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

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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, intraplate 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; 1987; Watson, 1984; Atherton and Ghani, 2002; Nielson 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 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. Miles et al., 2014; Oliver et al., 2008 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 a 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, south-east-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 (Naggar and Atherton, 1970; Pitcher and Berger, 1972; 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 north-west 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 ± 2.6 Ma adjacent to the Great Glen Fault indicate that localised Acadian shear zones occurred as far north as the North-west 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 odds with the overall timing of Iapetus closure, dated at late Wenlock (*c.* 420 Ma) (Soper, 1992).

The isotope compositions of most plutons (Halliday, 1984; Stephens and Halliday, 1984; Thirlwall, 1989) together with the presence of inherited zircons (Pidgeon and Aftalion, 1978) suggest a significant component of crustal recycling was involved in magma genesis (O’Nions et al., 1983; Frost and O’Nions, 1985; Harmon et al., 1984) in addition to a lithospheric mantle-derived component (Harmon et al., 1984; Stephens and Halliday, 1984).

Attempts to reconcile the calc-alkaline characteristics and post–subduction emplacement ages of the magmas have included the dehydration of a stationary slab of subducted oceanic crust (Thirlwall, 1981). Watson (1984) suggested that partial melting of previously metasomatised lithospheric mantle occurred in response to lateral, post-subduction shear. Further suggestions have included slab detachment and continued subduction after ocean closure based on deep-seismic reflection profiling (Freeman et al., 1988). However, models that invoke any component of subduction cannot account for the proximity of Southern Uplands magmatism to the projected line of the Iapetus Suture, nor can they explain the occurrence of granites south of the suture in eastern Ireland and Northern England (Fig. 1).

Zircon U-Pb ages indicate that most Caledonian magmatism was coincident with, or mostly post-dated, final Iapetus subduction (Oliver et al., 2008; Miles et al., 2014). The latter stages of ocean subduction together with the attempted subduction of more buoyant continental lithosphere has been related to large amounts of extension at the ocean-continent transition, which in some instances can lead to slab break-off (Davies and von Blanckenburg, 1995). Atherton and Ghani (2002) were the first to apply the slab break-off model to explain post-subduction Caledonian magmatism, proposing that asthenospheric replacement of the detached lithospheric slab resulted in partial melting of the overlying LILE- and LREE-enriched lithospheric mantle. These melts are said to have resulted in new crustal additions of magmas which are reflected in the emplacement of an extensive regional swarm of appinite-lamprophyre dykes. Repeated emplacement of mafic melts is likely to have resulted in crustal recycling by partial melting of mafic to intermediate lower crust to form plutons and volcanoes (Brown et al., 2008; Miles et al., 2013). The replacement of metasomatised lithosphere by buoyant asthenosphere is also likely to have resulted in rapid uplift and extensional collapse, consistent with high exhumation and denudation rates (Watson, 1984) and deposition of the Old Red Sandstone within transtensional basins during the Early Devonian. These observations are consistent with thermomechanical modelling of slab detachment, which suggest that uplift is often focussed in a *c.* 300 km area within the overriding plate immediately above the detached slab (e.g. Gerya et al., 2004). Although difficult to prove unequivocally, Neilson et al. (2009) highlight that slab breakoff is best able to explain magma chemistry, volumes and timing in relation to tectonism in the Grampian terrane. Magma emplacement in the upper crust is likely to have been aided by faulting caused by thermal weakening and the onset of plate-scale sinistral strike slip.

In contrast to recently obtained zircon U-Pb ages (Miles et al., 2014), most ages from the K-Ar, Ar-Ar and Rb-Sr methods suggest that around half the total volume of Caledonian magma was emplaced during Acadian transpression, and almost exclusively to the south of the Highland Boundary Fault. The weakly cleaved margins of some plutons and their associated dykes also suggest that at least some magmatism occurred during Acadian transpression (Soper and Kneller, 1990). The discrepancies between dating methods are likely to reflect differences in closure temperature between different isotopic systems (Miles et al., 2014). In support of this, K-Ar ages from cleavage-parallel micas confirm that the country rocks south of the Highland Boundary Fault were heated above the Ar closure temperature in biotite and muscovite (300-350°C) during the thermal peak of Acadian deformation (250-350 °C, Merriman, 2006) at 404-394 Ma. It is therefore likely that K-Ar systems in igneous rocks were reset at this time. Rb-Sr systems, with closure temperatures of 400-525°C, should not have been reset. However recrystallisation and reactions with fluids probably decrease the closure temperatures (e.g. Villa, 1998; Jenkin et al. 2001). The > 900°C closure temperature for the U-Pb zircon system is above the granite liquidus, and can therefore confidently be interpreted across all terranes as primary crystallisation ages. This reasoning can be extended to monazite (715°C) and sphene (625°C) ages.

In light of these new zircon ages, the origin of magmatism across northern Britain during the Caledonian now requires a unifying model.

4. Methodology for displaying age distributions

In addition to the large dataset of zircon ages from the Grampian and Northern Highlands terranes compiled by Oliver et al (2008), we include the following data sets; a) additional ages from the Northern Highlands terrane given by Goodenough et al. (2011) and Kocks et al. 2014, b) an age from the Lorn Lavas in the Grampian Terrane from Neilson et al. (2009), c) recently acquired zircon ages from the Trans-Suture granites (Miles et al., 2014), and d) ages of plutons from the extension of each terrane into Ireland (from Chew & Stillman, 2009). Where few zircon U-Pb data for igneous bodies are available (e.g. the Midland Valley), we have used published Rb-Sr ages. Importantly, the data are weighted by the outcrop area of their host pluton or extrusive body, in an attempt to make the age spectra better proxies for magma volumes through time. Area weighting will overestimate the volumetric contribution of extrusive bodies compared with most intrusions, and so their outcrop area is divided by an arbitrary compensating factor of five. Also, Neilson et al. (2009) estimate that a large volume of post-subduction volcanic rocks have been removed by erosion; over 2000 km^3 of lavas and tuffs from the Etive pile alone. We have not included eroded volcanic rocks in our study. K-Ar ages from cleavage-parallel micas are used to date Acadian deformation, and they have not been area-weighted.

Digital maps of the pluton boundaries from the British Geological Survey and Geological Survey of Ireland were imported into the QuantumGIS application, in which polygon areas could be measured. The Weardale pluton is only known from borehole core. However gravity modelling (Kimbell et al., 2010) indicates that the Early Devonian granites in Northern England are steep-sided cylinders. The area of the Weardale pluton is therefore taken as the sum of the areas of these subsurface pipes. The extent to which outcrop area scales with volume in other Caledonian plutons is of course dependent on their three-dimensional geometry, which for most plutons is poorly known. However, gravity data suggest that most Caledonian granites, including those with the largest surface areas such as the Cairngorm, Leinster, Weardale and Fleet plutons, have significant negative Bouguer anomalies and reach depths of at least *c.* 12 km (Parslow and Randall, 1973; Rollin, 1984; Emenike, 1986; Kimbell et al., 2010). Furthermore, a number of these gravity studies suggest that most plutons are steep-sided. The surface areas of plutons are therefore likely to scale with volume. Despite the inherent uncertainties, we suggest that area-weighting gives a better approximation to relative changes in magma volumes with time than do unweighted age spectra.

We have used revised Rb-Sr and K-Ar decay constants for the data displays but, for the probability distribution functions, both adjusted and unadjusted curves are displayed. The Rb-Sr ages have been adjusted to a revised decay constant of 1.393×10^{-11} (Nebel et al., 2011). This 1.9% lowering of the Rb decay results in ages older by about 8 Ma at 400 Ma, a significant increment at the age resolution relevant to this paper. A revised value of the K-Ar decay constant from the value of 5.543×10^{10} a^{-1} (Steiger & Jäger, 1977) is still under discussion. However most analyses suggest that the constant is too high, perhaps by as much as 1.4% (Min et al., 2000). We have used the more conservative 1% decrease suggested by

Dickin (2005, pp. 275-276) and supported by comparisons with zircon U-Pb ages (Jourdan et al., 2009). This adjustment results in K-Ar ages that are older by 4 Ma at 400 Ma.

To calculate the probability distribution functions (PDF), each mean age and 1σ population error was used to calculate a Gaussian distribution (Figs. 2 and 3). Each age distribution was then weighted according to the pluton's surface area and divided by the number of available ages for that pluton. Finally, the distribution functions for each age determination were summed regionally (Fig. 2) and across each tectonic terrane (Fig. 3). The total surface area of plutons is therefore represented by the surface area beneath the summed PDF.

5. Results

Episodes of deformation are recognised by K-Ar and Ar-Ar age spectra using cleavage parallel-micas (Fig. 3). Superimposed on these episodes of deformation is an area-weighted age spectrum constructed using all available granite zircon U-Pb ages, showing how magma volumes vary at a regional scale between 440 and 380 Ma (Fig. 2). Also shown are area-weighted age spectra for individual terranes (Fig. 3), enabling a comparison of magmatism across terranes.

5.1 Regional variations in magma volumes

A regional analysis of relative magma volumes between 440 and 380 Ma includes *c.* 8500 km^2 of granite outcrop (Fig. 2). Magmatism began at 435 Ma (mid Llandovery) and persisted until 380 Ma (late Devonian). The area of exposed granite increased towards the end of Iapetus subduction, reaching a peak of *c.* 200 km^2 by 425 Ma before being suppressed during a 5 Ma period of transpression between 425 and 420 Ma. Rates of granite emplacement increase again from 420 Ma to 405 Ma, with a maximum surface area of 800 km^2 by 405 Ma coincident with a phase of regional transtension. Granite surface areas decrease markedly to below 100 km^2 between 404 and 395 Ma during Acadian transpression.

5.2. Northern Highlands terrane granites

The age spectrum of granites from the Northern Highlands terrane (Fig. 3a) is, with small-volume additions, an area-weighted version of that by Oliver et al. (2008). It includes *c.* 700 km^2 of granite outcrop, much less than that in the Grampian/Connemara terranes (*c.* 4000 km^2) or the Trans-Suture terranes (*c.* 3500 km^2). Granitic magmatism began about 430 Ma (late Wenlock), as in the Grampians and Trans-Suture suites, but lasted only until about 418 Ma (earliest Devonian). No significance is attached to the values of the two age peaks in this small sample (n = 11). The lack of match between the age spectra in the Northern Highlands and Grampian terranes is no surprise, given the need for at least 700 km of sinistral strike-slip during or after granite emplacement (Dewey & Strachan, 2003). The Northern Highlands granites were therefore emplaced not across strike from the Grampian granites, but along strike to the north-east.

5.3. Grampian terrane granites

The age spectrum of granites from the Scottish Grampian terrane (Fig. 3b) is also an area-weighted version of that by Oliver et al. (2008). It includes *c.* 2600 km^2 of granite outcrop, over three times that in the Northern Highlands. As in the Northern Highlands, magmatism began about 430 Ma (late Wenlock), but here it lasted three times longer, waning by 400 Ma (mid-Emsian) and ending at around 390 Ma (Eifelian). There is a strong broad age peak at 407 Ma (base Emsian) which is probably significant in this size of sample (n = 41).

A new age spectrum has been added from the southwestward continuation of the Grampian terrane into Ireland (Fig. 3c), using the dataset of Chew & Stillman (2009). Because only 8 U-Pb ages are available, also included in this dataset are three Re-Os ages and 20 adjusted (1.9%) Rb-Sr ages. This granite suite totals *c.*1700 km^2, dominated by the Donegal batholith and by the Galway granite, which is hosted in the detached Connemara terrane. Magmatism began at about 426 Ma (Ludlow) in both areas, and lasted until 388 Ma (Eifelian). It therefore has a similar time span to the Scottish Grampians, but the age peaks (at 413 Ma and 395 Ma) do not match.

Neilson et al. (2009) note that intrusive magmas were very likely accompanied by considerable volumes of volcanic rocks that have since been eroded across the Grampian terrane. It is estimated that > 2000 km^3 of volcanic material has been eroded from the Etive lava pile alone. Although we focus our analysis on existing plutonic units, we note that the timing of the Lorn lavas (425 ± 0.7 Ma) and Etive dyke swarm (thought to have fed the Etive lava pile between 418 - 414 Ma) reported by Neilson et al (2009) are broadly consistent with the timing of granite magmatism in this area.

5.4. Midland Valley terrane extrusives and granitoids:

The Midland Valley terrane has a small number of relevant dated igneous rocks (n = 7, Oliver et al., 2008), more extrusive than intrusive. An area-weighted age spectrum is included (Fig. 3d) though, as previously explained, the implied volumes are probably overestimates compared with the implied volumes for intrusions. The data are Rb-Sr ages, with an unadjusted age peak at 415 Ma (Lochkovian), which shifts back to 423 Ma (base Pridoli) after 1.9% adjustment. The Midland Valley terrane lacks evidence of the extensive Devonian magmatism of bordering terranes.

5.5. Central-Southern Uplands and Leinster-Lakesman terranes granites

The U-Pb age spectrum of the Trans-Suture granites (Fig. 3e) is derived from *c.* 2500 km^2 of granite outcrop – almost the same area as for the Scottish Grampian granites – together with *c.* 870 km^2 of geophysically well-constrained subcrop of the Weardale granite. The total of *c.* 3500 km^2 is over 80% of that in the whole of the Grampian/Connemara terranes, a volumetric importance than has been underemphasised in previous work. Granitic magmatism began about 426 Ma (early Ludlow), barely later than in the Grampian terrane, peaked between 411 and 398 Ma, (Pragian and Emsian) but lasted until about 387 Ma (base Givetian). The age range is similar to that in the Grampian terranes both in Scotland and Ireland. The age peak at 405 Ma is close to the peak in the Scottish Grampian terrane, though its large amplitude may be due to the small sample size (n = 18).

5.6. Central-Southern Uplands and Leinster-Lakesman terranes lamprophyres

A further relevant age spectrum is for K-Ar ages from biotite micas in lamprophyre intrusions in the Southern Uplands and Lakesman terranes (Fig, 3f). These ages have an adjusted range from 424 to 402 Ma, similar to that of the Trans-Suture granites, and a flat age peak within the Earliest Devonian transtensional window. These data are therefore compatible with the hypothesis that the lamprophyres record mantle melts that advected heat into the lower crust below the Trans-Suture zone (Brown et al., 2008).

The lamprophyre ages, unlike the K-Ar ages from the granites, show no sign of resetting during Acadian transpression. This may reflect differences in biotite compositions, which are known to have significant effect on Ar diffusion and thus on the closure temperature of the K-Ar system. The mobility of diffusing atoms in biotite is controlled by the atomic packing density of the mineral structure, which in turn varies as a function of composition (Grove, 1993). Closure temperatures are lower for Fe-rich biotite than for Mg-rich biotite and diffusivities are thought to be significantly lowered by the replacement of the hydroxyl group by halogens such as F. Biotite compositions in Early Devonian lamprophyres tend to be more Mg- and F-rich than those formed in evolved granitic magmas (Canning et al., 1996). The lamprophyre biotite was therefore more resilient than the granite biotite to Ar diffusion and isotopic re-setting and their K-Ar ages are therefore more likely to record magma emplacement events than those obtained from granite K-Ar ages, which record re-setting events.

In summary, the area-weighted mean ages of the granites from the Scottish Grampians, Irish Grampians and Trans-Suture suite are 409.5, 407.9 and 404.4 Ma respectively, and their respective age ranges are almost identical; 429-390, 426-388 and 426-387 Ma (Figs. 2 and 3). The anomalous Caledonian granites in terms of age are, on our analysis, those in the Northern Highlands, with an older mean age of 422.4 Ma and narrower range of 430-418 Ma (Fig. 3).

6. Discussion

Our analysis (Figs 2 and 3) demonstrates that magmatic rocks were largely absent across all terranes during Iapetus subduction (*c.* 455 Ma to 425 Ma). Furthermore, in contrast to previous work (e.g. Brown et al., 2008; Neilson et al., 2009), magmas emplaced south of the Highland Boundary Fault (the Trans-Suture suite) are both synchronous with other granite suites throughout Northern Britain (Miles et al., 2014) and more volumetrically significant than previously thought.

Also evident is a possible correlation between the early Devonian phase of upper crustal transtension in the Grampian and Trans-Suture terranes and emplacement of large volumes of granite (Figs. 2 and 3). Conversely, the preceding and succeeding episodes of transpression – the Iapetan and Acadian phases – appear to correlate with suppressed volumes of granite emplacement. Here we explore magmatic-tectonic links in detail both before and after Iapetus closure.

6.1 Pre-collision magmatism up to 425 Ma

A convergent tectonic regime such as that associated with subduction of the Iapetus is commonly associated with large volumes of magma production relative to collisional regimes (Scholl and von Huene, 2009; Hawkesworth et al., 2009; 2013). However, the surface area of exposed granites does not exceed 200 km^2 during subduction of the Iapetus beneath the Midland Valley between 455 Ma and 425 Ma (Fig. 2), and represents only *c.* 2% of all preserved Caledonian magmas. Magma production was therefore apparently low throughout the period of active subduction up to *c.* 425 Ma. In addition to an absence of *in-situ* magmas, sediments in the Southern Uplands accretionary prism formed in direct response to Iapetan subduction, lack penecontemporaneous detrital zircons (Phillips et al. 2003; Waldron et al., 2008) indicative of an active arc (Fig. 4). In detail, when the differences between crystallisation ages and sediment deposition ages are compared with global datasets (Cawood et al., 2012a), their distribution is more indicative of collisional (or extensional) rather than convergent tectonic settings. It is therefore striking that despite strong evidence for an accretionary wedge model (see section 2) and subduction, there is apparently little or no evidence that contemporary magmatic rocks were exposed to erosion during accretion of the Southern Uplands sediments. Three possible scenarios have been proposed to explain the absence of syn-subduction magmatism:

1. Flat–slab subduction (Oliver et al., 2008), analogous to some areas of the eastern Pacific today with little or no asthenospheric mantle wedge;
2. Strike-slip displacement of the active arc;
3. Limited preservation of primary and detrital arc material in the geological record (Bluck, 2000; 2013).

Low angle, or flat-slab, subduction is currently recognised in many non-volcanic regions of active subduction and results in the segmentation of volcanic arcs such as the Andes (e.g. Kay and Mpodozis, 2002). Lower pressures and temperatures within the subducting plate, together with suppression of the asthenospheric mantle wedge limit the extent of partial melting, reducing rates of active magmatism. Shallow angle subduction is a plausible explanation for the absence of magmatism during Iapetus subduction, but is impossible to assess independently. Strike slip displacement of the active arc merely raises the issue of why magmatism did not occur along-strike on the margin.

It is worth noting that the absence of *in situ* magmas that can be linked directly to periods of subduction is a pattern that is being seen more frequently in the igneous and detrital zircon record (Hawkesworth et al., 2009; 2013). The absence of pre-collision zircons in the geological record is increasingly being viewed as an artefact that reflects the poor preservation potential of subduction regimes. By contrast, the assembly of continents during phases of plate collision is associated with the stabilisation of crust and the preservation of intracontinental basins and their detrital zircons.

Northward subduction beneath Laurentia is reflected by the build-up of accretionary sediments in the Southern Uplands accretionary prism between *c.* 455 Ma and 420 Ma (Oliver et al., 2008). Coincident with this period of northward subduction are mica Rb/Sr and K/Ar cooling ages of 455 Ma and 420 Ma respectively in the Grampian terrane (Dempster 1985). These ages imply substantial cooling and exhumation, with estimated erosion rates of 1.4 mm a^{-1} (Oliver et al., 2008). At this time, Laurentia experienced what was presumably a tropical climate at around 20^{o}S (Cocks and Torsvik, 2002). The absence of tectonic activity in the Grampian terrane at this time implies that this erosion was driven primarily by a tropical climate. In support of this, Bluck (2000) estimates that up to 20 km of cover was removed from the Grampian terrane by *c.* 430 Ma. Similar amounts of erosion would presumably also have affected the Midland Valley terrane and any arc, which when active would presumably have had a crustal thickness in excess of 30 km. Although now obscured by younger, Paleozoic sedimentary rocks, the Midland Valley has a crustal thickness of around 30 km (Freeman et al., 1988). Any underlying remnants of an arc must therefore have undergone extensive erosion to attain its present-day crustal thickness. In light of such high erosion rates, it is at least plausible that the absence of arc material may reflect a lack of preservation in the geological record, caused by extensive erosion throughout the late Ordovician and early Silurian.

A likely depocentre for sediments eroded from the Grampian and Midland valley terranes would be the Southern Uplands accretionary prism (Fig. 1). However, the distribution of zircon ages relative to sediment deposition ages (Fig. 4) is not characteristic of convergent tectonic settings (Cawood et al., 2012a). A further complication is that detrital zircon ages in the Southern Uplands (and Midland Valley) cannot be matched with sources found in the Grampian terrane today (Phillips et al., 2003; Cawood et al., 2012b). Despite this, Cawood et al (2012b) note that the age distribution of detrital zircons suggests a Laurentian rather than

Avalonian provenance, and that the Southern Uplands block was not in its current location relative to the Grampian terrane before the end of the Silurian. By contrast, Phillips et al. (2003; 2009) suggest that the age distribution of detrital zircons in the Southern Uplands is similar to that of Avalonia and not Laurentia, with the implication that the source of sediment in the accretionary prism lay to the south rather than to the north. Despite uncertainties about the exact fate of sediments derived from the Midland Valley and Grampian terranes, the absence of penecontemporaneous arc-derived zircons in the accretionary prism is both clear (Fig. 4) and surprising during a period of active subduction.

In contrast to sediments in the Southern Uplands accretionary prism, small Silurian sandstone and conglomerate inliers on the southern margin of the Midland Valley have been shown to contain a significant proportion of locally-derived, calc-alkaline igneous detritus, together with penecontemporaneous detrital zircons with ages as young as *c.* 430 Ma (Phillips et al., 2009). This evidence is considered to reflect the presence of an active arc at this time. Furthermore, the ages of igneous clasts appear to become younger as sedimentation progressed, suggesting that granitic magmas were repeatedly being intruded (Bluck 2013). Although limited in present-day extent, Bluck (1983; 2013) suggests that these small inliers of sediment, rich in arc-like debris, represent part of a once extensive and now largely lost fore-arc basin, analogous to modern fore-arc sequences in Java and Sumatra. This once extensive fore-arc is thought to have been removed, either by overthrusting of the Southern Uplands accretionary prism or by lateral movement along strike slip faults. A fore-arc basin may also have acted as the primary depocentre for arc-derived detritus, preventing sedimentary material from reaching the accretionary prism that lay to the south.

Most crustal recycling (*c.* 70%) in modern arcs is considered to occur by subduction erosion and sediment subduction (von Huene et al., 2004; Stern 2011). By contrast, the preservation of the Southern Uplands accretionary prism indicates that subduction erosion was not effective in removing material during Iapetus subduction. The absence of *in-situ* granites (and their erosional products) in Northern Britain linked to subduction of the Iapetus is therefore not primarily a reflection of this. However, their apparent absence, together with evidence of high erosion rates and the eradication of sedimentary depocentres by tectonic movements, may well reflect the poor preservation potential of active arcs and subduction environments more generally. The poor preservation of arc materials is consistent with more globally observed patterns in the geological record (Hawkesworth et al., 2009; 2013). Whilst impossible to prove, the loss of arc magmas and their sedimentary derivatives due to erosion and tectonic removal offers an equally plausible explanation for the apparent absence of *in* *situ* granites and their erosional products as models of shallow subduction (Oliver et al., 2008).

6.2 Post-subduction magmatism (425 – 390 Ma)

The end of subduction reflects a transition from a convergent to a collisional tectonic regime, and would conventionally result in a marked reduction in magma production (e.g. Scholl and von Huene, 2009; Hawkesworth et al., 2009; 2013). However, as highlighted in Figure 2, most Caledonian magmatism occurred post-subduction and in a plate-boundary tectonic environment characterised by alternating episodes of transpression and transtension (Fig. 3). Assuming an average depth of 12 km for most plutons (e.g. Parslow and Randall, 1973; Rollin, 1984; Emenike, 1986; Kimbell et al., 2010), the rates of magma emplacement were of the order of 10 km^3/m.y/km between *c.* 430 and 400 Ma. We note that Neilson et al (2009) suggest that considerable volumes of volcanic rocks from this period have been eroded and that rates of magma emplacement may therefore have exceeded this estimate of 10 km^3/m.y/km. Nevertheless, these estimates are comparable with rates of magma emplacement at active continental arcs of between 10 and 100 km^3/m.y/km (e.g. Ducea and Barton, 2007). Despite relatively low rates of magma emplacement compared to most continental arcs, these rocks offer an interesting opportunity to investigate the causes of magmatism in a plate-boundary, post-subduction setting that appears to have been responsible for most of the Caledonian granitic rocks in the UK.

Cleavage ages from the Southern Uplands, Leinster-Lakesman and Cymru terranes, reflect two regional deformation events (Fig. 3g-h). The later one (404-394 Ma, Emsian) is thought to record the main penetrative Acadian cleavage (e.g. Merriman et al., 1995, Dong et al., 1997; Sherlock et al., 2003). The origin of the earlier peak (426-419 Ma, Ludlow to Pridoli), which is also dominant in the Fenland terrane, is less clear. It has been variously linked with rapid pre-cleavage burial and illite growth (Merriman et al., 1995), with the onset, rather than peak, of Acadian deformation (Dong et al., 1997), and with one phase of the Brabantian deformation in Belgium (Carney et al., 2008). We suggest that the age peak records recrystallisation of clay minerals during the late Silurian ‘Iapetan’ soft collision of Avalonia with Laurentia.

Both Iapetan and Acadian events are drawn (Fig. 3) as reference markers across the Trans-Suture terranes and the Midland Valley terrane, but are faded out across the Grampian terrane, where, as noted previously, evidence for penetrative deformation of these ages is lacking. There is no evidence of these events in the Northern Highlands terrane, where the dominant deformation event is the Scandian shortening marked on Fig. 3.

Figures 2 and 3 show a marked correlation between the maximum volumes of Caledonian granitic magmatism and the phase of early Devonian transtension dated here as 418-404 Ma. Based on outcrop area, about 70% of the granites in the Scottish Grampian terrane were intruded then, 55% of those in the Irish Grampian/Connemara terranes, and 61% of the Trans-Suture granites. It is likely that transtension promotes melting by thinning the lithosphere, either regionally or locally, and raising the geothermal gradient. It also creates crustal intrusion sites, particularly along steep faults and shear zones, and there are many examples of Caledonian granites associated with predominantly SW-NE structures (e.g. Hutton, 1982; Jacques & Reavy, 1994, McArdle & Kennedy, 1987).

Also evident in Figures 2 and 3 is that Acadian transpression – dated here at 404-394 Ma – began to suppress magmatism, and to localise emplacement. Based on outcrop area, only 11% of the granites in the Scottish Grampian terrane were intruded after 404 Ma, 29% of those in the Irish Grampian/Connemara terranes, and 32% of the Trans-Suture granites. Given the evidence (Mendum and Noble, 2010) that even the Great Glen Fault had Acadian age displacements, even the Grampian terrane may have responded to the Acadian event.

It is notable that the Trans-Suture granites with intrusion histories that overlap the Acadian event (e.g. Shap, Weardale and Skiddaw) have small diameters and vertical pipe-like geometries, well defined by gravity modelling (Kimbell et al., 2010). This is an intrusion geometry that might be expected in a transpressional setting, where only localised transtensional jogs along crustal faults would provide space for magma to rise from mid- or lower crustal hot zones (e.g. Glazner, 1991).

6.3 Kinematic control on Caledonian granite magmatism

In contrast to previous work (e.g. Oliver et al., 2008; Brown et al., 2008; Neilson et al., 2009), no strong difference in the granite ages is evident between the Trans-Suture and Grampian/Connemara terranes (Fig. 3). Furthermore, the major element chemistry of the Trans-Suture suite is remarkably similar to that of other terranes (Fig. 5). Magmas from all terranes fall mostly within the post-collisional field on the tectonomagmatic discrimination diagram of Batchelor and Bowden (1985). These findings strongly suggest that a common causal mechanism should be sought and that a revised tectonic model is required.

The slab breakoff models of Atherton and Ghani (2002) and Neilson et al. (2009) (Fig 6a) are consistent with the timing, compositions and volumes of magmatism across the Grampian terrane. However, in light of the similarities identified here between magmas emplaced across northern Britain, we propose that the north-west dipping Iapetus slab did not only break off below Laurentia, but peeled back below the Iapetus Suture for about 100 km to the south-east below Avalonia (Fig 6c). This break-off began at about 430 Ma (mid-Wenlock) when the soft collision of Avalonia with the Laurentian accretionary prism began. Hot dry asthenospheric mantle flowed upwards and north-westward to impinge directly on the base of the Avalonian continental crust or at least on thin, mostly delaminated lithospheric mantle. The plane of delamination below Avalonia may well have been controlled by relict weak mantle discontinuities from the Ordovician subduction history.

Slab breakoff models have been proposed for the magmatism that post-dated the mid-Silurian (~433 Ma, end-Llandovery) end to Salinic subduction-arc volcanism on the Laurentian margin in Newfoundland (e.g. Van Staal et al., 2014). However, correlations with the European Caledonides are complicated by the involvement of the distinct Ganderia continent. The Avalonian continent did not impinge with Ganderia by Acadian subduction from the southeast until about 420 Ma (end-Silurian). However, larger volumes of arc volcanics than in Scotland and Ireland are preserved above both subduction zones.

Slab breakoff models imply that magma production and emplacement may be independently controlled. Magma production – in both the lithospheric mantle and overlying crust – related to slab drop-off is essentially a gravitationally driven process, due to the excess density of the down-going slab (Davies and von Blanckenburg, 1995). Numerical models support the idea that lamprophyres formed in response to lithospheric thinning following slab drop-off were an important trigger for the initiation of crustal hot zones and in the generation of granitic magmas (Brown et al., 2008). These models are supported by the compositional and temporal links identified between many of the Caledonian granites and nearby lamprophyre magmas (e.g. Holden et al., 1987; Rock and Hunter, 1987; Fowler and Henney, 1996; Canning et al., 1996; Brown et al., 2008).

By contrast, the emplacement of magmas into the shallow crust is influenced by the deformation and thermal regime in the affected continental lithosphere. Episodes of deformation are therefore likely to have suppressed magma emplacement to a greater degree than magma production during the latter stages of the Caledonian beneath Northern Britain. We note that similar tectonic controls have been identified during Mesozoic plutonism in California (Glazner, 1991). Here, major episodes of plutonism correlate with oblique convergence, while orthogonal episodes of convergence are characterised by lulls in plutonism (but continuation of volcanism). As appears evident in the British Caledonides, oblique tectonic settings facilitate pluton emplacement at releasing bends along strike-slip faults. However, we highlight one important difference between the British Caladonides and the Mesozoic plutons of California: while orthogonal convergence along the California margin favoured the accumulation of magmas at the base of the crust or extrusive volcanism (Glazner, 1991), there is little evidence for greater volcanic activity during orthogonal convergence of the Iapetus across the British Caladonides (Fig. 2).

7. Conclusions

1. Area-weighted age spectra from the late Caledonian granites of Northern Britain show a marked apparent absence of magmatism during Iapetus subduction between 455 and 425 Ma. This absence is likely to reflect either flat-slab subduction or erosional removal of the arc.
2. Area-weighted age spectra for the late Caledonian, post-subduction granites show the volumetric importance of granites emplaced south of the Highland Boundary Fault (the Trans-Suture suite) that are similar to the main granites of the Grampian terrane.
3. The age spectra also show that the Trans-Suture granites, rather than being much later than the Grampian terrane granites have a similar age range and that a common origin is implied.
4. It is the granites in the Northern Highlands terrane that have anomalous ages, older than those in the Grampian terrane by an average of 13 Ma. Because of the large displacements on the intervening terrane boundary, this age difference may reflect along-strike rather than across-strike diachroneity in intrusion ages and tectonic settings.
5. A slab drop-off model best explains the late Caledonian granites, but one in which the lithospheric mantle delaminated below the Iapetus Suture and for about 100 km below the Avalonian margin.
6. The age spectra from the Trans Suture and Grampian granites suggest that high rates of magma generation coincided with regional lithospheric transtension between about 418 and 404 Ma (earliest Devonian). Adjusted ages of lamprophyre dykes, genetically linked mantle melts, also fall in the transtension window.

7. Magma generation was reduced during the Acadian transpression from about 404 to 394 Ma, as dated by K-Ar and Ar-Ar ages on cleavage-parallel mica and illite. The relatively weak Acadian shortening allowed local transtensile sites for granite intrusion, but was responsible for the field evidence of overlap of intrusions and cleavage formation.
8. The Early Devonian granites of Britain and Ireland are a well-studied, world-class example of the modulation of granitic magma emplacement by alternating transpression and transtension.
9. Area-weighted age spectra provide a useful means of assessing how magma volumes vary as a function of tectonic environment.

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FIGURE CAPTIONS

Fig. 1. a) Terrane map of northern Britain and Ireland with locations of late Caledonian granites. Only the main Trans-Suture granites are individually named. b) Schematic mid-Devonian palaeocontinental reconstruction modified from Woodcock et al. (2007) with location of main map.

Fig. 2. Area-weighted probability distribution function for zircon age data from late Caledonian intrusive rocks across Northern Britain: aggregated from age spectra (a, b, c, e) on Fig. 3, where data sources are specified.

Fig. 3. Area-weighted probability distribution functions for different tectonic terranes (a to e). Dating method is highlighted in the figure. Age spectrum for Trans-Suture lamprophyres is based on K-Ar ages (f). Cleavage ages in the Wales and the Lake District and in Anglia are based on K-Ar and Ar-Ar methods. Data for (a, b, d) from Oliver et al. (2008), Goodenough et al. (2011), Kocks et al. 2014 and Neilson et al. (2009), for (c) from Chew & Stillman (2009), and for (e-h) from the sources listed in Supplementary Data S1. Dashed curves are the unadjusted age spectra for Rb-Sr and K-Ar.

Fig. 4 Difference between the crystallisation age for detrital zircon grains (ages from Waldron et al., 2008 and Phillips et al., 2003) and the depositional age of the Southern Uplands accretionary sediments in which they occur plotted as a cumulative proportion curve following the approach of Cawood et al. (2012). General fields are shown for convergent (A), collisional (B) and extensional (C) tectonic environments.

Fig. 5. R1–R2 plot (De la Roche et al. 1980) of major element chemical data for the Trans-Suture granite suite, superimposed on fields for the Grampian terrane granites in Scotland (Neilsen et al., 2009) and Donegal (Ghani, 1997; Atherton & Ghani, 2002) and the Coastal Batholith of Peru (Pitcher et al. 1985). Trans-Suture data are from Shap, Criffell and Fleet (Miles, 2012), Cheviot (Haslam, 1986), Foxdale (Hall, 1972) and Leinster (Sweetman, 1987). Tectonomagmatic discriminant fields for granitoids are after Batchelor & Bowden (1985).

Fig. 6 Summary diagram for slab detachment and lithospheric delamination. a) Slab break-off model of Atherton and Ghani (2002) and Neilson et al., 2009. b) Bi-directional slab drop-off model of Oliver et al. (2008). c) Modified slab drop-off model proposed here (see text for details).

Figure_1

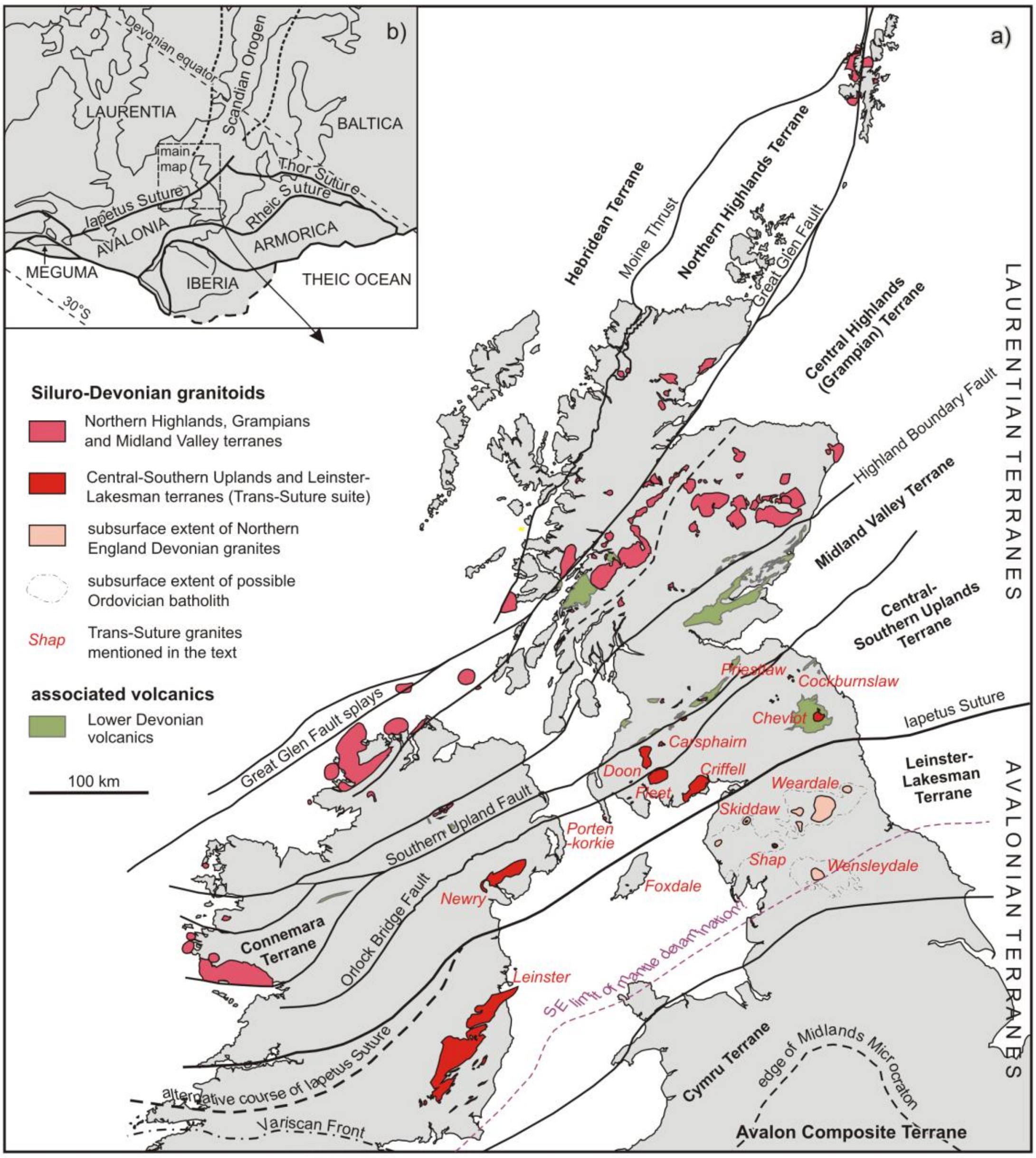

b)
Devonian equator
LAURENTIA
Scandian Orogen
BALTICA
main map
Thor Suture
Iapetus Suture
Rheic Suture
AVALONIA
ARMORICA
MEGUMA
IBERIA
THEIC OCEAN
30°S
a)
Hebridean Terrane
Moine Thrust
Northern Highlands Terrane
Great Glen Fault
Central Highlands (Grampian) Terrane
Highland Boundary Fault
Midland Valley Terrane
Central-Southern Uplands Terrane
Iapetus Suture
Leinster-Lakesman Terrane
LAURENTIAN TERRANES
AVALONIAN TERRANES
Great Glen Fault splays
Southern Upland Fault
Orlock Bridge Fault
Connemara Terrane
alternative course of Iapetus Suture
Variscan Front
Cymru Terrane
edge of Midlands Microcraton
Avalon Composite Terrane
SE limit of mantle delamination
Priestlaw
Cockburnslaw
Cheviot
Carsphairn
Doon
Criffell
Fleet
Weardale
Skiddaw
Porten-korkie
Shap
Wensleydale
Foxdale
Newry
Leinster
Siluro-Devonian granitoids
Northern Highlands, Grampians and Midland Valley terranes
Central-Southern Uplands and Leinster-Lakesman terranes (Trans-Suture suite)
subsurface extent of Northern England Devonian granites
subsurface extent of possible Ordovician batholith
Shap
Trans-Suture granites mentioned in the text
associated volcanics
Lower Devonian volcanics
100 km

Figure_2

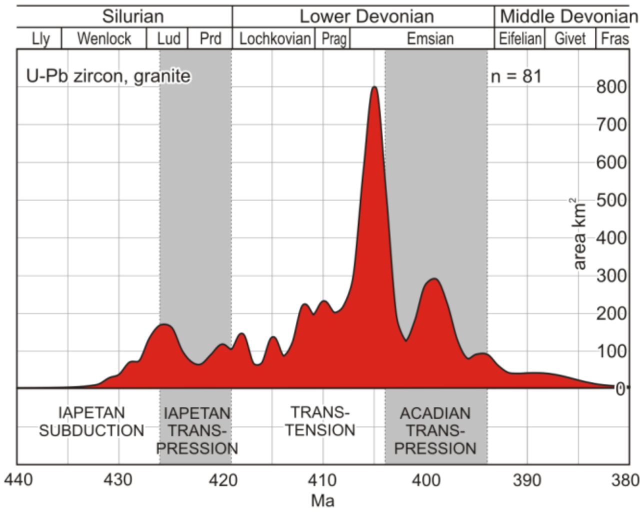

Silurian
Lower Devonian
Middle Devonian
Lly
Wenlock
Lud
Prd
Lochkovian
Prag
Emsian
Eifelian
Givet
Fras
U-Pb zircon, granite
n = 81
800
700
600
500
400
300
200
100
0
area km²
IAPETAN SUBDUCTION
IAPETAN TRANS-PRESSION
TRANS-TENSION
ACADIAN TRANS-PRESSION
440
430
420
410
400
390
380
Ma

Figure 3

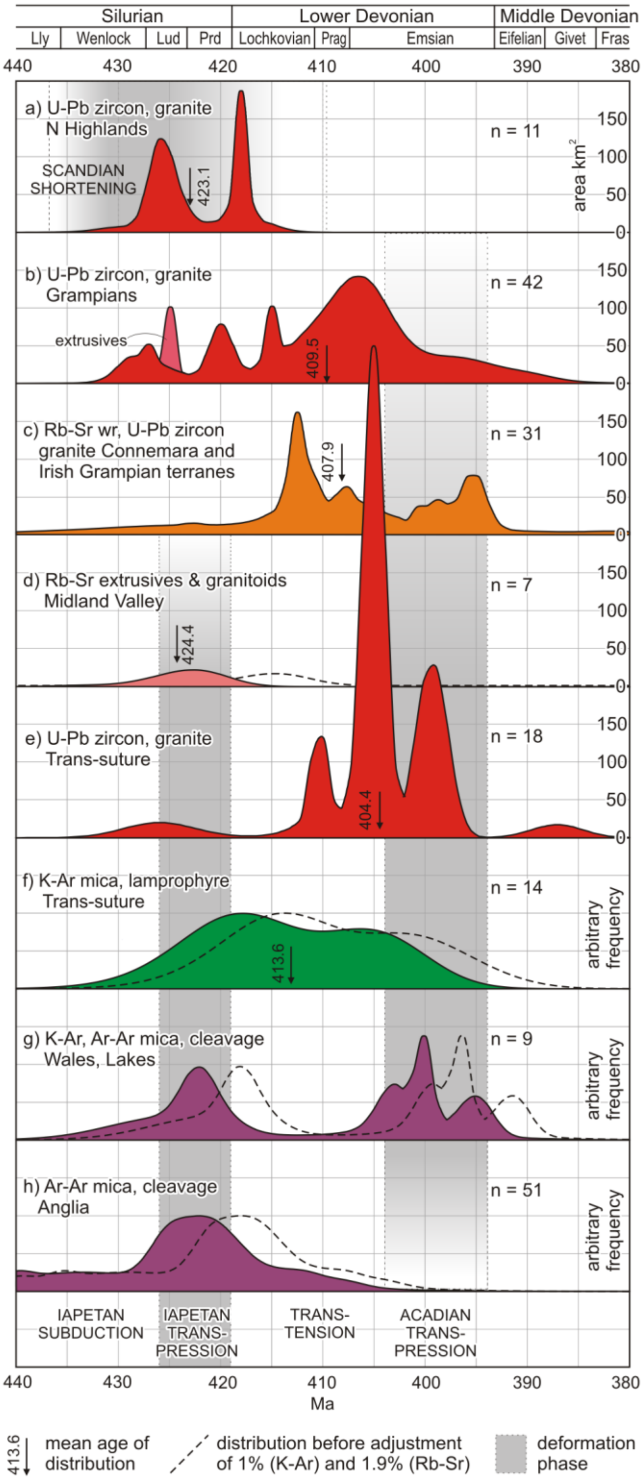

Silurian
Lower Devonian
Middle Devonian
Lly
Wenlock
Lud
Prd
Lochkovian
Prag
Emsian
Eifelian
Givet
Fras
440
430
420
410
400
390
380
a) U-Pb zircon, granite
N Highlands
SCANDIAN
SHORTENING
423.1
n = 11
area km^2
150
100
50
0
b) U-Pb zircon, granite
Grampians
extrusives
409.5
n = 42
c) Rb-Sr wr, U-Pb zircon
granite Connemara and
Irish Grampian terranes
407.9
n = 31
d) Rb-Sr extrusives & granitoids
Midland Valley
424.4
n = 7
e) U-Pb zircon, granite
Trans-suture
404.4
n = 18
f) K-Ar mica, lamprophyre
Trans-suture
413.6
n = 14
arbitrary
frequency
g) K-Ar, Ar-Ar mica, cleavage
Wales, Lakes
n = 9
h) Ar-Ar mica, cleavage
Anglia
n = 51
IAPETAN
SUBDUCTION
IAPETAN
TRANS-
PRESSION
TRANS-
TENSION
ACADIAN
TRANS-
PRESSION
Ma
413.6
mean age of
distribution
distribution before adjustment
of 1% (K-Ar) and 1.9% (Rb-Sr)
deformation
phase

Figure 4

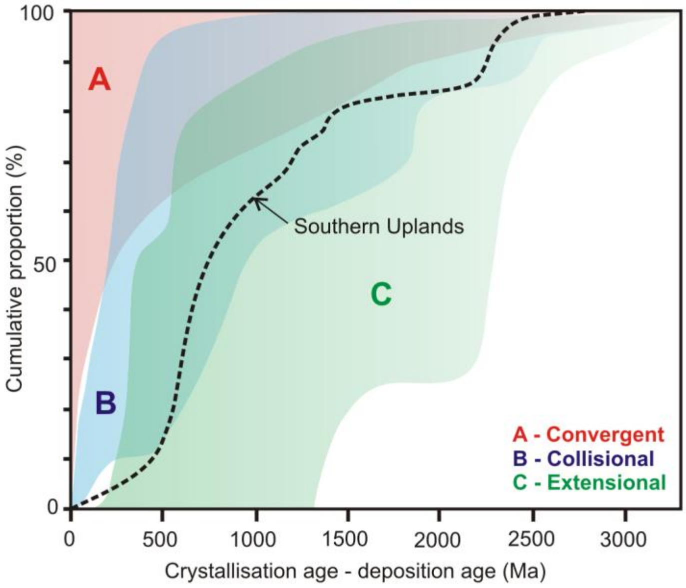

100
50
0
Cumulative proportion (%)
A
B
C
Southern Uplands
A - Convergent
B - Collisional
C - Extensional
0
500
1000
1500
2000
2500
3000
Crystallisation age - deposition age (Ma)

Figure 5

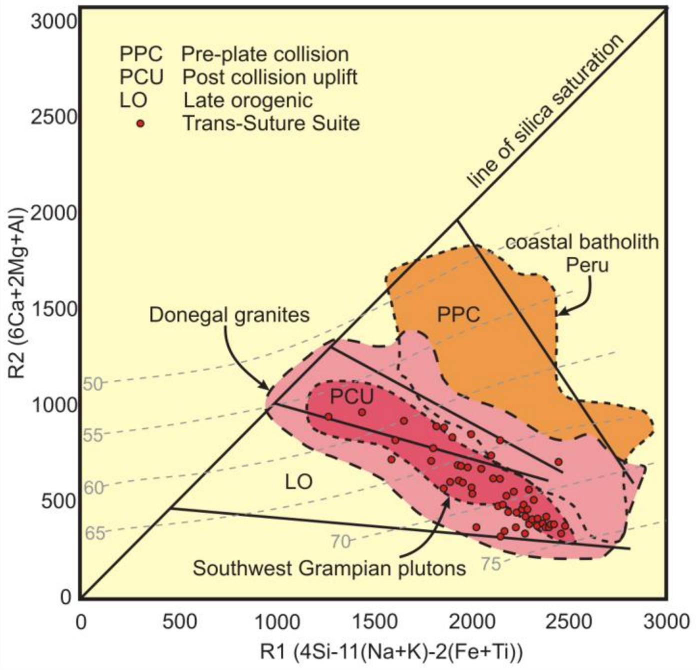
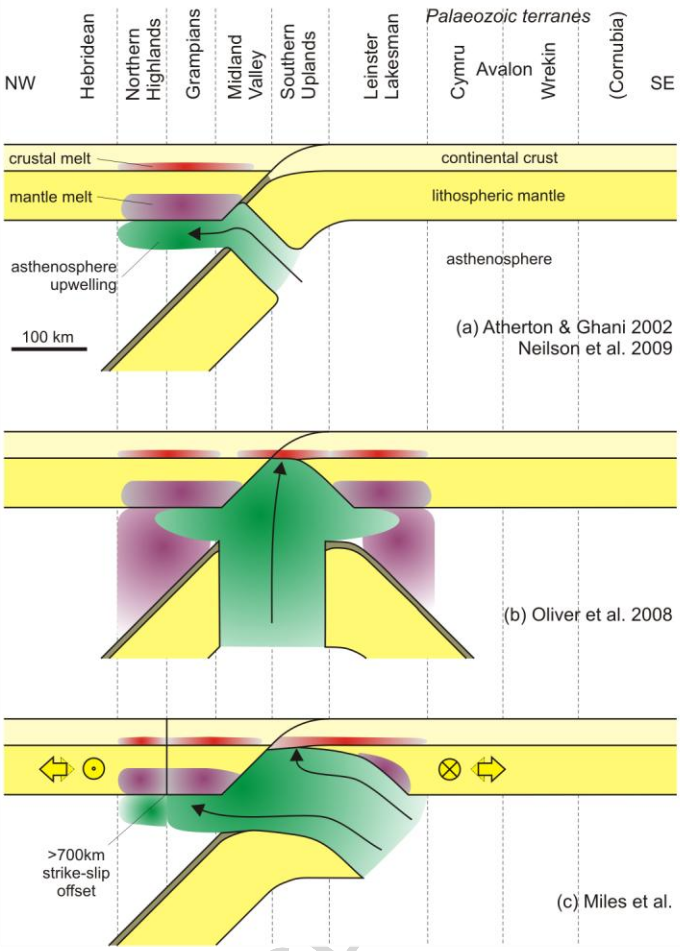
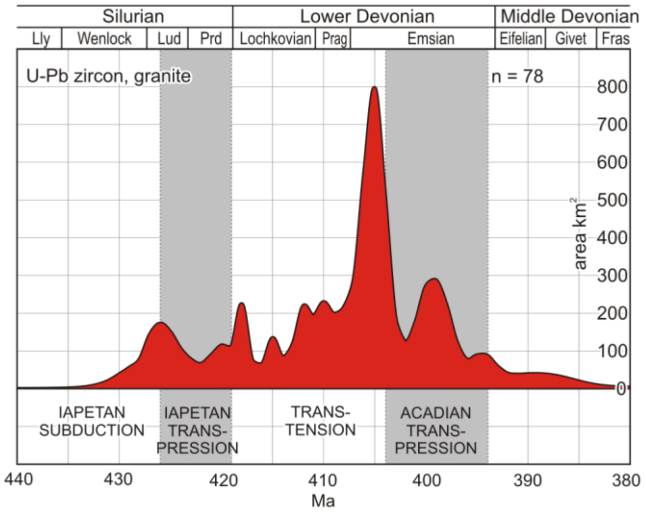

PPC Pre-plate collision
PCU Post collision uplift
LO Late orogenic
● Trans-Suture Suite
line of silica saturation
coastal batholith Peru
PPC
Donegal granites
PCU
LO
Southwest Grampian plutons
50
55
60
65
70
75
3000
2500
2000
1500
1000
500
0
R2 (6Ca+2Mg+Al)
0
500
1000
1500
2000
2500
3000
R1 (4Si-11(Na+K)-2(Fe+Ti))

Figure 6


NW
Hebridean
Northern Highlands
Grampians
Midland Valley
Southern Uplands
Leinster Lakesman
Palaeozoic terranes
Cymru
Avalon
Wrekin
(Cornubia)
SE
crustal melt
continental crust
mantle melt
lithospheric mantle
asthenosphere upwelling
asthenosphere
100 km
(a) Atherton & Ghani 2002
Neilson et al. 2009
(b) Oliver et al. 2008
>700km strike-slip offset
(c) Miles et al.



Graphical Abstract

Highlights for "Tectonic controls on post-collisional granite genesis and emplacement: the Late Caledonian suite of Britain and Ireland". Miles et al.

- Zircon age spectra from British Caledonian magmas are weighted according to surface area to investigate tectonic controls on magma generation and emplacement.
- The area-weighted age spectra reveal an apparent absence of granitic magmatism during Iapetus subduction and a predominance of post-subduction magmas.
- We review the apparent absence of subduction-related magmatism in the context of the poor preservation potential of such settings.
- Magma generation was controlled by gravitationally driven kinematics following slab detachment and delamination caused by final subduction of the Iapetus Ocean. Magma emplacement was subsequently modulated by alternating episodes of transpression and transtension in the overlying continental lithosphere.
- Area-weighted age spectra offer a valuable means of investigating magmatic-tectonic relations.