ma to 498 ± 16 Ma. Post-analysis imaging indicates these are mixtures between two CL domains. Group P (five analyses from four zircons), which yield a concordia age of 454 ± 12 Ma (MSWD = 2.2), are associated with distinctive CL textures interpreted to reflect dissolution–reprecipitation processes (e.g. Corfu et al., 2003; Kirkland et al., 2009). Group M comprises four analyses wholly within homogeneous rims from three grains that yield a concordia age of 493 ± 8 Ma (MSWD = 1) interpreted to date high-grade metamorphism (Fig. 8c).

3.3. Sample BB6 (residual diatexite) [NK 05690 63276]

Zircons (50–200 μm) extracted from this rock are rounded to euhedral with aspect ratios up to 7:1. Most comprise oscillatory-zoned cores with homogeneous overgrowths up to a few tens of microns wide (see Johnson et al., 2016). Compared to sample 1307, U–Pb analyses have higher uncertainties reflecting lower U contents (Supplementary Table 1). The concordant data are subdivided into the four groups identified for sample 1307. Group S comprises six analyses of three oscillatory zoned cores that yield a maximum $^{207}Pb^*/^{206}Pb^*$ age of 1917 ± 90 Ma and a minimum $^{238}U/^{206}Pb^*$ age of 992 ± 46 Ma, interpreted to date detrital components. Group Z comprise two analyses from a single zircon with $^{238}U/^{206}Pb^*$ dates of 729 ± 50 Ma and 686 ± 60 Ma, interpreted to reflect analytical mixtures. Group P comprises eight analyses from six grains (Supplementary Table 1), ranging in age from ∼1300 Ma to 362 ± 24 Ma with CL textures consistent with modification due to dissolution–reprecipitation. Group M comprises four analyses from four separate grains entirely within homogeneous rims. These yield a concordia age of 477 ± 18 Ma (MSWD = 1.3), interpreted to date high-grade metamorphism (Fig. 8d).

3.4. Sample DV05-01 (deformed diorite) [NJ 58780 66370]

Zircons (100–300 μm) are subhedral to euhedral and have aspect ratios up to 3:1. Core regions commonly display oscillatory zoning and are overgrown by homogeneous-CL-response overgrowths up to 10 μm wide (Fig. 7). All 14 analyses are within analytical uncertainty of concordia. As with sample BB7, $^{207}Pb^*/^{206}Pb^*$ ages correlate with common Pb contents, and we use a regression from common Pb to calculate an age for this sample. Assuming a contemporaneous initial Pb equivalent to Stacey and Kramers (1975) at 490 Ma ($^{207}Pb/^{206}Pb$ = 0.869), a lower intercept through all the data (Group I) yields an age of 493 ± 8 Ma (MSWD = 1.3). Assuming a more recent composition of common Pb does not change the lower intercept age. The 493 Ma date is interpreted as the crystallisation age of the diorite (Fig. 8e).

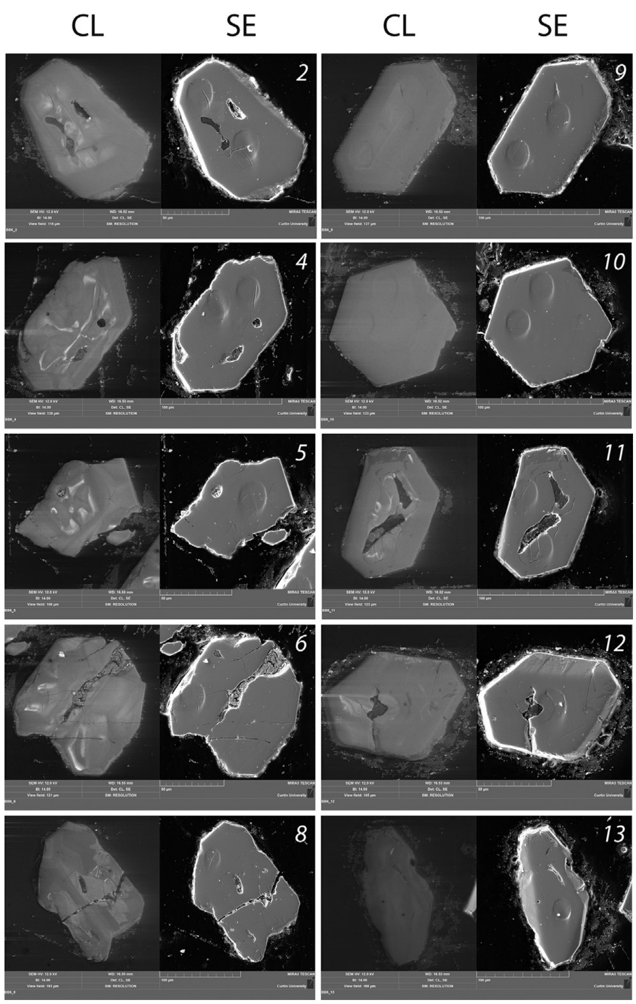

Figure 5. Cathodoluminescence (CL) and secondary electron (SE) images from selected zircon grains in diorite sample BB7 [NK 05556 63394].

4. Discussion

Field evidence around Inzie Head, where diorite sheets are intimately intermingled with granitic leucosome (Fig. 4a–c), demonstrates temporal overlap between mafic magmatism and crustal anatexis, at least locally. At Portsoy, mafic layers, interpreted by Viete et al. (2010) as metavolcanic rocks, occur within the Cowhythe Gneiss, although the relationship between mafic magmatism and high-grade metamorphism here is less clear. U–Pb data indicate a crystallisation age of 486 ± 9 Ma for the Inzie Head diorite (BB7; Fig. 8a), identical (within uncertainty) to the crystallisation age (493 ± 8 Ma) for the Portsoy diorite (DV05-01; Fig. 8e). Assuming the diorites are of a single generation, they cannot be consanguineous with the ca. 470 Ma gabbros of the Grampian Basic Suite [Newer Gabbros of Read (1919)], as suggested previously (Johnson et al., 2001a,b, 2003).

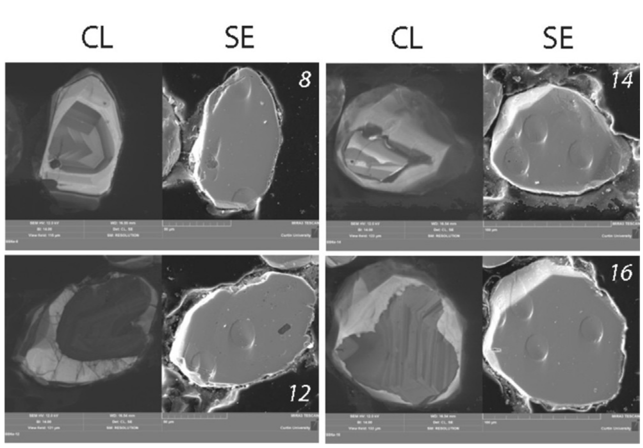

Figure 6. Cathodoluminescence (CL) and secondary electron (SE) images from selected zircon grains in the granite sheet sample, 1307 [NK 03251 65403].

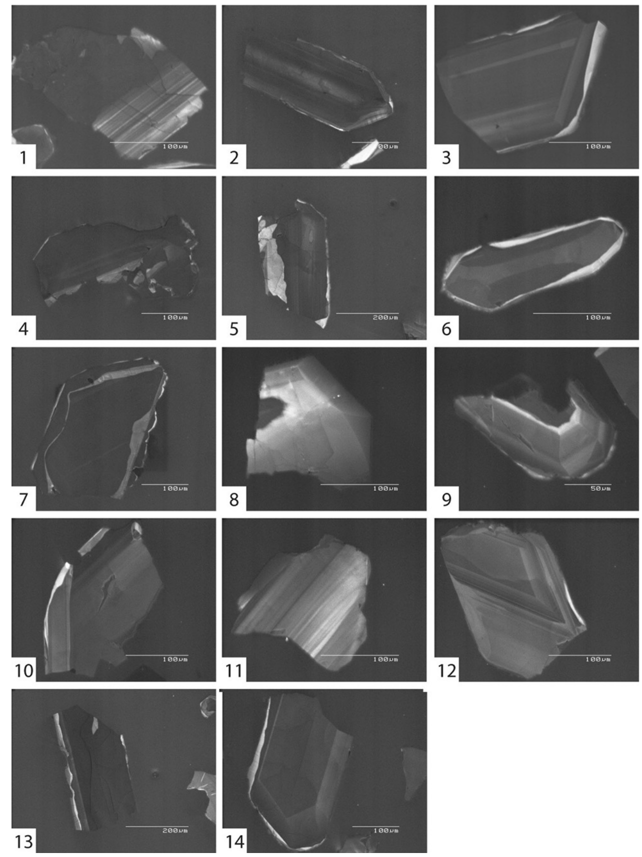

Figure 7. Cathodoluminescence (CL) images from selected zircon grains in diorite sample DV05-01 [NJ5878066370].

In the case of DV05-01, the diorite was sampled from the Portsoy Gabbro package, a member of the Grampian Basic Suite, which has been previously dated at 474 ± 2 Ma and 471 ± 1 Ma (Oliver et al., 2008; Carty et al., 2012). However, on the basis of major and trace element geochemistry, Viete et al. (2010) identified two geochemical suites within the Portsoy Gabbro. The first, more sub-alkaline and potassic suite, has arc-like signatures in its REE patterns (e.g. enrichment in LILEs, low Nb/La) whereas the second, more alkaline and sodic suite, has geochemical signatures consistent with decompression melting. Both geochemical suites have REEs patterns indicating garnet-absent source regions interpreted to indicate lithospheric thicknesses of less than 70 km (Viete et al., 2010). It is possible that the ca. 490 Ma Buchan Block diorites formed in an extended arc (back-arc) setting immediately prior to arc-continent collision and onset of the Grampian Orogeny, whereas the ca. 470 Ma Grampian Gabbro Suite formed in response to syn-orogenic extension and decompression melting of the asthenosphere. The shear zone network of Ashcroft et al. (1984), which has N–S- to E–W-trending sections and bounds the Buchan Block (Fig. 2), may have acted as an upper- to mid-crustal locus for melt intrusion and heat advection from pre-Grampian times. This

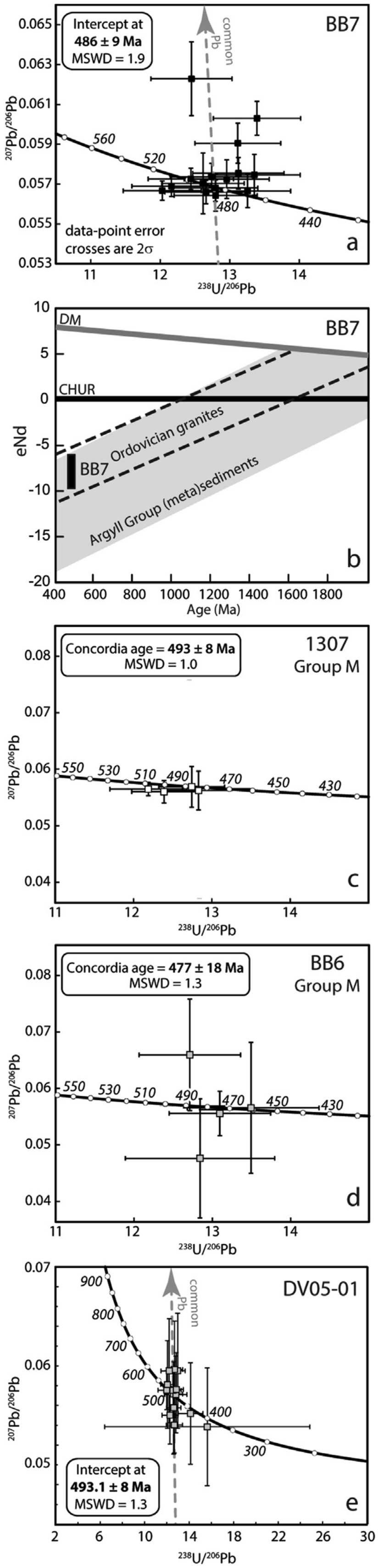

Figure 8. Isotopic data from zircon. (a) Tera–Wasserburg concordia diagram for the diorite sample (BB7) from near Inzie Head. (b) ε_{Nd} values in BB7 converted from ε_{Hf} assuming a terrestrial array relationship (no garnet in the source rocks). The field of the host Argyll Group metasediments and Caledonian granites of Ordovician age is shown. (c) and (d) Tera–Wasserburg concordia diagram including all Group M (metamorphic) analyses from samples 1307 (granite sheet) and BB6 (diatexite), respectively, both of which are within the Inzie Head Gneiss. (e) Tera–Wasserburg concordia diagram for sample DV05-01, the deformed diorite from the Portsoy Gabbro.

would suggest that the Buchan Block represents an autochthonous, albeit tectonothermally discrete (with distinct N–S or E–W tectonic grain in parts, and enhanced lithospheric stretching and advective heating), domain of the Grampian Terrane.

The evolved Hf isotopic composition of zircon from the Inzie Head diorite requires a significant crustal component in the magmas, consistent with field evidence that the diorites are mingled with granitic leucosome (Johnson et al., 2001a,b; Fig. 4a–c). The diorite has a composition at the juvenile end of the field defined by Argyll Group metasedimentary rocks, identical to Ordovician granites that, in the Buchan Block, have been interpreted to have been derived from partial melting of Argyll Group metasediments (Johnson et al., 2003; Fig. 8b). The Hf isotopic signature of the diorites suggests they represent mafic magmas strongly contaminated *in situ* with crustal melt.

Metamorphic zircon overgrowths (Group M; $n = 4$) from the granite sheet (1307) at Inzie Head yield an age (493 ± 8 Ma; MSWD = 1.0) that is statistically indistinguishable from the magmatic age of the diorites. This demonstrates that some crustal melting, at least locally, occurred at around 490 Ma, significantly earlier than the age of peak metamorphism in the Grampian Terrane according to most other studies (Friedrich et al., 1999; Soper et al., 1999; Flowerdew et al., 2000; Oliver et al., 2000; Baxter et al., 2002; Carty et al., 2012; Viete et al., 2013). Metamorphic zircon overgrowths (Group M; $n = 4$) from the diatexite at Inzie Head (BB6) yield a comparatively imprecise age of 477 ± 18 Ma (MSWD = 1.3), due to both low U in some analyses and high common Pb in others, an age that is within uncertainty of both the ca. 490 Ma and ca. 470 Ma events.

Field evidence and new geochronology from rocks of the Buchan Block demonstrate an earlier, pre- to early-Grampian tectonothermal event. Evidence that arc magmatism and associated high-grade, high dT/dP metamorphism occurred simultaneously at ca. 490 Ma is consistent with a back-arc setting for the Buchan Block immediately prior to ophiolite obduction, arc-continent collision and the onset of Grampian Orogeny at ca. 488 Ma. This pre-Grampian phase of subduction-related tectonometamorphism may have been synchronous with the formation of rare blueschists in western Ireland that are suggested to have a forearc origin (Gray and Yardley, 1979), perhaps representing part of a paired metamorphic belt (Miyashiro, 1961; Brown, 2010). Elsewhere along the Caledonian margin, in northern Norway, Cambrian to Early Ordovician (520–480 Ma) events are inferred to relate to the arrival and accretion of outboard terranes in a dynamic subduction environment (Kirkland et al., 2007, 2008).

Existing geodynamic models for the high heat flow in the Buchan Block generally focus on magmatism and associated advective heating, with drivers for mantle melting including lithospheric-scale extension, slab break-off, a flip in subduction polarity and/or subduction of a spreading ridge following the initial arc-continent collision (Yardley and Senior, 1982; Kneller, 1985; Oliver, 2002; Viete et al., 2010; Tanner, 2014). Our data suggest that high dT/dP metamorphism occurred at ca. 490 Ma, immediately prior to, or in the earliest stages of, accretionary orogenesis, as well as later during Grampian regional metamorphism at ca. 470 Ma (Friedrich et al., 1999; Soper et al., 1999; Flowerdew et al., 2000; Oliver et al., 2000; Baxter et al., 2002; Carty et al., 2012; Viete et al., 2013).

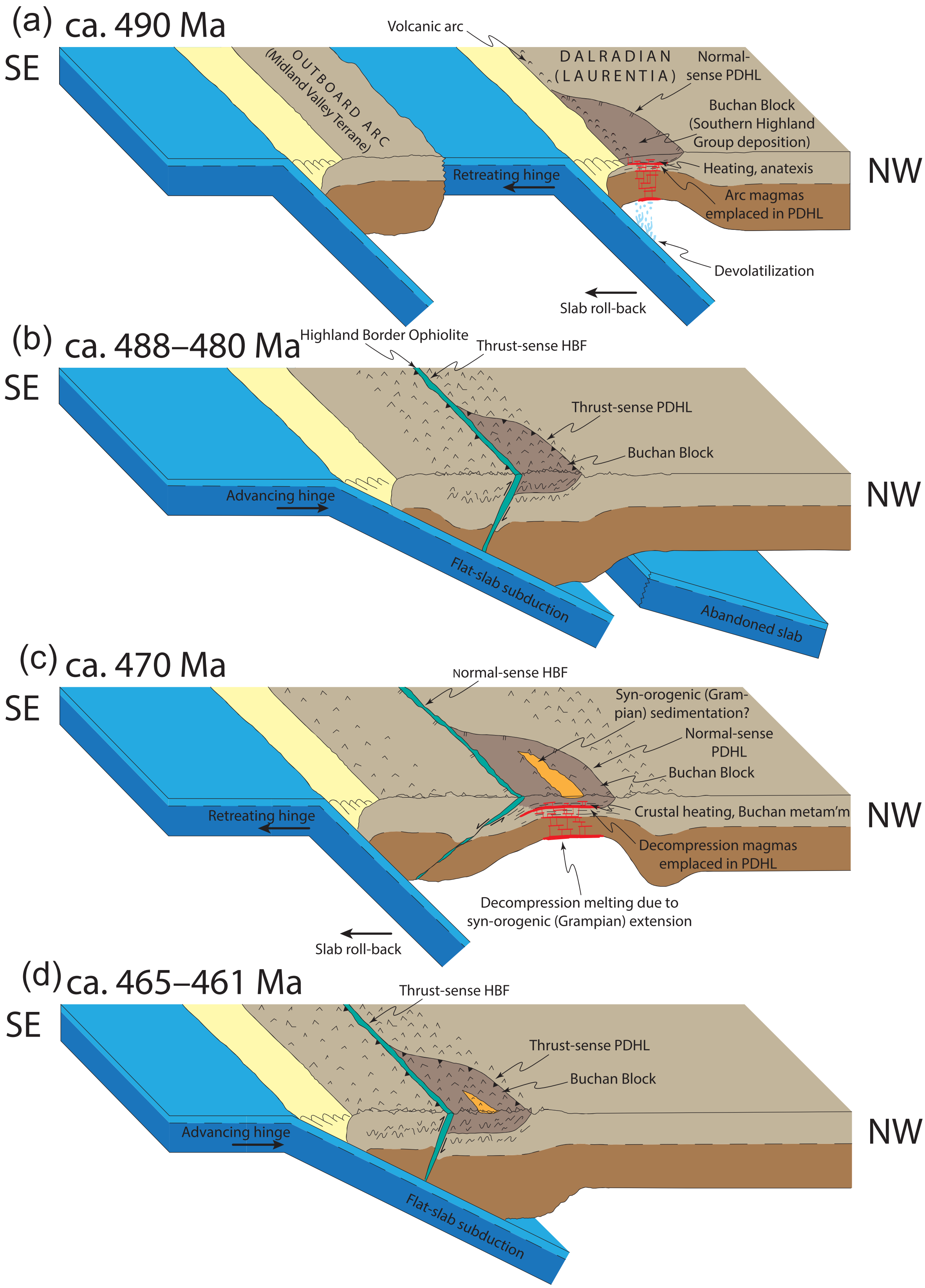

Figure 9. Tectonic sketches illustrating the tectonic switching model proposed to explain polyphase magmatism and crustal anatexis within the Buchan Block by advective heating and high d*T*/d*P* metamorphism during back-arc extension at ca. 490 Ma and then (Grampian) syn-orogenic extension at ca. 470 Ma. Periods of slab rollback, crustal extension and heating (panels a and c) are punctuated by episodes of (Grampian) crustal thickening and cooling at 488–473 Ma and 465–461 Ma (shown in panels b and d). Panels b–d follow the shortening–extension–shortening model of Viete et al. (2010, 2013) for the Grampian Orogeny. HBF = Highland Boundary Fault; PDHL = Portsoy–Duchray Hill Lineament.

We suggest that the tectonic switching model of Collins (2002) can account for the multiple and punctuated phases of tectonothermal activity observed for the Buchan Block. According to this model, behaviour of the overriding plate (the orogeny) is controlled by dynamics of an outboard subduction zone. Periods of lithospheric extension and high crustal heat flow (attenuation of isotherms, decompression melting/arc magmatism) are related to slab rollback and subduction hinge retreat, whereas intervening periods of lithospheric shortening and cooling are related to subduction hinge advance due to arrival of buoyant oceanic crust or to arc collision (i.e. arrival of a micro-continental ribbon). Heat generated from an extension (rollback) phase persists into the early stages of the subsequent shortening phase.

Our proposed model for punctuated tectonothermal activity during the Grampian Orogeny is illustrated in Fig. 9. Subduction-related tectonism may have started with rollback prior to ca. 490 Ma, producing a back-arc environment with associated arc magmatism and high dT/dP metamorphism in the Buchan Block (Fig. 9a). Arrival of an outboard arc then produced a phase of shortening (the initial phase of the Grampian Orogeny) starting at ca. 488 Ma (see Fig. 9b, at ca. 480 Ma), before rollback of a subduction zone located further to the SE began at ca. 473 Ma. Associated lithospheric-scale extension led to decompression melting, magmatism and advective heating of the middle crust, producing the widespread ca. 470 Ma Grampian (classic Barrovian and Buchan) regional metamorphism (Fig. 9c). Resumed hinge advance by ca. 465 Ma cut off the heat supply for Grampian metamorphism and produced the final shortening phase of the Grampian Orogeny (see Fig. 9d, at ca. 461 Ma). The Grampian (488–461 Ma) phases of the model (Fig. 9b–d) follow Viete et al. (2010, 2013), who proposed tectonic mode switches and a shortening–extension–shortening history during the Grampian Orogeny to explain: (1) a top-W–top-E–top-W sequence of shear kinematics in the Portsoy Shear Zone; (2) 'syn-orogenic' decompression melting at asthenospheric depths <70 km to produce the Grampian Gabbro Suite; (3) a discrete phase of widespread Buchan and Barrovian metamorphism at 473–465 Ma.

Interestingly, Johnson and Strachan (2006) proposed a back-arc setting for the origin of metamorphic heat in the Scandian Orogeny, which started at ca. 440 Ma, overprinting cryptic evidence of Grampian (ca. 470 Ma) tectonothermal activity in rocks of the Northern Highland Terrane (Fig. 1). It is possible that, in response to subduction rollback, the locus for back-arc extension moved north following cessation of the final shortening phase of the Grampian Orogeny, at ca. 461 Ma.

The dynamic model for accretionary orogenesis of Collins (2002) elegantly accounts for polymetamorphism (and polyphase magmatism and migmatisation) during the Grampian Orogeny; in particular, the punctuated advective heating it predicts is consistent with the discrete nature of Grampian tectonothermal activity. The enigmatic origin of kyanite after andalusite reported from rocks at Portsoy (Chinner and Heseltine, 1979; Chinner, 1980; Beddoe-Stephens, 1990) may find solution in early-Grampian shortening (thickening and burial at ca. 488 Ma) having been imparted on a hot back-arc region that experienced mafic magmatism and localised, high dT/dP metamorphism at ca. 490 Ma. In addition, the record of steepening geothermal gradients during Barrovian metamorphism, observed in the geochemistry of Grampian amphiboles (Zenk and Schultz, 2004), may also be explained by successive, discrete metamorphic episodes at ca. 490 Ma then ca. 470 Ma.

5. Conclusions

The Buchan Block is polymetamorphic and records discrete and brief (several Myr or less) tectonomagmatometamorphic events at ca. 490 Ma and ca. 470 Ma, with little evidence for tectonothermal activity in the intervening period. Gradualist views hold that shortening heats and extension cools the crust. This may be the case for time scales sufficient to allow crustal-scale thermal conduction and (re-)establishment of a steady-state geotherm (i.e. 10^7–10^8 yr). However, for scenarios in which the stress state of the lithosphere changes rapidly in response to changes in subduction zone dynamics (i.e. every 10^6–10^7 yr), advection dominates over large-scale conduction, and extension heats (by magmatism and attenuation of isotherms) whereas shortening cools (by dilation of isotherms) the crust.

Acknowledgements

We are grateful to D. Chew, G. Oliver, R. Strachan and an anonymous reviewer for comments on this and/or earlier iterations of the paper. G. Lister contributed ideas that influenced the 'tectonic switching' model presented here. We acknowledge use of the Microscopy & Microanalysis Facility, John de Laeter Centre, Curtin University for instrumentation partially funded by the university, state, and commonwealth governments. We appreciate funding and support from the Research School of Earth Sciences, Australian National University for analysis of sample DV05-01 performed there. GeoHistory Facility instruments were funded via an Australian Geophysical Observing System grant provided to AuScope Pty Ltd. by the AQ44 Australian Education Investment Fund program. The NPII multi-collector was purchased through ARC LIEF LE150100013.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.gsf.2017.02.002.

References

Ague, J.J., Baxter, E.F., 2007. Brief thermal pulses during mountain building recorded by Sr diffusion in apatite and multicomponent diffusion in garnet. Earth and Planetary Science Letters 261, 500–516.
Ashcroft, W.A., Kneller, B.C., Leslie, A.G., Munro, M., 1984. Major shear zones and autochthonous Dalradian in the north-east Scottish Caledonides. Nature 310, 760–762.
Barrow, G., 1893. On an intrusion of muscovite-biotite gneiss in the south-eastern highlands of Scotland, and its accompanying metamorphism. Quarterly Journal of the Geological Society of London 49, 330–358.
Barrow, G., 1912. On the geology of Lower Dee-side and the southern Highland Border. Proceedings of the Geologists' Association 23, 274–IN271.
Baxter, E.F., Ague, J.J., Depaolo, D.J., 2002. Prograde temperature-time evolution in the Barrovian type-locality constrained by Sm/Nd garnet ages from Glen Clova, Scotland. Journal of the Geological Society 159, 71–82.
Beddoe-Stephens, B., 1990. Pressures and temperatures of Dalradian metamorphism and the andalusite-kyanite transformation in the northeast Grampians. Scottish Journal of Geology 26, 3–14.
Brown, M., 2010. Paired metamorphic belts revisited. Gondwana Research 18, 46–59.
Carty, J.P., 2001. Deformation, Magmatism and Metamorphism in the Portsoy Shear Zone, North-East Scotland. University of Derby.
Carty, J.P., Connelly, J.N., Hudson, N.F.C., Gale, J.F.W., 2012. Constraints on the timing of deformation, magmatism and metamorphism in the Dalradian of NE Scotland. Scottish Journal of Geology 48, 103–117.
Cawood, P.A., Nemchin, A.A., Smith, M., Loewy, S., 2003. Source of the Dalradian Supergroup constrained by U-Pb dating of detrital zircon and implications for the East Laurentian margin. Journal of the Geological Society 160, 231–246.
Cawood, P.A., Nemchin, A.A., Strachan, R., 2007. Provenance record of Laurentian passive-margin strata in the northern Caledonides: implications for paleodrainage and paleogeography. Geological Society of America Bulletin 119, 993–1003.
Chew, D.M., Daly, J.S., Magna, T., Page, L.M., Kirkland, C.L., Whitehouse, M.J., Lam, R., 2010. Timing of ophiolite obduction in the Grampian orogen. Bulletin of the Geological Society of America 122, 1787–1799.
Chew, D.M., Fallon, N., Kennelly, C., Crowley, Q., Pointon, M., 2009. Basic volcanism contemporaneous with the Sturtian glacial episode in NE Scotland. Earth and Environmental Science Transactions of the Royal Society of Edinburgh 100, 399–415.
Chew, D.M., Graham, J.R., Whitehouse, M.J., 2007. U–Pb zircon geochronology of plagiogranites from the Lough Nafooey (= Midland Valley) arc in western

Ireland: constraints on the onset of the Grampian orogeny. Journal of the Geological Society 164, 747–750.
Chew, D.M., Strachan, R.A., 2014. The Laurentian Caledonides of Scotland and Ireland. Geological Society, London, Special Publications 390, 45–91.
Chinner, G., 1980. Kyanite isograds of Grampian metamorphism. Journal of the Geological Society 137, 35–39.
Chinner, G., Heseltine, F., 1979. The Grampide andalusite/kyanite isograd. Scottish Journal of Geology 15, 117–127.
Collins, W., 2002. Hot orogens, tectonic switching, and creation of continental crust. Geology 30, 535–538.
Corfu, F., Hanchar, J.M., Hoskin, P.W., Kinny, P., 2003. Atlas of zircon textures. Reviews in Mineralogy and Geochemistry 53, 469–500.
Dempster, T.J., 1985. Uplift patterns and orogenic evolution in the Scottish Dalradian. Journal of the Geological Society 142, 111–128.
Dempster, T.J., Rogers, G., Tanner, P.W.G., Bluck, B.J., Muir, R.J., Redwood, S.D., Ireland, T.R., Paterson, B.A., 2002. Timing of deposition, orogenesis and glaciation within the Dalradian rocks of Scotland: constraints from U-Pb zircon ages. Journal of the Geological Society 159, 83–94.
Dewey, J.F., 2005. Orogeny can be very short. Proceedings of the National Academy of Sciences 102, 15286–15293.
Dewey, J., Mange, M., 1999. Petrography of Ordovician and Silurian sediments in the western Irish Caledonides: tracers of a short-lived Ordovician continent-arc collision orogeny and the evolution of the Laurentian Appalachian-Caledonian margin. Geological Society, London, Special Publications 164, 55–107.
Dewey, J.F., Dalziel, I.W., Reavy, R.J., Strachan, R.A., 2015. The Neoproterozoic to Mid-Devonian evolution of Scotland: a review and unresolved issues. Scottish Journal of Geology 51, 5–30.
Dewey, J.F., Shackleton, R.M., 1984. A model for the evolution of the Grampian tract in the early Caledonides and Appalachians. Nature 312, 115–121.
Draut, A.E., Clift, P.D., Amato, J.M., Blusztajn, M., Schouten, J., 2009. Arc–continent collision and the formation of continental crust: a new geochemical and isotopic record from the Ordovician Tyrone Igneous Province, Ireland. Journal of the Geological Society 166, 485–500.
Fettes, D.J., Graham, C.M., Harte, B., Plant, J.A., 1986. Lineaments and basement domains: an alternative view of Dalradian evolution. Journal of the Geological Society 143, 453–464.
Flowerdew, M.J., Daly, J.S., Guise, P.G., Rex, D.C., 2000. Isotopic dating of overthrusting, collapse and related granitoid intrusion in the Grampian orogenic belt, northwestern Ireland. Geological Magazine 137, 419–435.
Friedrich, A.M., Bowring, S.A., Martin, M.W., Hodges, K.V., 1999. Short-lived continental magmatic arc at Connemara, western Irish Caledonides: implications for the age of the Grampian orogeny. Geology 27, 27–30.
Gray, J., Yardley, B., 1979. A Caledonian blueschist from the Irish Dalradian. Nature 278, 736–737.
Harte, B., Hudson, N.F.C., 1979. Pelite facies series and the temperatures and pressures of Dalradian metamorphism in E Scotland. In: Geological Society, London, Special Publication, 8, pp. 323–337.
Hyndman, R.D., Currie, C.A., Mazzotti, S.P., 2005. Subduction zone backarcs, mobile belts, and orogenic heat. GSA Today 15, 4–10.
Johnson, M., Strachan, R., 2006. A discussion of possible heat sources during nappe stacking: the origin of Barrovian metamorphism within the Caledonian thrust sheets of NW Scotland. Journal of the Geological Society 163, 579–582.
Johnson, T.E., Kirkland, C., Reddy, S., Evans, N., McDonald, B., 2016. The source of Dalradian detritus in the Buchan Block, NE Scotland: application of new tools to detrital datasets. Journal of the Geological Society 173, 773–782.
Johnson, T., Kirkland, C.L., Reddy, S.M., Fischer, S., 2015. Grampian migmatites in the Buchan Block, NE Scotland. Journal of Metamorphic Geology 33, 695–709.
Johnson, T.E., Hudson, N.F.C., Droop, G.T.R., 2001a. Melt segregation structures within the Inzie Head gneisses of the Northeastern Dalradian. Scottish Journal of Geology 37, 59–72.
Johnson, T.E., Hudson, N.F.C., Droop, G.T.R., 2001b. Partial melting in the Inzie Head gneisses: the role of water and a petrogenetic grid in KFMASH applicable to anatectic pelitic migmatites. Journal of Metamorphic Geology 19, 99–118.
Johnson, T.E., Hudson, N.F.C., Droop, G.T.R., 2003. Evidence for a genetic granite-migmatite link of the Dalradian of NE Scotland. Journal of the Geological Society 160, 447–457.
Kirkland, C.L., Alsop, G.I., Daly, J.S., Whitehouse, M.J., Lam, R., Clark, C., 2013. Constraints on the timing of Scandian deformation and the nature of a buried Grampian terrane under the Caledonides of northwestern Ireland. Journal of the Geological Society 170, 615–625.
Kirkland, C.L., Daly, J.S., Whitehouse, M.J., 2007. Provenance and terrane evolution of the Kalak Nappe Complex, Norwegian Caledonides: implications for Neoproterozoic paleogeography and tectonics. Journal of Geology 115, 21–41.
Kirkland, C.L., Daly, J.S., Whitehouse, M.J., 2008. Basement-cover relationships of the Kalak Nappe Complex, Arctic Norwegian Caledonides and constraints on Neoproterozoic terrane assembly in the North Atlantic region. Precambrian Research 160, 245–276.
Kirkland, C.L., Whitehouse, M.J., Slagstad, T., 2009. Fluid-assisted zircon and monazite growth within a shear zone: a case study from Finnmark, Arctic Norway. Contributions to Mineralogy and Petrology 158, 637–657.
Kneller, B., 1985. Dalradian basin evolution and metamorphism. Journal of the Geological Society 142, 4.
Lambert, R.S.J., McKerrow, W.S., 1976. The Grampian Orogeny. Scottish Journal of Geology 12, 271–292.
Lister, G., Forster, M., 2009. Tectonic mode switches and the nature of orogenesis. Lithos 113, 274–291.
McKerrow, W., Mac Niocaill, C., Dewey, J., 2000. The Caledonian orogeny redefined. Journal of the Geological Society 157, 1149–1154.
Mitchell, A., 1978. The Grampian orogeny in Scotland: arc-continent collision and polarity reversal. The Journal of Geology 86, 643–646.
Miyashiro, A., 1961. Evolution of metamorphic belts. Journal of Petrology 2, 277–311.
Moresi, L., Betts, P., Miller, M., Cayley, R., 2014. Dynamics of continental accretion. Nature 508, 245–248.
Oliver, G.J.H., 2001. Reconstruction of the Grampian episode in Scotland: its place in the Caledonian orogeny. Tectonophysics 332, 23–49.
Oliver, G., 2002. Chronology and Terrane Assembly, New and Old Controversies. In: The Geology of Scotland. Geological Society, London, pp. 201–211.
Oliver, G.J.H., Chen, F., Buchwaldt, R., Hegner, E., 2000. Fast tectonometamorphism and exhumation in the type area of the Barrovian and Buchan zones. Geology 28, 459–462.
Oliver, G.J.H., Wilde, S.A., Wan, Y., 2008. Geochronology and geodynamics of Scottish granitoids from the late neoproterozoic break-up of Rodinia to Palaeozoic collision. Journal of the Geological Society 165, 661–674.
Ramsay, D.M., Sturt, B.A., 1979. The status of the Banff nappe. Geological Society Special Publication 8, 145–151.
Read, H.H., 1919. IV.—The two magmas of Strathbogie and Lower Banffshire. Geological Magazine (Decade VI) 6, 364–371.
Read, H.H., 1955. The Banff Nappe: an interpretation of the structure of the Dalradian rocks of north-east Scotland. Proceedings of the Geologists' Association 66, 1–IN1.
Read, H.H., 1923. The Geology of the Country Round Banff, Huntly and Turriff (lower Banffshire and North-west Aberdeenshire). HM Stationery Office.
Read, H.H., 1952. Metamorphism and migmatisation in the Ythan Valley, Aberdeenshire. Transactions of the Edinburgh Geological Society 15, 265–279.
Soper, N.J., 1994. Was Scotland a Vendian RRR junction? Journal of the Geological Society (London) 151, 579–582.
Soper, N.J., Ryan, P.D., Dewey, J.F., 1999. Age of the Grampian orogeny in Scotland and Ireland. Journal of the Geological Society 156, 1231–1236.
Stacey, J.T., Kramers, J., 1975. Approximation of terrestrial lead isotope evolution by a two-stage model. Earth and Planetary Science Letters 26, 207–221.
Stenhouse, I.R., Forster, M.A., Lister, G.S., 2014. The timing of sedimentation and Buchan metamorphism in the Grampian Terrane in Scotland from $^{40}Ar/^{39}Ar$ apparent age spectra. Journal of the Geological Society 171, 343–352.
Stephenson, D., Mendum, J.R., Fettes, D.J., Leslie, A.G., 2013a. The Dalradian rocks of Scotland: an introduction. Proceedings of the Geologists' Association 124, 3–82.
Stephenson, D., Mendum, J.R., Fettes, D.J., Smith, C.G., Gould, D., Tanner, P.W.G., Smith, R.A., 2013b. The Dalradian rocks of the north-east Grampian Highlands of Scotland. Proceedings of the Geologists' Association 124, 318–392.
Sturt, B.A., Ramsay, D.M., Pringle, I.R., Teggin, D.E., 1977. Precambrian gneisses in the Dalradian sequence of northeast Scotland. Journal of the Geological Society 134, 41–44.
Tanner, P.W.G., 2014. A kinematic model for the Grampian Orogeny, Scotland. In: Geological Society Special Publication, 390, pp. 467–511.
Thompson, A., Schulmann, K., Jezek, J., Tolar, V., 2001. Thermally softened continental extensional zones (arcs and rifts) as precursors to thickened orogenic belts. Tectonophysics 332, 115–141.
Van Staal, C., Dewey, J., Mac Niocaill, C., McKerrow, W., 1998. The Cambrian-Silurian tectonic evolution of the northern Appalachians and British Caledonides: history of a complex, west and southwest Pacific-type segment of Iapetus. Geological Society, London, Special Publications 143, 197–242.
Viete, D., Oliver, G., Wilde, S., 2014. Discussion of 'Metamorphic P–T and retrograde path of high-pressure Barrovian metamorphic zones near Cairn Leuchan, Caledonian orogen, Scotland'. Geological Magazine 151, 755–758.
Viete, D.R., Forster, M.A., Lister, G.S., 2011. The nature and origin of the Barrovian metamorphism, Scotland: $^{40}Ar/^{39}Ar$ apparent age patterns and the duration of metamorphism in the biotite zone. Journal of the Geological Society 168, 133–146.
Viete, D.R., Oliver, G.J.H., Fraser, G.L., Forster, M.A., Lister, G.S., 2013. Timing and heat sources for the Barrovian metamorphism, Scotland. Lithos 177, 148–163.
Viete, D.R., Richards, S.W., Lister, G.S., Oliver, G.J.H., Banks, G.J., 2010. Lithospheric-scale extension during Grampian orogenesis in Scotland. Geological Society Special Publication 335, 121–160.
Vorhies, S.H., Ague, J.J., 2011. Pressure-temperature evolution and thermal regimes in the Barrovian zones, Scotland. Journal of the Geological Society 168, 1147–1166.
Wallace, L.M., McCaffrey, R., Beavan, J., Ellis, S., 2005. Rapid microplate rotations and backarc rifting at the transition between collision and subduction. Geology 33, 857–860.
Yardley, B.W.D., Senior, A., 1982. Basic magmatism in Connemara, Ireland: evidence for a volcanic arc? Journal of the Geological Society 139, 67–70.
Zenk, M., Schultz, B., 2004. Zoned Ca-amphiboles and related P-T evolution in metabasites from the classical Barrovian metamorphic zones in Scotland. Mineralogical Magazine 68, 769–786.