Gondwana Research 39 (2016) 250–260

Contents lists available at ScienceDirect

Gondwana Research

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

Tectonic controls on post-subduction granite genesis and emplacement: The late Caledonian suite of Britain and Ireland

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ARTICLE INFO

Article history:
Received 18 August 2015
Received in revised form 10 December 2015
Accepted 10 February 2016
Available online 11 March 2016

Handling Editor: A.S. Collins

Keywords:
Zircon
Plutons
Caledonian
Tectonics

ABSTRACT

Rates of magma emplacement commonly vary as a function of tectonic setting. The late Caledonian granites of Britain and Ireland are associated with closure of the Iapetus Ocean and were emplaced into a varying regime of transpression and transtension throughout the Silurian and into the early Devonian. Here we evaluate a new approach for examining how magma volumes vary as a function of tectonic setting. Available radiometric ages from the late Caledonian granites are used to calculate probability density functions (age spectra), with each pluton weighted by outcrop area as a proxy for its volume. These spectra confirm an absence of magmatic activity during Iapetus subduction between *c.* 455 Ma and 425 Ma and a dominance of post-subduction magmas between *c.* 425 Ma and 380 Ma. We review possible reasons why, despite the widespread outcrop of the late Caledonian granites, magmatism appears absent during Iapetus subduction. These include shallow angle subduction or extensive erosion and tectonic removal of the arc.

In contrast to previous work, we find no strong difference in the age or major element chemistry of post-subduction granites across all terranes. We propose a common causal mechanism in which the down-going Iapetus oceanic slab peeled back and detached beneath the suture following final Iapetus closure. The lithospheric mantle was delaminated beneath the suture and for about 100 km back beneath the Avalonian margin. While magma generation is largely a function of gravitationally driven lithosphere delamination, strike slip dominated kinematics in the overlying continental crust is what modulated granitic magma emplacement. Early Devonian (419–404 Ma) transtension permitted large volumes of granite emplacement, whereas the subsequent Acadian (late Early Devonian, 404–394 Ma) transpression reduced and eventually suppressed magma emplacement.

1. Introduction

Rates of magma generation and emplacement differ markedly between different tectonic settings (e.g., Zellmer and Annen, 2008). While extensional regimes generally result in rapid magma ascent through dykes, intra-plate settings may promote magma storage and differentiation within the crust due to sill emplacement and increased geothermal gradients. By contrast, arcs are associated with a range of extensional, transtensional or compressional regimes with varying rates of magma generation and emplacement (e.g., Glazner, 1991). The Caledonian magmas of Northern Britain were emplaced into just such a varied tectonic environment during, and immediately after, Silurian subduction of the Iapetus Ocean. These magmas offer an excellent opportunity to investigate how rates of magma generation and emplacement are controlled by different tectonic regimes.

Collectively, the Caledonian magmatic rocks of northern Britain represent a significant volume (total surface area *c.* 8500 km^2 now exposed) of calc-alkaline and predominantly granitic magma. Paradoxically, however, there is little evidence to link these magmas to the subduction of Iapetus oceanic lithosphere. The magmas that are preserved have been shown to post-date final closure of the Iapetus by as much as 40 Ma, and many authors have highlighted differences in composition between the Caledonian granites and those formed in active subduction, pre-plate collision environments such as the Andes (Pitcher, 1982; Watson, 1984; Pitcher, 1987; Atherton and Ghani, 2002; Neilson et al., 2009; Miles et al., 2014).

The tectonic environment that followed Iapetus closure, and within which most of the preserved magmatism occurred, was dominated by widespread episodes of transtension and transpression and reflects a complex interplay of oblique interactions between Avalonia, Laurentia and Baltica (Soper et al., 1992; Torsvik et al., 1996; Dewey and Strachan, 2003) and deep, lithospheric-scale slab detachment associated with final ocean closure (Atherton and Ghani, 2002). In the context of tectonic controls, magma may have been generated in response to tectonic convergence and collision and then subsequently in response to intra-plate deformation as reflected in the alternating episodes of transpression and transtension. Assessing the response of magmatic activity within this tectonic framework requires estimates of when

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http://dx.doi.org/10.1016/j.gr.2016.02.006
1342-937X/

magmas were generated and the volumes of magma emplaced at different stages of tectonic activity. An extensive literature of Rb–Sr, Ar–Ar and K–Ar ages exist for the Caledonian magmas. However, only recently have significant numbers of more reliable zircon ages become available (e.g., Oliver et al., 2008; Miles et al., 2014 and references therein). This absence of robust ages has hampered attempts to constrain the exact origin and timing of Caledonian magmatism, while no attempt has yet been made to estimate changes in magma volume through time.

We present a newly compiled set of zircon age spectra from all tectonic terranes of the British Caledonides and for the first time weight these distributions by the outcrop area of the individual plutons. Our results indicate how magma volumes vary spatially and temporally as a function of tectonic setting. We confirm that magmatism was largely absent during Iapetus subduction and review whether this apparent absence reflects a preservational bias in the geological record or a genuine absence of magmatic activity (Oliver et al., 2008). Furthermore, our data reveal how post-subduction magma emplacement was modulated by alternating episodes of transtension and transpression. These findings, together with estimates of how magma volumes vary spatially throughout Northern Britain during the late Caledonian, are used to investigate tectonic controls on magma emplacement as part of a refined model for Caledonian magmatism.

2. Tectonic history of the Caledonian Orogen

The Caledonian Orogeny involved successive deformation phases (McKerrow et al., 2000) beginning with the Grampian Phase in which the continent-facing Midland Valley arc collided with the Laurentian margin at about 470–460 Ma (Mid-Ordovician; Dewey and Shackleton, 1984; Cocks and Torsvik, 2002). This phase of collision is associated with obduction of the Ballantrae ophiolite (Oliver, 2001) and emplacement of predominantly S-type, foliated granites in the NW Highlands (Pankhurst and Sutherland, 1982). Erosion-driven exhumation of the Grampian terrane, with little tectonic activity, followed between 465 and 440 Ma (Late Ordovician), with linked, small-volume, non-foliated S-type granites generated by decompression melting (e.g., Oliver, 2002).

Deep marine sedimentation began at 455 Ma in the Southern Uplands accretionary prism (Fig. 1), where numerous packages of sediments are bounded by major syn-sedimentary reverse faults (McKerrow et al., 1977; Leggett et al., 1979). The beginning of accretion signalled the onset of an NW-dipping subduction zone bordering Laurentia (Oliver, 2002). The sediments of the Southern Uplands accretionary prism are, however, unusual in that they did not significantly sample any associated magmatic arc (Phillips et al., 2003; Waldron et al., 2008). At about the same time, southeast-dipping subduction of Iapetus lithosphere under Avalonia ceased, probably as the margin over-ran the Iapetus spreading ridge (Woodcock, 2012), and it is reflected in an absence of latest Ordovician igneous rocks on this margin.

At 430 Ma (mid-Silurian), oblique collision of Baltica and Laurentia resulted in the Scandian Phase and activation of the Moine Thrust system in NW Scotland (Kinny et al., 2003). The absence of Scandian deformation in the Grampian terrane indicates that the Northern Highlands and Hebridean terranes must have been separated from it at that time by many hundreds of kilometres (Dewey and Strachan, 2003). Later sinistral strike slip along the Great Glen Fault between about 425 and 400 Ma eventually brought the Northern Highlands and Grampian terranes together.

Also at about 430 Ma, clockwise transection of folds by cleavage indicates that accretion in Ireland and the Southern Uplands switched from orthogonal to sinistrally transpressive (Anderson, 1987; Dewey et al., 1997; Dewey and Strachan, 2003), and turbidite deposition in the trench overlapped onto the Leinster–Lakesman terrane. Additionally, a mid-Silurian weakening in deformation within the Southern Uplands accretionary prism (Kemp, 1987) and a change from foliated to unfoliated lamprophyre dykes (Rock et al., 1986) suggest that Laurentia–Avalonia convergence and subduction of the Iapetus Ocean ceased by about 420 Ma (late Silurian). Following an apparent magmatic gap of about 20 Ma, granitic magmatism resumed at about 430 Ma, in the Central-Southern Uplands and – by about 420 Ma – in the Leinster–Lakesman terranes as well as the Highlands terranes. Late Silurian cooling ages in Moine and Dalradian metamorphic rocks reflect exhumation of the Laurentian margin at this time (Dempster et al., 1995; Dallmeyer et al., 2001). However, the absence of tectonic activity within the Grampian terrane suggests that much of this exhumation was climate driven (Oliver et al., 2008).

Following the end of Iapetus subduction, the early Devonian is characterised by as much as 10–20 km of exhumation and erosion (Flinn, 1977; Clayburn, 1981; Watson, 1984; Atherton and Ghani, 2002). In contrast to earlier exhumation, Early Devonian exhumation is coincident with widespread deposition of the non-marine Old Red Sandstone Supergroup (ORS) within transtensional basins controlled by sinistral strike slip and normal faults (Bluck, 1984; Smith, 1995; Dewey and Strachan, 2003). The metamorphic grade in rocks conformably below the Old Red Sandstone suggests that it reached a thickness of around 3.5 km in NW England and North Wales (Soper and Woodcock, 2003). Subsidence within intermontane basins due to lithospheric transtension probably accommodated this thickness of non-marine sediments (Soper and Woodcock, 2003). A suite of lamprophyre dykes intruded into all the assembled Caledonian terranes between 425 and 400 Ma (Rock et al., 1986) supports sedimentological evidence for regional extension or transtension (Brown et al., 2008). It is during this interval of very high denudation and simultaneous transtension that the majority of granites were intruded in the Grampian terrane (Oliver et al., 2008) and across the Iapetus Suture zone (Miles et al., 2014) (Fig. 1).

The onset of Acadian transpression at 404 Ma is reflected in the appearance of regionally clockwise-transecting sinistrally transpressive cleavages, marking the end of Early Devonian sinistral transtension (Soper et al., 1987; Dong et al., 1997; Soper and Woodcock, 2003). Acadian deformation in Britain and Ireland is mild relative to the type area in the Appalachians (e.g., Bradley et al., 2000; Murphy and Keppie, 2005), and it resulted in folding, slaty cleavage, and low-grade metamorphism throughout the Leinster–Lakesman terrane and the Cymru zone of the Avalon terrane (Soper and Woodcock, 2003). Acadian folding northwest of the Iapetus Suture is weak, for instance the Strathmore syncline in the Midland Valley (Soper et al., 1992; Smith, 1995), and Dewey and Strachan (2003) suggest that such structures may in part also relate to early transtension. Acadian cleavage is only locally recognised in these Laurentian terranes, such as along the Moniaive Shear Zone that is coeval with emplacement of the Fleet pluton in the Southern Uplands (Phillips et al., 1995; Miles et al., 2014). Deformed leucogranite veins with emplacement ages of 400.8 $\pm$ 2.6 Ma adjacent to the Great Glen Fault indicate that localised Acadian shear zones occurred as far north as the Northwest Highlands (Mendum and Noble, 2010). The northward weakening of Acadian deformation may be due to its link, not with Iapetus closure, but with collision or flat-slab subduction in the Rheic Ocean, some 400 km to the south (Woodcock et al., 2007).

3. Magmatic history of the Caledonian Orogen

Subduction and its associated magmatism ceased along the southern (Avalonia) Iapetus margin by *c.* 455 Ma (mid-Caradoc) due to subduction of the Iapetus spreading ridge (Woodcock, 2012). By contrast, voluminous and predominantly calc-alkaline magmatism on the Laurentian margin (Fig. 1) began during the mid-Silurian (*c.* 430 Ma) and continued through to the mid-Devonian (Oliver et al., 2008). The Caledonian granites exhibit compositions that distinguish them from granites emplaced in active arc settings such as the Andes (Pitcher, 1982) and are instead more indicative of post-collisional environments (Atherton and Ghani, 2002; Neilson et al., 2009). A subduction origin is also at