Dalradian structure and metamorphism

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This is a longer and fully referenced text for the article published in The Edinburgh Geologist*, No. 53 (Spring 2013), 10-15. For figures, see the published article.*

In *Edinburgh Geologist* number 50 we looked at the evolution and age of the Dalradian sedimentary basin. Here the story is continued with an assessment of the structural architecture of the Dalradian succession and the associated metamorphic patterns, for which increasing isotopic and petrological data are doing much to clarify the nature and timescale of the tectonothermal processes involved.

The Dalradian basin lay on the edge of Laurentia as it broke away from the supercontinent of Rodinia and the Iapetus Ocean opened up. The ocean probably reached its maximum width in the Early Ordovician and then began to close. At around 474 Ma a volcanic arc system collided with the Laurentian margin, the results of which can now be traced from the Taconic terranes of eastern North America through Ireland and Scotland at least as far as Shetland (Fig. 1). In Scotland this collision gave rise to the Grampian tectonothermal event. Around 430 Ma years, the microcontinent of Avalonia docked against Laurentia and shortly afterwards, around 425 Ma the continental mass of Baltica collided with Laurentia initiating the Scandian event (Fig. 1); these collisions did not greatly affect the Grampian terrane.

Grampian Event

As the volcanic arc closed with the continental edge, oceanic crust was obducted onto the youngest Dalradian sediments along what is now the Highland Border. These ophiolitic rocks now form a series of serpentinised bodies with associated cherts and black shales collectively comprising the Garron Point Group (Tanner & Sutherland, 2007), that rests on the highest beds of the Trossachs Group of the Dalradian succession, giving a maximum age for initiation of the Grampian Event of ca 474Ma. As collision progressed the volcanic arc probably became buried under the leading edge of the continent compressing and deforming the Dalradian succession, the crust thickened and the deeper rocks became progressively metamorphosed.

The deformation is generally considered in four discrete phases (D1-D4). The folds related to all four phases have gently plunging and broadly coaxial. The first two phases effectively producing major, broadly flat lying, recumbent folds. The second two phases generally producing more upright structures.

The early structures are dominated in the Southern Highlands by the Tay Nappe a major regional scale fold that causes large-scale inversion of the beds. To the northeast the nappe dies out and is effectively absent in the Buchan area such that the beds there are largely right-way-up. Effectively the pile of deformed Dalradian rocks was thickest in the SW and Perthshire and relatively thin in the NE. The main growth of metamorphic porphyroblasts occurred from syn-D2 to syn-D3. A minimum age for the Grampian tectonometamorphism is given by the earliest of the post-tectonic granite intrusions at ca 455 Ma (Oliver *et al*, 2008). The Grampian Event was therefore relatively short lived, lasting around 10 Ma and peaking at 470-465 Ma.

Buchan Block

In general terms the age and nature of the arc-collision events is similar along the Laurentian edge from f N America through Ireland and Scotland to Shetland (Oliver *et al*, 2000; Cutts *et al*, 2011) but an exception is the Buchan Block of NE Scotland. This is bounded to the west by the Portsoy-Duchray Hill Lineament, a long-lived shear zone, and to the south by the Deeside Lineament, a somewhat enigma structure, now marked by a series of major granite plutons (Fig. 2). Both these lineaments are thought to reflect major lines of weakness in the underlying basement. The Buchan Block was originally considered as a distinct entity, structurally, stratigraphically, and metamorphically different from the rest of the Dalradian succession. However, it is now accepted that the lithostratigraphical divisions of the Buchan block can be correlated with areas farther SW. The deformation sequences are also comparable, although D2 and D4 are poorly developed in Buchan.
The region however differs in a number of characteristics.

1. As noted above the Dalradian succession in Buchan does not have the major nappe development and crustal thickening seen in Perthshire and the SW. This is reflected in regional geophysical patterns where the Buchan Block exhibits much higher gravity values than the rest of the Dalradian region (Trewin & Rollin, 2002); a characteristic interpreted as reflecting a relatively shallow basement under only a moderately thickened Dalradian succession.
2. The orientation of the major fold axes (primarily D1 and D3) is approximately N-S in the Buchan region as opposed to a NE-SW orientation over the rest of the Dalradian (Fig. 2). The latter orientation is parallel to the Highland Boundary Fault and the presumed zone of continent-arc collision.

3. The Buchan Block was an area of very high heat flow as evidenced by the style of metamorphism and associated ‘Older Granite’ masses and the suite of ‘Newer Gabbros’.

Metamorphism

The early workers identified two styles of metamorphism in the Dalradian belt. Firstly, the Barrovian indicative of intermediate pressure metamorphism (i.e.intermediate heat flow) and characterised by garnet and kyanite. It was first defined in the Angus glens by Barrow, and is now considered to typify the bulk of the Dalradian crop. Secondly, the Buchan indicative of low pressure metamorphism (i.e. high heat flow) and characterised by cordierite and andalusite. It was first defined in the Buchan region by Read. Although initially considered to be separate events it is now accepted that the growth of the porphyroblasts in the two regions is broadly synchronous and that there are wide transitional zones between the two types both to the west and to the south (Harte & Hudson, 1979) It is important to note that the highest grade rocks (i.e. middle and upper amphibolite facies) within the Dalradian belt occur in the Eastern Highlands (Fig. 2). Consequently it is convenient to consider the Barrovian area in two parts, the classical area in the SE Highlands (Barrovian s.s) and that comprising Perthshire and the SW (Barrovian s.l.).

The background cause of Dalradian metamorphism was thermal relaxation of the over-thickened crust (England & Thompson, 1984; Thompson & England, 1984). However, this does not explain the intense metamorphism seen in the Eastern Highlands, the speed with which peak temperatures were reached as evidenced by the near synchronous development of peak temperatures across the garnet, kyanite and sillimanite mineral zones in the classical Barrovian region (Baxter *et al* 2002). These factors require significant additional heat input (Baxter *et al*, 2002; Viete *et al*, 2011b). Thus fluids, magmas or both must have introduced considerable quantities of additional heat. In Buchan the Newer Gabbro suite is an integral part of this input; the highest grade rocks (sillimanite + k-feldspar) of the region occurring in the aureoles. The Older Granites may also be seen as agencies of the heat input.

The highest heat flow occurred in Buchan reducing to the west and south, with the adjacent areas having increased temperatures due to heat transfer from the Buchan ‘hotspot’. Thus the classical Barrovian areas reflect thermal regimes enhanced relative to those of Perthshire and the SW

Timing

In the Barrovian (s.s.) area syn-D2 garnet growth has been dated at 472.9 +/-2.9 Ma and syn-to post-D3 at 464 +/-2.7 Ma with peak temperatures across the garnet, kyanite and sillimanite zones broadly synchronous at ca 465 Ma (Oliver, 2000; Baxter *et al*, 2002; Ague & Baxter, 2007). This accords with data presented by Viete *et al*, (2011b) that the Barrovian thermal event lasted from between 1 and 10Ma in the biotite zone. This may have reflected background heating produced by the thermal relaxation of the overthickened crust whereas the high temperatures producing that peak conditions in the Buchan and Barrovian (s.s.) regions were driven by short episodic heat pulses which probably occurred over a period of <1 Ma and was terminated by rapid exhumation (Ague & Baxter, 2007, Viete *et al*, 2011a, Vorhies & Ague, 2011). Pulsed heat input may have resulted in variations in peak conditions from place to place and from time to time on a timescale of ca.1 Ma.; thus the two phases of sillimanite growth described by Harte & Hudson (1979) could relate to two such pulses (Viete *et al*, 2011a).

In Buchan there is a close association between the intrusion of the Newer Gabbros, the Older Granites and the peak of metamorphism. The Newer Gabbros have been dated at ca 471 Ma (Dempster *et al*, 2002, Carty *et al*, 2012). The older foliated granites have also been dated at ca. 470 Ma (Oliver *et al* 2008). The peak of porpyhroblast growth must follow closely after the intrusions suggesting that peak metamorphism was broadly in the period 470-469 Ma.This would imply that the highest temperatures were reached in the Buchan area possibly 3-4 Ma before that in the Barrovian (s.s.) region. This accords with the timing of peak conditions relative to the deformation sequence, that is syn-D2 in Buchan and syn-D3 in the Barrovian region (Carty *et al*, 2012; Vorhies & Ague, 2011). If these differences are real it suggests that the heat input was focused in Buchan and moved out into adjacent areas, possibly by conduction (Baxter *et al*, 2002; Carty *et al*, 2012), although the relatively thicker crust south of the Deeside |Lineament may also have played a role

Portsoy-Duchray Hill Lineament

This is a major long-lived north-south lineament. It was probably the site of partial crustal rupture in Argyll Group times (Fettes *et al*., 2011). Westward thrusting, closely associated with gabbroic intrusion during the main porphyroblast growth, led to overloading of the footwall and the inversion of andalusite to kyanite in a zone ca 10km wide west of the current outcrop of the thrust/shear zone (Beddoe-Stephens, 1990). Intrusion of the Portsoy Gabbro, peak metamorphic conditions and D2 thrusting are broadly synchronous at ca. 471Ma. (Carty *et al*, 2012).

Models

Why is the Buchan block different? Perhaps the simplest possibility is that the volcanic arc, which collided with the Dalradian margin, did so obliquely with the major indentation in the

SW and that the induced stress along the continental edge was relieved by slippage on a line of weakness in the basement, now recognised as the Deeside Lineament. The Buchan Block would not therefore have suffered the compression and crustal thickening experienced by the main Dalradian areas. The relief of stress may also have allowed some rebound and extension of the |Buchan block leading to decompression melting and to the enhanced heat flow. Subsequent compression led to thrusting on the Portsoy line and the major D3 (D4??) folding. Another possibility would involve a fragmented arc, one element colliding with Southern regions and a second fragment colliding with Buchan possibly less forcibly and at a slightly different angle than that to the south.

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Figure Captions.

Fig. 1. Stratigraphical column showing the elements of the Caledonian Orogeny. Global reconstructions show stages in the convergence of continents: L, Laurentia, B, Baltica, AV, Avalonia, SC, Scotland, red dashes, volcanic arc system.

Fig 2. Major structural elements of the Dalradian Belt. Inset map shows the metamorphic facies of the Eastern Highlands and the position of the high grade rocks.