Lithos 177 (2013) 148–163

Contents lists available at ScienceDirect

Lithos

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

Timing and heat sources for the Barrovian metamorphism, Scotland

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ARTICLE INFO

Article history:
Received 11 February 2013
Accepted 16 June 2013
Available online 25 June 2013

Keywords:
Geochronology
Orogenesis
Bimodal magmatism
Regional metamorphism
Contact metamorphism

ABSTRACT

New SHRIMP U/Pb zircon ages of 472.2 ± 5.8 Ma and 471.2 ± 5.9 Ma are presented for the age of peak metamorphism of Barrovian migmatites. $^{40}Ar/^{39}Ar$ ages for white mica from the Barrovian metamorphic series are presented, and are recalculated using recently-proposed revisions to the ^{40}K decay constants to allow more precise and accurate comparison with U/Pb ages. The $^{40}Ar/^{39}Ar$ ages are found to vary systematically with increasing metamorphic grade, between c. 465 Ma for the biotite zone and c. 461 Ma for the sillimanite zone.

There is no evidence for any significant metamorphic heating during the first 15 Myr of the Grampian Orogeny (before c. 473 Ma) or the final 4 Myr (after c. 465 Ma). The Barrovian metamorphism occurred over a period of ~8 Myr within the ~27-Myr Grampian Orogeny. The Barrovian metamorphism records punctuated heating, was temporally and spatially associated with large-scale bimodal magmatism, and developed within crust that was not overthickened. The temporally distinct nature of the Barrovian metamorphic episode within the Grampian Orogeny, and its heating pattern and tectonic context, are not consistent with significant heat contribution from thermal equilibration of overthickened crust. Rather, the Barrovian metamorphism records a transient phase of crustal thermal disequilibrium during the Grampian Orogeny.

Temporal and spatial association with Grampian bimodal magmatism is consistent with production of the Barrovian metamorphic series within the middle crust as the result of advection of heat from the lower crust and/or mantle. The Barrovian metamorphic series – the classic example of 'orogenic regional metamorphism' – did not form in response to crustal thickening and thermal relaxation, but appears to record large-scale contact metamorphism.

1. Introduction

The Barrovian metamorphic series crops out in the SE of the Grampian Terrane, Scotland (Fig. 1), on the southern margin of the Scottish Highlands. The metamorphic sequence is celebrated as the setting for the work of Barrow (1893, 1912), who was the first to use indicative mineral assemblages to map regional metamorphism. The metamorphic progression across the Barrovian metamorphic series was defined by Barrow (1893, 1912) by the sequential first appearance of clastic mica (chlorite), biotite, garnet, staurolite, kyanite and sillimanite in the pelite metamorphic assemblage in the direction of increasing metamorphic grade, to the NW, away from the Highland Boundary Fault (HBF) (Fig. 1). Since Barrow's work, the Barrovian metamorphic series has become ensconced in the geological literature as the classic example of 'intermediate P/T' metamorphism, typically regarded as a consequence of continental collision (e.g. Spear, 1993). Such metamorphism is often referred to as Barrovian-type metamorphism.

The Barrovian metamorphism occurred at c. 470 Ma (Baxter et al., 2002; Oliver et al., 2000) during the Grampian Orogeny of Lambert and McKerrow (1976). The effects of the Grampian Orogeny in Scotland are mostly restricted to the Grampian Terrane, which crops out north of the HBF and south of the Great Glen Fault (Fig. 2). The Grampian Orogeny is also recorded in geological domains that crop out in certain regions of western and Northern Ireland, including the Connemara, Donegal, NW Mayo, Ox Mountains and Tyrone Central Inliers and Slishwood Division (see Fig. 2). Deformation and metamorphism during the Grampian Orogeny affected the sedimentary units of the Neoproterozoic to Ordovician (Strachan and Holdsworth, 2000) Dalradian Supergroup.

U/Pb zircon and Sm/Nd garnet geochronology has been used to restrict the total duration of the main tectonothermal phase of the Ordovician-age Grampian Orogeny of Scotland and Ireland to 12 to 15 million years, between 478 and 463 Ma (Friedrich et al., 1999a; Oliver et al., 2000). U/Pb zircon and Sm/Nd garnet geochronology has also been used to date the timing of metamorphic mineral growth during the Grampian-age Barrovian metamorphism at c. 470 Ma

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http://dx.doi.org/10.1016/j.lithos.2013.06.009

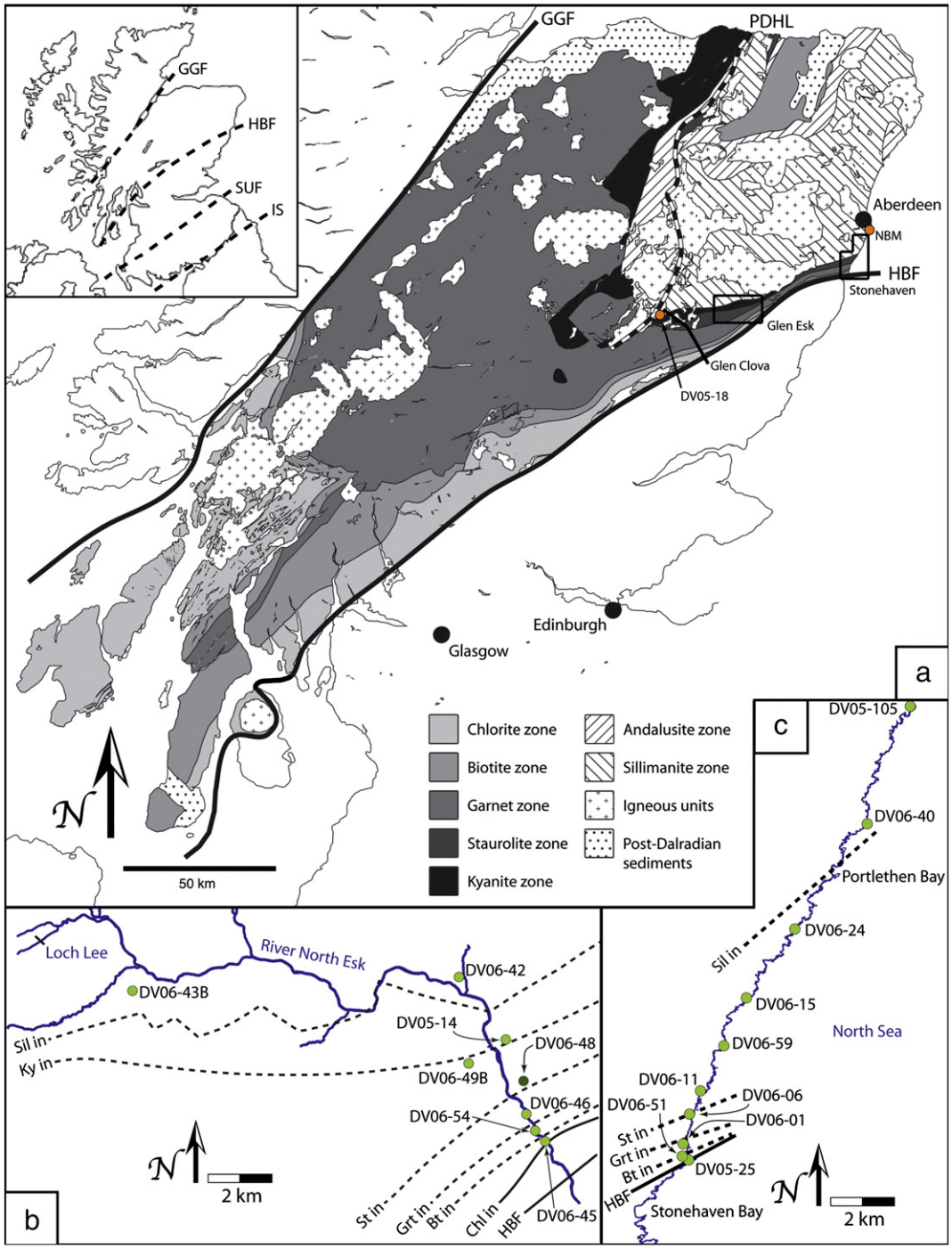

Fig. 1. Map of the Grampian Terrane, Scotland, showing (a) the distribution of metamorphic mineral isograds, magmatic bodies and post-Grampian sediments and the location of U/Pb SHRIMP samples (orange dots), (b) sample localities for $^{40}Ar/^{39}Ar$ samples (green dots) from the Glen Esk transect (enlargement of rectangle of Fig. 1a) and (1c) sample localities for $^{40}Ar/^{39}Ar$ samples (green dots) from the Stonehaven transect (enlargement of polygon of Fig. 1a). Inset at top left of Fig. 1a provides a broader location map. GGF: Great Glen Fault, HBF: Highland Boundary Fault, IS: Iapetus Suture, PDHL: Portsoy–Duchray Hill Lineament, SUF: Southern Uplands Fault. Compiled after Barrow (1912), Elles and Tilley (1930), Hudson (1980), Fettes et al. (1986), Harte (1987) and Viete et al. (2011a). Mineral abbreviations follow the recommendations of Kretz (1983).

(Baxter et al., 2002; Oliver et al., 2000; Vorhies et al., 2013). Recent high-precision 'geospeedometry' and Sm/Nd garnet geochronology works have shown that the Barrovian metamorphism within the Grampian Orogeny occurred over short time scales of a few million years (Baxter et al., 2002; Dewey, 2005; Dewey and Mange, 1999; Oliver et al., 2000; Viete et al., 2011a) or less (Ague and Baxter, 2007) and involved episodic heating (Ague and Baxter, 2007; Viete et al., 2011b). Importantly, the short duration of Barrovian metamorphism has been demonstrated for rocks across the sequence, from the lower-grade (e.g. biotite and garnet) zones to the high-grade core (Ague and Baxter, 2007; Viete et al., 2011a). Such short time scales for the Barrovian regional metamorphism and an association with episodic heating have raised new questions regarding the origin of the heat and the tectonic context for the metamorphism (see Ague and Baxter, 2007; Viete et al., 2011a,b; Vorhies and Ague, 2011). Chief among these is the relative contribution of metamorphic heat derived