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A combined geochronological approach to investigating long lived granite magmatism, the Shap granite, UK

A.J. Miles^a & N.H. Woodcock^b

^a *School of Geography, Geology and the Environment, University of Leicester, University Road, Leicester, LE1 7RH, UK.*

^b *Department of Earth Sciences, University of Cambridge, Downing Street, Cambridge CB2 3EQ, UK*

Abstract

With the advent of more precise dating methods, it has become apparent that zircon dates from granite plutons frequently indicate older emplacement ages than other dating methods. Here we attempt to reconcile a number of dating methods from the *c.* 5 km² Caledonian Shap granite, Northern England. The results reveal a more complex and protracted evolution than indicated by application of any single dating method. Zircon U-Pb dates give a weighted mean age of 415.6 ± 1.4 (2 σ) Ma. A mafic enclave, dated at 412 ± 2 (2 σ) Ma (revised Rb-Sr feldspar age from Davidson et al., 2005), contains resorbed K-feldspar and zircon crystals scavenged from the host crystal mush. These ages are at odds with field relations in the thermal aureole that suggest final emplacement at approximately 404 Ma or later during Acadian deformation. Previously reported Re-Os ages on molybdenites associated with magmatic fluids, have given ages of 405.2 ± 1.8 (2 σ) Ma (Selby et al., 2008) and confirm the overlap of at least some magmatic activity with Acadian deformation. A similar emplacement age is supported by Rb-Sr whole-rock-mineral and biotite K-Ar dates when adjusted for revised decay constants (402 ± 3 Ma and 401 ± 7 Ma, respectively, Wadge et al., 1978). The lower closure temperatures of these systems relative to the U-Pb system in zircon means that they are more likely to record the timing of final granite emplacement. These data suggest that most zircons grew before final granite emplacement, by about 10 Ma on average. We

suggest that the majority of zircon crystals record pre-emplacement magmatic activity within a deeper part of the system. Mafic enclaves and their scavenged cargo of crystals record the assembly of a mid-crustal batholith where crystals remained at least locally mobile at 412 Ma. Gravity data support the existence of an extensive, 1500 km² intrusive body, originally at about 15 km depth beneath Shap. This batholith is likely to have remained below the granite solidus for much of its existence due to conductive heat loss, but episodic influxes of silicic magma between c. 412 and 405 Ma are thought to have enabled periods of rejuvenation. These influxes are recorded by complex compositional zoning patterns within K-feldspar megacrysts. The Shap granite itself is likely to represent a rejuvenated crystal slurry, emplaced as a cylindrical cupola above the main magma body during Acadian transpression. This study highlights the importance of integrating different dating techniques and that final emplacement of granites can only be indicated by the youngest zircon ages.

1. Introduction

The incremental assembly of large magma bodies is a natural consequence of the low temperature and brittle nature of the upper crust, which limits rates of magma emplacement (Clemens and Mawer, 1992; Coleman et al., 2004; Lipman, 2007). In support of this, high precision methods of dating minerals (e.g. thermal ionisation mass spectrometry, high resolution ion probe dating and U-series disequilibria) commonly reveal spectra of crystallisation ages in granite plutons, suggesting that magmatic systems remain episodically active on the order of thousands to millions of years (e.g. Brown and Fletcher, 1999; Oberli et al., 2004; Glazner et al., 2004; Coleman et al., 2004; Charlier et al., 2005; Bindeman et al., 2006; Claiborne et al., 2006; Matzel et al., 2006; Miller et al., 2007; Walker et al., 2007; Lipman, 2007; Schaltegger et al., 2009; Memeti et al., 2010; Schoene et al., 2012; Farina et al., 2012; Wotzlaw et al., 2013; Broderick et al., 2015; Barboni et al., 2015; Samperton et al.,

2015; Annen et al., 2015; Cassidy et al., 2015; Buret et al., 2017; Fritschle et al., 2017). However, it is apparent that crystals within a single sample may also record markedly different ages and/or compositional histories (e.g. Broxton et al., 1989; Cooper and Reid, 2003; Costa et al., 2003; Claiborne et al., 2006; Ramos and Reid, 2005; Walker et al., 2007; Davidson et al., 2001; 2005; 2007; Barbey et al., 2008; Lissenberg, 2009; Schoene et al., 2012; Barboni et al., 2015; Cassidy et al., 2015). These complexities reflect the propensity of zircon in particular to survive crystal recycling between successive magma pulses and to record protracted crystallisation histories (e.g. Miller et al., 2007; Claiborne et al., 2010; Barboni et al., 2015). Using zircon age populations to estimate rates of magma emplacement and storage in the crust have therefore become increasingly difficult to reconcile with thermal models (e.g. Lissenberg, 2009; Schoene et al., 2012). Furthermore, the relationship between zircon dates and magma emplacement are often obscure (Barboni et al., 2015) and frequently differ markedly from other methods of dating.

The delivery of mixed crystal populations into growing batholiths is compatible with the formation of evolved melts by melt segregation from deep crustal hot zones (Annen et al., 2006; Annen 2009; Solano et al., 2014). In these models, hot, mantle-derived basalts are emplaced into the lower crust and generate a region of crystal mush. The evolved melt phase is derived from crystallisation of mafic magmas and partial melting of crustal rocks. The importance of crustal melting in generating granitic melts was recently highlighted by Collins et al. (2016) who suggest that aqueous fluids exsolved from mafic underplate promote water-fluxed partial melting at ambient pressure-temperature conditions within the lower crust. Zircons (and other mineral phases) with a range of crystallisation ages may develop during this 'incubation period' during which most silicic magma is generated. Some accessory minerals may also be prevented from interacting with later melts due to being isolated, or

armoured, within other silicate phases (e.g. Miller et al., 2007; Paterson, 2009), leading to further age and compositional differences between adjacent crystals. Evolved melts are thought to accumulate by movement along grain boundaries until a mobile magma can ascend to shallower levels where batholiths may grow (Jackson et al., 2003; 2005; Solano et al., 2012; 2014). Antecrysts – crystals that crystallised from earlier magmas formed during the incubation period – may potentially be transported to higher crustal levels during magma ascent. Accessory minerals may therefore preserve a record of magmatic processes from much deeper and older parts of the magmatic system.

Over the past two decades, many authors have interpreted textural and crystal heterogeneities within batholiths as evidence for incremental assembly by small magma pulses from deep crustal hot zones over timescales of as much as $c. 10^6$ years (e.g. McNulty et al., 1996; Coleman et al., 2004; Glazner et al., 2004; Gray et al., 2008). However, large plutons commonly contain complex and widespread arrays of structures (e.g. tubes, troughs, diapirs and plume heads) that are said to reflect processes such as mixing and convection within largely constructed mush bodies, some of which approach, and may even exceed 50% crystals (e.g. Wiebe, 1996; Wiebe and Collins, 1996; Marsh, 1996, 2006; Miller and Miller, 2002; Walker et al., 2007, Paterson, 2009; Paterson et al., 2016; Plail et al., 2018). Mixed crystal populations may therefore reflect a combination of inheritance from lower crustal hot zones and further dispersion at the emplacement level. However, the scale over which these processes operate within batholiths remains unclear (e.g. Paterson, 2009).

It is also apparent that most crystals only spend a small fraction of the total magma storage history at temperatures above the critical crystallinity at which a crystal mush may be mobile (Cooper and Kent, 2014; Szymanowski et al., 2017). Despite this, rapid mobilisation of

magmas stored at near-solidus temperatures may occur episodically within batholiths and crystal mushes during infiltration of new magmas caused by compaction or by the injection of new magma into the system. Magmatic systems may therefore remain ephemerally active over time periods of as much as 10^6 years. The rejuvenation of whole batholiths seems unlikely due to the large thermal input required, but local rejuvenation and crystal mobility seems probable.

These complexities have brought into question the traditional view that large granite batholiths represent bodies of mainly molten magma emplaced over geologically short periods of time (e.g. Buddington, 1959; Pitcher and Berger, 1972; Petford et al., 2000) and that single zircon ages can yield the crystallisation age of an intrusion. It is therefore necessary to compare different dating methods to fully appreciate the extended assembly history of granites.

Here we examine the emplacement history of the Caledonian Shap granite in Northern Britain. A number of dating methods have been applied to this granite where final emplacement is well constrained by field relations (Soper and Kneller, 1990). These relations suggest that emplacement post-dated *most* zircon growth, on average by some 10 Ma. We suggest that different dating systems record different magmatic events over a range of depths within the crust over a protracted period of time. We conclude that final granite emplacement can only be indicated by the youngest zircon ages.

2. The Caledonian Orogeny and associated magmatism

The Caledonian Orogeny involved successive episodes of subduction and deformation, culminating in the assembly of Avalonia, Laurentia and Baltica between the early Ordovician and early Devonian (McKerrow et al., 2000). NW-directed subduction of the Iapetus Ocean began at about 455 Ma (Late Ordovician), associated with deep marine sedimentation and thrust faulting in the Southern Uplands accretionary prism (McKerrow et al., 1977; Leggett et al., 1979). SE-directed subduction along the southern, Avalonian margin of the Iapetus was terminated at this time by subduction of the Iapetus spreading ridge (Woodcock, 2012).

Convergence between Laurentia and Avalonia switched from orthogonal to sinistrally transpressive at 430 Ma (mid-Silurian) evidenced by the clockwise transection of folds by cleavage in Ireland and the Southern Uplands (Anderson, 1987; Dewey et al., 1997; Dewey and Strachan, 2003). Deformation in the Southern Uplands accretionary prism weakened at this time (Kemp, 1987) and Laurentia-derived sediments lapped onto Avalonia. Lamprophyre dykes emplaced before 430 Ma are foliated whereas those emplaced after 430 Ma are not (Rock et al., 1986) suggesting that Laurentia/Avalonia convergence and Iapetus subduction ceased then.

Up to 10-20 km of exhumation and erosion is evident in the Scottish Grampian and Northern Highlands terranes following Iapetus closure (Flinn, 1977; Clayburn, 1981; Watson, 1984; Atherton and Ghani, 2002), and coincides with deposition of non-marine clastic sediments (mostly lower Devonian Old Red Sandstone, ORS) within bordering fault-controlled

transtensional basins (Bluck, 1984; Smith, 1995; Dewey and Strachan, 2003). A stratigraphic thickness of at least 3.5 km of Lower ORS is thought to have accumulated within the basin in NW England, based on the metamorphic grade of units that lie conformably below the ORS (Soper and Woodcock, 2003). The majority of Caledonian magmatism (Fig. 1) coincided with the formation of these transtensional basins in Early Devonian time, across all terranes south of the Great Glen, including the Avalonian Leinster-Lakesman terrane (Brown et al., 2008; Oliver et al., 2008; Miles et al., 2016). The vast majority of this magmatism was granitic and calc-alkaline in composition but this was accompanied by a coeval suite of lamprophyre dykes formed by small-degree melting of metasomatised mantle lithosphere (Rock et al., 1986; Brown et al., 2008; Miles et al., 2013; 2014; 2016).

The Early Devonian magmatic phase post-dates Iapetus subduction by over 20 Ma (Oliver et al., 2008; Miles et al., 2016) and includes magmas emplaced south of the Iapetus Suture and its former subduction arc. The compositions of the Caledonian magmas, although calc-alkaline, match magmas formed in post-collisional settings (Atherton and Ghani, 2002; Neilson et al., 2009; Miles et al., 2016). To explain these compositions, Atherton and Ghani (2002) proposed that slab break-off followed Iapetus closure, resulting in the replacement of highly metasomatised lithosphere by more buoyant asthenosphere. Subsequent gravitational collapse combined with highly oblique interaction between Avalonia and Laurentia led to the formation of transtensional basins, while the emplacement of asthenospheric mantle triggered lower crustal melting and granite formation (Atherton and Ghani, 2002; Nielson et al., 2009; Miles et al., 2013; 2014; 2016).

Previous analyses suggested that the granites south of the Highland Boundary Fault (the Trans-Suture Suite, Brown et al., 2008) were younger and genetically unrelated to those

further north (Fig. 1). However, more recent Trans-Suture zircon dates are similar to granites in the Grampian terrane, north of the Highland Boundary Fault (Miles et al., 2014; 2016; Fritschle et al., 2017). Miles et al (2016) proposed a common causal mechanism for all magma generation south of the Great Glen involving detachment of the down-going slab and peeling back of the lithosphere south of the suture.

Early Devonian transtension was followed by Acadian transpression and the development of clockwise-transecting sinistrally transpressive cleavage, mainly in Avalonian terranes (Soper et al., 1987; Dong et al., 1997; Soper and Woodcock, 2003). One cluster of cleavage ages from the Southern Uplands, Northern England and Wales mostly lie between 404-394 Ma (Emsian, Early Devonian; Merriman et al., 1995; Dong et al., 1997; Sherlock et al., 2003). Crucially, cleavage development overlapped the generation of metamorphic aureoles around the Shap and Skiddaw granites (Soper and Roberts, 1971; Boulter and Soper, 1973; Soper and Kneller, 1990) and the granite emplacement ages are therefore crucial for determining the sequence and timing of the Acadian deformation phase in the Lake District (Woodcock & Soper, 2006). An earlier cluster of cleavage ages at 426 to 420 Ma (Ludlow to Pridoli, late Silurian) in England and Wales dates a pre-Acadian resetting event synchronous with Iapetus closure. This event cannot date cleavage formation and crustal thickening in NW England, because deposition was continuous through this period and into at least 3.5km of now-eroded ORS.

3. The Shap Granite

The mineralogy of the Shap granite is broadly I-type (Chappell and White, 1974). Despite this, the moderately high initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of 0.707 (Wadge et al., 1978), high $\delta^{18}\text{O}$ values of +11%, low initial ϵNd values of -2 and high levels of large-ion lithophile (LIL) and

radioactive elements are usually associated with more evolved S-type granites (Harmon and Halliday, 1980; Halliday 1980). Contamination from local sediments is ruled out by the absence of any strong negative P anomaly or positive B anomaly characteristic of local sedimentary rocks (O'Brien et al., 1985). It has been suggested instead that magmatic fluids have increased the content of fluid mobile LIL elements (O'Brien et al., 1985; Selby et al., 2008) and is consistent with the extensive occurrence of late-stage sulphide minerals. Zircon Hf and O isotope compositions suggest a predominantly lower crustal origin for the Shap magmas (Miles et al., 2014).

The Shap granite (Fig. 1) has three textural varieties (Stages I, II and III, Harker, 1928). Stages I and II show more gradational inter-relationships than with Stage III (Fig. 2). All three varieties contain Carlsbad-twinned orthoclase megacrysts up to 5cm in length that increase in abundance from 15% in Stage I, to 30% in Stage II and up to 60% in Stage III. Although contacts between Stages I and II are often diffuse, the Stage I granite was mostly emplaced before Stage II, with rafts of Stage I granite within the younger Stage II granite. The Stage III granite is a minor constituent of the pluton and is found as 1cm – 1m wide dyke-like bodies that cross-cut Stages I and II. Xenoliths of country rock derived from the Borrowdale Volcanic and Dent Groups are present close to the granite margin.

Orthoclase megacrysts in the Stage I granite sometimes have thin plagioclase overgrowths and are set in a matrix composed of *c.* 35% plagioclase (zoned from andesine to albite), 20% orthoclase, 15% biotite and 15% quartz (Figs. 2 and 3). The Stage II granite makes up *c.* 90% of the exposure and is typically composed of 30% orthoclase megacrysts set in a groundmass of 25% plagioclase, 20% quartz, 15% orthoclase and 10% biotite (Figs. 2 and 3). Megacrysts may show a weak alignment. The Stage III granite is similar in composition to the Stage II

granite but contains *c.* 60% orthoclase megacrysts and less biotite. Stages I and II contain similar populations of accessory minerals, including sphene, apatite, magnetite, zircon, monazite and allanite. These minerals are generally euhedral in shape and occur both interstitially and as inclusions within all major mineral phases. Apatite, sphene and biotite commonly form clots in most areas. Biotite is generally euhedral to subhedral and often altered to chlorite. Plagioclase crystals are generally euhedral, compositionally zoned from andesine-oligoclase cores to albite-oligoclase rims and commonly contain inclusions of biotite.

Orthoclase megacrysts are generally euhedral to subhedral (Fig. 2 and 3). However, late-stage overgrowths enclose other mineral phases in some samples (Fig. 3), suggesting variable degrees of late stage feldspar growth. The crystals exhibit perthitic exsolution textures (Lee et al., 1995; Cox et al., 1986; Lee et al., 1995) and show complex compositional zoning (Cox et al., 1996). They contain inclusions of plagioclase, biotite and quartz that increase in size and abundance towards the rims of the megacrysts (Fig. 7).

The origin of K-feldspar megacrysts in granites has been much debated, with some authors favouring textural coarsening at sub-solidus conditions (e.g. Le Bas, 1982; Johnson and Glazner, 2009) and others a purely magmatic origin (Vernon and Paterson, 2008; Moore and Sisson, 2008; Farina et al., 2010; Vernon, 2010). A number of arguments favour the magmatic hypothesis for Shap: 1) the textural alignment of some megacrysts; 2) higher Ba contents in the megacrysts than in the groundmass suggesting earlier crystallisation (Cox et al., 1996); 3) chemical and isotopic zoning in the megacrysts suggesting growth in magmas with varying compositions (Cox et al., 1996); 4) increase in size and frequency of inclusions towards the rims of the megacrysts indicating simultaneous growth of megacrysts and

inclusions in the magma; 5) zonal alignment of inclusions, consistent with growth from a magma; 6) entrainment of early megacrysts within enclaves of more mafic melt (Fig. 2a-c).

Fine to medium-grained aplites also cross cut the main granite and are composed mostly of quartz and orthoclase. These bodies are usually < 2 cm in width, with some up to a metre. Rare pod-shaped aplites, up to 0.5 m in size, within the Stage II granite record an earlier episode of aplitic emplacement into a plastic crystal mush (Caunt, 1986).

Elliptical microdioritic enclaves up to 2 m in length are present within the Stage I and II granites (Fig. 2a-c). These fine-medium enclaves consist of plagioclase, quartz, biotite and orthoclase. Rounded orthoclase megacrysts make up around 5-8% of most enclaves, with some found straddling the contact between enclaves and granite host. Those found within the enclaves are more rounded than those found in the granite due to resorption, and frequently have oligoclase overgrowths.

Hydrothermal activity is concentrated around joints and veins and is associated with a wide range of secondary minerals. Two main vein assemblages are present: one contains quartz, calcite, bismuthinite and chalcopryrite, and the second contains quartz, calcite, haematite, fluorite and barite (Selby et al., 2008). Both vein types commonly intrude the centres of the Stage III granite bodies and result in a darkening of orthoclase megacrysts within a 5 m radius.

4. Methodology

Zircon crystals were separated using standard heavy liquid techniques before being hand-picked and mounted in epoxy blocks. Polished grain mounts were imaged by SEM (JEOL

6310 Scanning Electron Microscope, Kingston University, London). Mounts were repolished using felt laps and cleaned ultrasonically in petroleum spirit prior to ion microprobe analysis. U-Th-Pb dating was carried out using a Cameca ims 1270 ion microprobe at the University of Edinburgh in 2010 (data published in Miles et al., 2014) and in March 2017. Both sessions used identical analytical procedures that are outlined in detail by Kelly et al. (2008) and summarized in Miles et al. (2014). Some crystals analysed in 2010 were subsequently analysed by LA-ICP-MS for a hafnium isotope study and then reimaged by SEM (results in Miles et al., 2014).

U/Pb ratios were calibrated against zircon Geostandard 91500 (Wiedenbeck et al., 1995: *c.* 1062.5 Ma). Reproducibility on the $^{206}\text{Pb}/^{238}\text{U}$ ratio of single repeats of 91500 were between 1 and 1.5% (1σ) for different sessions. Corrections for in situ common Pb were made using measured ^{204}Pb counts above that of the (?) detector background (0.2-1.5 ppb) and using the modern day composition of common Pb. Uncertainties associated with this correction (usually <15 ppb of ^{206}Pb) are included in the calculation of errors on the U/Pb and Pb/Pb ratios. Processing of data was carried out using in-house data reduction spreadsheets (R.W. Hinton).

Ages quoted in the text and in tables for single analyses are at the 1σ level. Calculated group ages are reported at 95% confidence limits (2σ).

QEMSCAN (Quantitative Elemental Mapping SCANning) images were obtained using a Quanta 650F, Field Emission Gun (FEG) Scanning Electron Microscope (SEM) equipped with two Bruker XFlash 6130 Energy Dispersive Spectrometers (EDS) at the Department of Earth Sciences, University of Cambridge. Analyses were performed by obtaining field-scans,

providing a complete characterisation of particle surfaces above a predefined electron backscatter threshold. The brightness coefficients were calibrated against quartz, gold and copper. Spectra were collected at 25 kV and 10 nA with 2000 total X-ray counts at spacings at 5, 10 or 20 μm , and compared to a Species Identification Protocol (SIP), which discriminates minerals by their X-ray and electron backscatter intensities.

5. Results

Zircon U-Pb ages obtained as part of this study are shown in normal type in Supplementary Table 1 while data from Miles et al. (2014) is shown in italics. Cathodoluminescence (CL) imaging of zircon crystals shows little evidence for inheritance or episodes of resorption (Fig. 4). However, a number of zircon crystals appear to have more homogenous cores and oscillatory zoned rims (Fig. 4), both of which have been dated in this study. For individual samples, we use the mean square weighted deviation, MSWD (or reduced chi-squared statistic), to assess the likelihood that dates of different crystals within a population are statistically equivalent (Wendt and Carl, 1991). A MSWD value greater than 1 indicates that the scatter in data exceeds that predicted from analytical errors and that the source of scatter is geological. MSWD values of less than 1 suggest that one or more sources of uncertainty have been overestimated. A value close to 1 indicates that the population of U-Pb ages is statistically equivalent. However, the acceptable MSWD value used to identify equivalent populations is also dependent on the number of analyses used in the weighted mean, n . The accepted values are expressed as $\pm 1 + 2\sqrt{2/f}$ where f is the degrees of freedom ($n-1$) (Wendt and Carl, 1991; Spencer et al., 2016). Zircon crystallization ages are reported in Table 1 and concordia with MSWD values are shown in a Supplementary figure. Although we cannot rule out the possibility of some Pb loss from these zircons, we see no relationship

between the U (or Th) content and absolute age (Table 1). We therefore conclude that Pb loss is not a significant factor and that the reported zircon ages are not significantly younger than the true ages.

Zircon ages from the Stage I granite (Sample AM0923) range from 428 ± 4 Ma to 403 ± 5 Ma with a mean weighted age of 414.6 ± 2.6 Ma (2σ) ($n = 12$, MSWD: 2.3) (Fig. 5). Although core ages are generally older than rims, it is not possible to reliably distinguish them as separate populations. Two grains show significant age differences of 22 Ma and 10 Ma between cores and rims.

Two samples from the Shap II granite were analysed (AM0932 and SH06). Zircons in sample AM0932 range in age between 416 ± 4 and 407 ± 5 Ma with a weighted mean age of 412.3 ± 4.0 Ma (2σ) ($n = 8$, MSWD: 1.1) (Fig. 5). There is no systematic difference between core and rim ages in this sample. Zircons in sample SH06 range from 412 ± 6 Ma to 406 ± 6 Ma with a weighted mean age of 418.6 ± 8.1 Ma (2σ) ($n = 8$, MSWD: 1.0) (Fig. 5). Core and rim ages lie within analytical error.

Zircon cores from two enclaves were analysed. One was emplaced into the Stage I granite (AM0925) while a second was emplaced into the Stage II granite (AM0926). In the former, zircon ages range between 425 ± 4 and 413 ± 4 Ma with a weighted mean age of 417.9 ± 3.2 Ma (2σ) ($n = 7$, MSWD: 0.9) (Table 1; Fig. 5). The enclave emplaced into the Stage II granite contains zircons with dates between 420 ± 4 Ma and 413 ± 4 Ma and a mean weighted age of 416.8 ± 3.8 Ma (2σ) ($n = 5$, MSWD: 0.5) (Table 1; Fig. 5).

Due to limited analytical precision (typically around 1% at the 1σ level for SIMS analysis), the majority of zircon dates lie within analytical error at the 2σ level. The distribution of ages is broadly unimodal (Fig. 6) and it is not possible to reliably distinguish separate zircon populations. We therefore use a weighted mean age for the entire population of 415.6 ± 1.4 (2σ) ($n = 39$, MSWD: 1.4). This use does not imply that crystallisation of all the analysed zircons necessarily occurred at about 415.6 Ma, only that this hypothesis cannot be disproved given current analytical errors. Still plausible, though statistically less likely, is the alternative hypothesis that zircons crystallised over the extended time period from 428 ± 8 Ma to 403 ± 10 Ma suggested by individual zircon ages.

Four QEMSCAN images of Stage II granite and its enclaves (example in Fig. 7a) have been used to count the typical textural sites in which zircon grains occur. The results from 174 zircons (Fig. 7b) show that the majority (65%) occur at intergrain boundaries in the groundmass. Another 30% occur as inclusions in groundmass minerals, most commonly (15%) in biotite. Only the remaining 5% of zircons occur as inclusions in the Kspar megacrysts and then mostly in their rims, not their cores. The majority of zircons therefore appear to be texturally late. However, more precise dating methods such as ID-TIMS commonly conclude that most zircon populations contain complex mixtures of primary and recycled crystals (e.g. Miller et al., 2007; Claiborne et al., 2010; Barboni et al., 2015). Due to the limited analytical precision of in situ dating methods and a lack of contextual age data, it is not possible to reliably verify these textural relations. However, in this study, we argue that most zircon crystals large enough for in situ dating are commonly antecrysts formed at deeper levels within the magmatic system.

6. Discussion

The mean zircon age of 415.6 ± 1.4 Ma reported here is significantly older than other reported ages from the Shap granite (Figs. 5 and 6). Here we investigate these differences and assess the degree to which most zircons record distinctly different stages of magma evolution compared to other dating methods.

6.1 The absence of inherited xenocrysts

When a single domain can be analysed, analytical uncertainties are accurately propagated and Pb-loss is not a significant issue, a concordant zircon U-Pb age reflects the time at which a particular area of a grain crystallised from a melt. However, it is increasingly apparent that crystals within a magma may have a variety of origins (e.g. Broxton et al., 1989; Cooper and Reid, 2003; Costa et al., 2003; Claiborne et al., 2006; Ramos and Reid, 2005; Walker et al., 2007; Davidson et al., 2001; 2005; 2007; Barbey et al., 2008; Barboni et al., 2015). We follow Miller et al (2007) in using the term xenocryst for crystals that are derived from older host rocks. Xenocrysts have U-Pb ages older, often much older, than any known phase of magmatism. They are commonly identified texturally by their different CL responses compared with magmatic crystals and by their partial resorption. Xenocrysts are distinct from crystals inherited from earlier magmatic pulses within the same magma complex. We follow previous authors (e.g. Bacon and Lowenstern, 2005; Charlie et al., 2005; Metzel et al., 2006; Walker et al., 2007; Miller et al., 2007) in terming such zircons antecrysts. In contrast to xenocrysts, antecrysts may exhibit similar compositional and petrographic characteristics, despite having grown in distinct parts of the magma reservoir (Miller et al., 2007). Crystals associated exclusively with the pulse of magma that solidified to form the rock in which they are now found are termed autocrysts.

Previous studies have consistently failed to identify xenocrysts in the Shap granite (Pidgeon and Aftalion, 1978; Miles et al., 2014). This is confirmed here by the absence of Ordovician (or older) zircons from the surrounding Borrowdale Volcanic Group and Windermere Supergroup. The absence of xenocrysts is also a common and distinguishing characteristic of other granites in the TSS (Brown et al., 2008) and is in contrast to other Caledonian granites north of the Highland Boundary Fault in Scotland (Pidgeon and Aftalion, 1978; Miles et al., 2014). The lack of resorption surfaces between zones also indicates an absence of inherited crystals and crystal cores (Fig. 4). This may simply reflect a lack of zircon in the granite source rocks. However, the absence of xenocrysts in even S-type members of the TSS (Pidgeon and Aftalion, 1978; Miles et al., 2014), suggests that zircon may also have been resorbed within the source region.

Isotope compositions indicate that most TSS granites are derived by partial melting of lower crustal source rocks (Halliday, 1984; Miles et al., 2014). A comparison of Pb isotope compositions has recognised a common Avalonian source for granites emplaced either side of the Iapetus Suture (Thirlwall, 1989). For granites emplaced north of the suture (Fig. 1), the implication is that magmas were derived from below the northward dipping suture (imaged seismically by Freeman et al., 1988) and almost exclusively within the lower crust (Thirlwall, 1989; Miles et al., 2013; 2014). Although the crustal architecture below Shap is less well constrained, elevated whole-rock La/Yb suggest that the Shap magmas were derived from a mafic source containing residual garnet in the lower crust (O'Brian et al., 1985). Furthermore, an input from local sediments can be ruled out by the absence of any strong negative P anomaly or positive B anomaly that are characteristic of local sedimentary units (O'Brien et al., 1985).

The generation of metaluminous melts from partial melting of hydrous, mafic lower crustal protoliths such as basalts and amphibolites requires temperatures of at least *c.* 900°C at 1GPa (e.g. Petford and Gallagher, 2001; Sisson et al., 2005; Annen et al., 2006; Miller et al., 2007). However, Collins et al. (2016) propose that exsolution of aqueous fluids from mafic magmas emplaced into the lower crust may promote water-fluxed partial melting at ambient pressure-temperature conditions (~750-800°C at 0.8GPa). At 900°C, zircon saturation in the resulting metaluminous granitic melts would require *c.* 600 ppm Zr according to the saturation models of Watson and Harrison (1983). Zr concentrations in both main varieties of the Shap granite are < 200 ppm (Miles. PhD thesis) and suggest zircon saturation temperatures of *c.* 780°C. Initial magmas formed in the lower crust at around 900°C are therefore likely to have been undersaturated in zircon and capable of resorbing entrained xenocrysts. Miller et al (2007) demonstrated that even large zircon crystals (>250 µm) will dissolve on timescales of a few hundred years within granitic melts formed in the lower crust. For smaller crystals, these timescales were shown to be as little as a few tens of years. Alternatively, initial melts may have been saturated in zircon if melting occurred under ambient pressure and temperature conditions due to water-fluxed melting (Collins et al., 2016). In this case, the absence of zircon xenocrysts may simply reflect a lack of zircons in the mafic protolith(s). Although there is a clear absence of zircon xenocrysts at Shap, it remains difficult to determine whether initial melts in the lower crust were zircon saturated.

We conclude that zircon xenocrysts are absent in the Shap granite. The observed assemblage of zircon crystals is therefore magmatic in origin. We next consider whether most zircon crystals are mainly antecrysts or autocrysts formed at the final level of emplacement.

6.2 Autocrysts formed at the level of emplacement?

Emplacement of the Shap granite has long been considered an important marker for Acadian deformation (Boulter and Soper, 1973; Soper and Kneller, 1990; Selby et al., 2008; Miles et al., 2016). Biotite in the metamorphic aureole overgrows the regional cleavage (Boulter and Soper, 1973) while a cogenetic dyke swarm bears a supposed Acadian tectonic foliation (Soper and Kneller, 1990). These field relations imply that the Shap granite was emplaced during the Acadian deformation. Ar-Ar and K-Ar dating of cleavage-forming minerals from England and Wales suggests that Acadian deformation occurred between 404 and 394 Ma (Emsian, Early Devonian) and peaked at about 400 Ma (Miles et al., 2016; revised to new decay constant from Merriman et al., 1995; Dong et al., 1997; Sherlock et al., 2003). K-Ar data from NW England alone (Merriman et al., 1995) give a revised cleavage age of 401 ± 7 Ma (Figs. 5 and 6) in Ludlow (late Silurian) rocks.

Merriman et al. (1995) also obtained an Ar-Ar total fusion age from their NW England samples that recalculates to 422 ± 3 Ma. However, this age (Pridoli, late Silurian) cannot date Acadian shortening and cleavage formation, which happened under a thick overburden, mostly of Devonian rocks. The crystallite thickness of micas in the dated rocks (Merriman et al., 1995) suggests that cleavage formation in NW England occurred at about 250°C. This temperature implies an overburden of 10 km at a low geothermal gradient (Merriman et al., 1995) or 4.5 km (3.5 km before shortening) at higher gradients (Soper & Woodcock, 2003). This overburden must have comprised mostly now-eroded Lower Devonian rocks, forcing the conclusion that the late Lower Devonian age of 401 ± 7 Ma best dates closure of the K-Ar system during Acadian cleavage formation.

In addition to Shap, the nearby Skiddaw granite also shows good field evidence for having been emplaced during the later stages of Acadian deformation. Here, andalusite in the inner thermal aureole pre-dates the main regional cleavage, while in the outer zone, it overgrows the regional cleavage (Soper and Roberts, 1971). In an attempt to avoid inherited or recycled zircon crystals, Selby et al (2008) selected single, small acicular zircon crystals from the Skiddaw granite for high precision ID-TIMS dating. In contrast to the larger zircon crystals required for *in situ* dating, such delicate crystals are unlikely to have survived transport between magma batches and are instead more likely to be autocrysts formed at the final level of emplacement. Seven grains were shown to overlap within error to give a concordia age of 398.8 ± 0.4 Ma. These authors consider this the most reliable estimate for final granite emplacement. This age is also consistent with the K-Ar age of 401 ± 7 Ma for the cleavage-parallel micas.

At Shap, the majority of zircons large enough for *in situ* dating clearly do not have ages that overlap with Acadian deformation (Figs. 5 and 6). However, this does not rule out the possibility that smaller zircon crystals and/or overgrowths may record a younger syn-Acadian history. Continued magmatic activity for up to 10 Ma after the majority of zircon crystallisation is supported by the revised Rb-Sr feldspar age of 412 ± 2 Ma (Davidson et al., 2005) and a Re-Os molybdenite age of 405.2 ± 1.8 Ma (Selby et al., 2008). The magmatic CO₂-rich fluids responsible for molybdenite mineralisation underwent boiling between 300°C and 450°C at 440 to 620 bars, equating to a trapping depth of 3 to 6.3 km assuming a hydrostatic pressure gradient of 98.1 bar km^{-1} (Selby et al., 2008). In contrast to the Shap granite, fluid inclusions show that molybdenite mineralisation at the Skiddaw granite (Re-Os age of 392.3 ± 2.8 Ma) was post magmatic and associated with non-magmatic fluids (Selby et al., 2008).

We conclude that although the exact timing of final granite emplacement is difficult to determine, the field relations around the Shap granite demonstrate that it broadly coincided with the Acadian deformation that culminated around 405 Ma. We agree with Selby et al (2008) that Acadian deformation was probably episodic and somewhat diachronous from before *c.* 405 Ma (emplacement of the Shap granite) to after *c.* 398 (emplacement of the Skiddaw granite). We see no feasible mechanism for forming the majority of zircon crystals at approximately 416 Ma as autocrysts at shallow depths without imprinting a pre-Acadian thermal signature on local country rocks. We instead suggest that the majority of zircon crystals are antecrysts formed during an earlier and deeper stage of magmatism.

6.3 Assembly of the Shap pluton in a mid-crustal mush zone?

Despite its small size, the Shap granite is characterised by a significant amount of textural heterogeneity (Fig. 2), reminiscent of much larger batholiths such as the $\sim 1100 \text{ km}^2$ Late Cretaceous Tuolumne pluton in the central Sierra Nevada, California. These textures imply movement, sorting and accumulation of crystal-bearing magmas at temperatures well below the granite liquidus (Paterson, 2009). The weak alignment of K-feldspar megacrysts within an undeformed matrix of other minerals at Shap also demonstrates a degree of crystal mobility. Abundant rounded mafic enclaves (Fig. 2) show that these magmas were injected into a poorly consolidated crystal mush. Partially resorbed K-feldspar megacrysts within the enclaves (Fig. 2) also show that crystals were scavenged and transported from a ductile mush. A recent study suggests that enclaves may form as buoyant plumes that ascend and detach from hybrid thermal boundary layers between existing crystal mushes and new injections of more mafic magma (Plail et al., 2018). Many smaller (cryptic) injections of other magmas have been inferred from the complex textural, chemical and isotopic record preserved in

zoned K-feldspar megacrysts (Cox et al., 1996). These crystals document a history of progressive hybridisation with only the most voluminous episodes of mafic magma injection preserved as enclaves. The equal proportions of euhedral and subhedral crystals in both main varieties of the Shap granite (Fig. 3) suggest variable degrees of melt-crystal disequilibrium between different populations of megacrysts formed in compositionally different magmas.

Experimental evidence suggests that K-feldspar saturation occurs at between 760-780°C in granitic melts with 4 wt% water at pressures of 3-5 kb (Piwinskii, 1968; Clemens and Wall, 1981). At these temperatures, granite magmas contain c. 50 vol.% crystals (Villaro et al., 2009). However, evidence is emerging that, even when the volume of crystals is >50 vol %, mushes remain mobile and able to interact and exchange crystals (Weibe, 1996; Weibe and Collins, 1998; Marsh, 1996, 2006; Miller and Miller, 2002; Bachmann and Bergantz, 2004; 2008; Hersum et al., 2005; Walker et al., 2007; Žák and Klomínský, 2007; Paterson, 2009). Furthermore, it has been shown that water-rich, felsic magma mushes may remain 70-80% molten within just 15 to 20°C of the granite solidus (Scaillet et al., 1997, 1998) and that subsequent thermal and mechanical rejuvenation may occur due to the injection of new magmas. Despite this, most crystals are likely to have only spent a small fraction of the total magma storage history at temperatures above the critical crystallinity at which a crystal mush may be mobile (Cooper and Kent, 2014; Szymanowski et al., 2017).

The age of at least one injection of mafic magma has been constrained by Davidson et al (2005), who reported a Rb-Sr isochron age of 412 ± 2 Ma (corrected here for the revised Rb decay constant, Nebel et al., 2011) on a single plagioclase-rimmed K-feldspar megacryst. This age demonstrates that at least some K-feldspar megacrysts had grown around 7 Ma prior to final granite emplacement. Despite limited analytical precision, we also note that only

zircons older than 413 Ma are found within the two enclaves studied here (Fig. 5). This finding suggests that zircon crystals may also have been scavenged from an already heterogeneous population of crystals at around 412 Ma. The lack of a pre-Acadian thermal aureole around the Shap granite indicates that K-feldspar megacrysts and mafic magma injections occurred prior to granite emplacement at 3-6 km depth (Selby et al., 2008). Furthermore, the small size of the exposed granite and its shallow emplacement would require rapid development of the ductile textures observed in the field due to rapid cooling. It is thought more likely that the majority of textural features and injections of mafic magmas occurred within a larger and deeper batholith.

Gravity modelling provides strong evidence for a much larger parental batholith to the Shap pluton. The gravity field shows that the Lake District is underlain by an extensive batholith with an estimated subsurface area of 1500 km² (Bott, 1967; 1974; Lee, 1986; 1989; Kimbell et al., 2010). Shap, together with Eskdale, Ennerdale, Broad Oak, Threlkeld and Skiddaw are the outcrops of this batholith. These exposed granites represent steep cylindrical bodies that root into a continuous granitoid batholith at about 10 km depth. Considering the 3-6 km of Silurian and Devonian overburden that has been removed since granite emplacement (Soper and Woodcock, 2003), it is likely that the active mush body resided at about 15 km depth in the crust. Zircon ages show that the Eskdale and Ennerdale granites are late Ordovician (Hughes et al., 1996) and therefore considerably older than the Shap (this study) and Skiddaw granites (Selby et al., 2008). The late Silurian to early Devonian batholith therefore formed in a region of the mid-crust that had hosted a late Ordovician magma body some 25 million years earlier.

6.4 Emplacement model for the Shap granite

We suggest that the evolution of the Shap granite should be considered in three distinct stages (Fig. 8). The first is likely to have involved the development of a lower crustal hot zone (Annen et al., 2006) by repeated injections of mafic, mantle-derived magma during regional transtension (Brown et al., 2008; Miles et al., 2016). The onset of this process is difficult to constrain, but the oldest zircon age of 428 ± 4 Ma provides a minimum estimate. In response to this, lower crustal rocks are likely to have undergone partial melting that is documented in the crust-like isotope signatures of whole-rocks and minerals (Halliday, 1984; Miles et al., 2014). These melts are also likely to have inherited high La/Yb values due to the presence of garnet in the lower crustal source region (O'Brian et al., 1985). The absence of xenocrysts may reflect an absence of zircon in the source rocks and/or resorption by zircon undersaturated magmas. During the incubation period of Annen et al (2006), evolved magmas are thought to develop within isolated areas of the hot zone. Within these regions of differentiated melt, a variety of accessory minerals may have developed with a range of compositions and ages. However, it remains unclear whether the weighted mean zircon age of 415.6 ± 1.4 Ma reflects crystallisation mainly within the lower crustal hot zone or within a shallower mid-crustal batholith.

The second stage of magma evolution involved assembly of the Lake District batholith within the mid crust (Fig. 8). Assembly is thought to have occurred due to the episodic ascent of accumulated granitic melts from the lower crustal hot zone. Although we cannot rule out the possibility that these ascending magmas carried a mixed population of accessory minerals from the lower crustal hot zone, most of the larger silicate minerals seem likely to have developed within this growing mid crustal batholith. At least one batch of mafic magma was injected into a poorly consolidated crystal mush at 412 ± 2 Ma (revised Rb-Sr feldspar age of Davidson et al., 2005) leading to the entrainment of existing K-feldspars and zircon crystals.

Complex textural and cryptic compositional zoning patterns within magmatic K-feldspars document numerous smaller injections of compositionally different magmas (Cox et al., 1996). Continued rejuvenation and episodic assembly of the 1500 km² Lake District batholith is thought to have continued for *c.* 10 Ma and until the culmination of Acadian transpression at *c.* 405 Ma.

Gravity surveys indicate that the Shap granite is a steep-sided, cylindrical cupola above the larger Lake District batholith (Lee, 1986; Kimbell et al., 2010). The cylindrical shape is consistent with emplacement into transtensional sites formed at releasing bends within transpressional settings (e.g. Glazner, 1991). It is possible that the transition from transtension to transpression encouraged the third and final stage of evolution involving the ascent of a rejuvenated crystal slurry from the underlying batholith.

The two main textural varieties seen in the field (Stages I and II) indicate two main stages of emplacement at around 405 Ma. The moderately diffuse boundaries between these different textural varieties suggest that they were emplaced in quick succession and prior to complete solidification of the Stage I granite. The rarity of larger, younger zircons with ages that overlap with final emplacement suggests that the majority of zircons large enough to date using in situ methods are antecrysts. It remains possible that smaller zircons and/or crystal overgrowths may document later stages of batholith growth and final granite emplacement as shown at Skiddaw by Selby et al (2008).

Revised whole-rock-mineral Rb-Sr (402 ± 3 Ma) and K-Ar ages (401 ± 7 Ma, Wadge et al., 1978) support final emplacement at around the time of Acadian deformation. These systems are more likely to record final emplacement due to their low closure temperatures (e.g. Villa,

1998). Magmatic fluids derived from the underlying batholith are thought to have exploited the Shap cupola and are responsible for late-stage molybdenite mineralisation (405.2 ± 1.8 , Selby et al., 2008). It seems logical that molybdenites should record the youngest magmatic event in any system due to the need to accumulate sufficient concentrations of metals in vapour phases (e.g. Edmonds and Wallace, 2017) which then migrate to the topmost parts of the system.

Conclusions and wider implications

A complex and extended magmatic history is evident from the combination of different dating methods at the Shap granite, Northern Britain. We report a new weighted mean zircon U-Pb age of 415.6 ± 1.4 (2σ) Ma. The absence of Ordovician (and older) zircon crystals rules out the possibility of xenocrysts inherited from source rocks. A Rb-Sr feldspar isochron age reported by Davidson et al (2005) from a mafic enclave has been revised in light of a new Rb decay constant and suggests infiltration of a more mafic magma into a semi-mobile crystal mush at 412 ± 2 (2σ) Ma. Mafic enclaves also contain resorbed K-feldspar and zircon crystals scavenged from the host granite and demonstrate an ability to disperse crystals within the growing batholith. These ages are at odds with field relations in the thermal aureole of the Shap granite that suggest final emplacement occurred at approximately 405 Ma during Acadian deformation. A syn-Acadian emplacement age is also supported by molybdenite Re-Os dates (405.2 ± 1.8 , Ma 2σ , Selby et al., 2008). Revised whole-rock-mineral Rb-Sr and K-Ar biotite ages (402 ± 3 Ma and 401 ± 7 Ma, respectively, Wadge et al., 1978) also indicate syn-Acadian emplacement. These systems are more likely to record final emplacement due to their tendency to be reset at relatively low temperatures. We interpret the apparent age gap of approximately 10 Ma between most zircon growth and final granite emplacement as

evidence for a protracted history of magmatic activity within the crust. We suggest a three stage evolution:

1. Mantle melting triggered by regional transtension led to lower crustal melting and to the formation of granitic melts in the lower crust. The oldest reported zircon age of 428 ± 4 Ma provides a minimum estimate for the onset of this magmatic activity in the lower crust.

2. The 1500 km² Lake District mid-crustal batholith, imaged by gravity, developed incrementally by ascending evolved melts that may also have carried a range of antecrysts from the lower crustal hot zone. Although most zircon crystals record a relatively early stage of magma evolution, it remains unclear whether they grew mostly in a lower crustal hot zone or within a shallower mid-crustal batholith. Either way, the majority of zircon crystals large enough for in situ dating record evidence for magmatic activity in deeper parts of the system. A similar conclusion was made by a combined zircon U-Pb and thermal modelling study of the Mt Capanne pluton in Italy (Barboni et al. 2015) and by high precision dating of zircons from Mount St Helens (Claiborne et al., 2010). Batholith assembly beneath the Lake District is thought to have occurred over 10 Ma or more due to episodic injections of new magmas. The most voluminous injections of new magma are preserved as enclaves, but smaller injections are suggested by complex zoning patterns in magmatic K-feldspar megacrysts. The crystal mush is likely to have been repeatedly rejuvenated by injections of new magma until the culmination of Acadian transpression at around 405 Ma.

3. Field relations clearly show that the Shap granite was emplaced during the Acadian Phase that culminated at around 405 Ma. The change in regional stress regime caused by the Acadian Phase may have aided the development of a small cylindrical cupola above the main Lake District batholith, potentially within a releasing bend in the regionally transpressional system.

This study adds to a growing consensus that granites are the product of protracted episodes of magmatic activity and that a range of dating methods are required to fully understand the emplacement of batholiths. Furthermore, it is evident that the majority of zircon crystallisation occurred at deeper crustal levels and prior to final emplacement. Caution is urged when using zircon U-Pb geochronology to investigate magma residence times and final granite emplacement.

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Figures

Figure 1: a) Terrane map of northern Britain and Ireland showing the locations of late Caledonian granites and volcanic rocks. Only the Shap granite is named. b) Map of the Shap granite (after Soper and Kneller, 1990). A selection of structural data is shown from the surrounding country rocks, including inclined bedding (single tick symbols), inclined cleavage (black triangular ticks) and cleavage/bedding form lines (dashed grey curves) that demonstrate that the near-vertical cleavage is deflected around the Shap granite. Numbers 1

and 2 refer to sample locations: 1 – Shap Pink quarry (AM0923, AM0925, AM0926, AM0932; 2 – Longfell Gill (Sh06).

Figure 2: Field photographs: a) polished slab at the Shap Wells Hotel. Diffuse boundaries are highlighted between different textural varieties of granite, with the Stage I granite particularly heterogeneous. Mafic, diorite enclave is visible within the Stage I granite and contains partially resorbed and rounded orthoclase megacrysts. b) A 45 x 15 cm mafic enclave within the Stage II granite. Entrained orthoclase megacrysts are rounded and partially resorbed. c) Multiple mafic enclaves within the Stage II granite. Some orthoclase megacrysts span the boundary between granite host and enclave and show increasing degrees of resorption within the enclaves. d) Near-vertical cleavage in the Coldwell Formation (Windermere Supergroup), Packhorse Hill, with contact metamorphic minerals overgrowing the regional cleavage. e) Mineralised area of Stage II granite with disseminated pyrite, chalcopyrite, bornite and pale blue molybdenite. f) Contact between Stage I and II granite. Euhedral and anhedral orthoclase megacrysts in the Stage I granite suggest variable degrees of disequilibrium between populations of megacrysts derived from different melts.

Figure 3: Scanned polished surfaces of granite samples from the Watson Collection (University of Cambridge). a) Stage I granite with euhedral zoned orthoclase megacrysts and a groundmass of anhedral orthoclase, quartz and biotite mainly interstitial between more euhedral plagioclase. Megacrysts formed before groundmass phases and have no overgrowths, suggesting little interstitial melt at the time of final emplacement. b) Stage II granite with darkened perthitic orthoclase megacrysts caused by later alteration near Stage III veins. Megacrysts show late-stage overgrowths invading some groundmass phases. Groundmass orthoclase is mostly euhedral with anhedral quartz, biotite and plagioclase. c)

and d) Two faces of the same Stage I granite showing a continuum of orthoclase textures from euhedral to anhedral. The same textures are visible in both megacrystic and groundmass orthoclase and suggest late-stage growth of K-feldspar from interstitial melts during final emplacement.

Figure 4: Representative cathodoluminescence (CL) images of zircon crystals from Stage I (upper) and II (lower) granite. Pits are from laser ablation analyses. Grain numbers are shown beside crystals.

Figure 5: Age-ranked plots showing $^{206}\text{Pb}/^{238}\text{U}$ dates for zircons from five studied samples. Box length represent 2SD analytical errors. Boxes bounded by solid lines are crystal core ages, dashed boundaries are crystal rim ages. Also shown is the revised Rb-Sr isochron age from Davidson et al (2005) and molybdenite Re-Os ages from Selby et al (2008). The Acadian deformation phase is defined using cleavage ages based on Ar-Ar and K-Ar methods (Merriman et al., 1995; Dong et al., 1997; Sherlock et al., 2003).

Figure 6: A compilation of age data. Zircon ages are plotted as a histogram. The mean weighted age of all zircons is shown with a vertical dashed line. Other ages are as described in Figure 5.

Figure 7: a) QEMSCAN image of a Stage II granite at 10 μm resolution, with mineral phases colour coded and labelled (Bi = biotite, Qtz = quartz, Kfs = Kspar phenocrysts, Pl = plagioclase, Zrn = zircon, Ttn = Titanite, IlMg = Ilmenite and Magnetite). b) Occurrence matrix in total of six QEMSCAN images showing percentage of zircon grains ($n = 174$) as

inclusions in a mineral (diagonal cells) or in inter-grain sites between minerals (off-diagonal cells).

Figure 8: a) Crustal-scale schematic model. Melt is generated in a ‘lower crustal hot zone’ formed by repeated emplacement of mantle-derived mafic magmas and lower-crustal melting. Any zircon xenocrysts are likely to have been resorbed by zircon undersaturated magmas. Silicic magma was generated after an ‘incubation period’ (Annen et al., 2006) and probably contained magmatic zircons with a range of U-Pb ages. Following accumulation, mobile magmas will have ascended to higher crustal levels. Zircon antecrysts may have been transported by these magmas to shallower depths. b) Evolution of mid-crustal batholith shown in boxed area in a). Repeated pulses of magma are emplaced into a growing crystal mush. New crystal growth is likely to have occurred here with further crystal movement caused by episodic rejuvenation of the mush. A 412 Ma isochron age from enclave-hosted feldspars (Davidson et al., 2005) suggests an episode of mafic magma injection at this time. Enclaves have inherited the mixed population of zircon antecrysts from the mush along with orthoclase megacrysts that existed at this time. The onset of Acadian transpression at around 405 Ma led to localised areas of extension within releasing bends. Steep-sided cupolas (like Shap) developed above the main mush body and preserved the large-scale heterogeneity developed over the preceding *c.* 10 Ma within the main batholith. Residual heat and interstitial melts produced a thermal aureole in the surrounding country rock that was broadly coincident with cleavage development. Where sufficient interstitial melt remained, zircon overgrowths developed and provide the closest approximation to the emplacement age. The Shap ‘cupola’ acted as a conduit for magmatic fluids to escape from the main mush body, leading to late-stage mineralisation.

References

- Anderson, T.B., 1987. The onset and timing of Caledonian sinistral shear in County Down. *Journal of the Geological Society* 144, 817–825.
- Annen, C., Blundy, J.D., Sparks, R.S.J., 2006. The genesis of intermediate and silicic magmas in deep crustal hot zones. *Journal of Petrology* 47, 505–539.
- Annen, C., 2011. Implications of incremental emplacement of magma bodies for magma differentiation, thermal aureole dimensions and plutonism-volcanism relationships. *Tectonophysics* 500, 3–10.
- Annen, C., Blundy, J.D., Leuthold, J., Sparks, R.S.J., 2015. Construction and evolution of igneous bodies: towards an integrated perspective of crustal magmatism. *Lithos* 230, 206–221.
- Atherton, M.P., Ghani, A.A., 2002. Slab breakoff: a model for Caledonian, Late Granite syn-collisional magmatism in the orthotectonic (metamorphic) zone of Scotland and Donegal, Ireland. *Lithos* 62, 65–85.
- Bachmann, O., Bergantz, G.W., 2004. On the origin of crystal-poor rhyolites: Extracted from batholithic crystal mushes. *Journal of Petrology* 45, 1565–1582.
- Bacon, C.R. and Lowenstern, J.B., 2005. Late Pleistocene granodiorite source for recycled zircon and phenocrysts in rhyodacite lava at Crater Lake, Oregon. *Earth and Planetary Science Letters* 233, 277–293.
- Barbey, P., Gasquet, D., Pin, C., Bourgeix, A.L., 2008. Igneous banding, schlieren and mafic enclaves in calc-alkaline granites: The Budduso pluton (Sardinia). *Lithos* 104, 147–163.
- Barboni, M., Annen, C., Schoene, B., 2015. Evaluating the construction and evolution of upper crustal magma reservoirs with coupled U/Pb zircon geochronology and thermal modelling: A case study from the Mt. Capanne pluton (Elba, Italy). *Earth and Planetary Science Letters* 432, 436–448.
- Bindeman, I.N., Schmitt, A.K., Valley, J.W., 2006. U-Pb zircon geochronology of silicic tuffs from the Timber Mountains/Oasis Valley caldera complex, Nevada: Rapid generation of large volume magmas by shallow-level remelting: Contributions to Mineralogy and Petrology 152, 649–665.
- Bluck, B.J., 1984. Pre-Carboniferous history of the Midland Valley of Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences* 75, 275–295.

- Bott, M.H.P., 1967. Geophysical investigations of the northern Pennine basement rocks. *Proceedings of the Yorkshire Geological Society* 36, 139-168.
- Bott, M.H.P., 1974. The geological interpretation of a gravity survey of the English Lake District and the Vale of Eden. *Journal of the Geological Society, London* 130, 309-331.
- Boulter, C.A. and Soper, N.J., 1973. Structural relationships of the Shap granite. *Proceedings of the Yorkshire Geological Society* 39, 365-369.
- Broderick, C., Wotzlaw, J., Frick, D., Gerndez, A., Ulianov, A., Gunther, D., Schaltegger, U., 2015. Linking the thermal evolution and emplacement history of an upper crustal pluton to its lower-crustal roots using zircon geochronology and geochemistry (southern Adamello batholith, N. Italy). *Contributions to Mineralogy and Petrology* 170, 1-17.
- Brown, S.J.A. and Fletcher, I.R., 1999. SHRIMP U-Pb dating of the pre-eruption growth history of zircons from the 340 ka Whakamaru Ignimbrite, New Zealand; evidence for > 250 k.y. magma residence times: *Geology* 27, 1035-1038.
- Brown, P.E., Ryan, P.D., Soper, N.J., Woodcock, N.H., 2008. The Newer Granite problem revisited: a transtensional origin for the Early Devonian trans-suture suite. *Geological Magazine* 145, 235–256. doi:10.1017/S0016756807004219
- Broxton, D.E., Warren, R.G., Byers, F.M., Jr., Scott, R.B., 1989. Chemical and mineralogic trends within the Timber Mountains-Oasis Valley caldera complex, Nevada; evidence for multiple cycles of chemical evolution in a long-lived silicic magma system. *Journal of Geophysical Research* 94, 5961-5985.
- Buddington, A.F., 1959, Granite emplacement with special reference to North America: *Geological Society of America Bulletin*, v. 70, no. 6, p. 671-747.
- Buret, Y., von Quadt, A., Heinrich, C., Selby, D., Walle, M., Peytcheva, I., 2017. From a long-lived upper-crustal magma chamber to rapid porphyry copper emplacement: Reading the geochemistry of zircon crystals at Bajo de la Alumbrera (NW Argentina). *Earth and Planetary Science Letters* 450, 120-131.
- Cassidy, M., Edmonds, M., Watt, S.F.L., Palmer, M.R., Gernon, T.M., 2015. Origin of basalts by hybridisation in andesite-dominated arcs. *Journal of Petrology* 56, 325-346.
- Caunt, S.L., 1986. Igneous and metamorphic processes in the Shap granite and its aureole (PhD Thesis) University of Leeds.
- Chappell, B.W. and White, A.J.R., 1974. Two contrasting granite types. *Pacific Geology* 8, 173-174.
- Charlier, B.L.A., Wilson, C.J.N., Lowenstern, J.B., Blake, S., van Calstern, P.W., Davidson, J.P., 2005. Magma generation at a large, hyperactive silicic volcano (Taupo, New

- Zealand) revealed by U/Th and U/Pb systematics in zircons. *Journal of Petrology* 46, 3-32.
- Claiborne, L.L., Miller, C.F., Walker, B.A., Wooden, J.L., Mazdab, F.K., Bea, F., 2006. Tracking magmatic processes through Zr/Hf ratios in rocks and Hf and Ti zoning in zircons: An example from the Spirit Mountain batholith, Nevada. *Mineralogical Magazine* 70, 517-543.
- Clayburn, J.A.P., 1981. Age and petrographic studies of some magmatic and metamorphic rocks in the Grampian Highlands. PhD Thesis, University of Oxford (unpublished).
- Clemens, J.D. and Mawer, C.K., 1992. Granite magma transport by fracture propagation. *Tectonophysics* 204, 339-360.
- Coleman, D.S., Gray, W., Glazner, A.F., 2004. Rethinking the emplacement and evolution of zoned plutons: Geochronologic evidence for incremental assembly of the Tuolumne Intrusive Suite, California, *Geology* 32, 433-436.
- Collins, W.J., Huang, H-Q., Jiang, X., 2016. Water-fluxed crustal melting produces Cordilleran batholiths. *Geology* 44, 143-146.
- Cooper, K.M. and Reid, M.R., 2003. Re-examination of crystal ages in recent Mount St Helens lavas: Implications for magma reservoir processes: *Earth and Planetary Science Letters* 213, 149-167.
- Cooper, K.M., and Kent, A.J.R., 2014. Rapid remobilisation of magmatic crystals kept in cold storage. *Nature* 506, 480-483.
- Costa, F., Chakraborty, S., Dohmen, R., 2003. Diffusion coupling between trace and major elements and model for calculation of magma residence times using plagioclase: *Geochimica et Cosmochimica Acta* 67, 2189-2200.
- Cox, R.A., Dempster, T.J., Bell, B.R., Rogers, G., 1996. Crystallisation of the Shap Granite: evidence from zoned K-feldspar megacrysts. *Journal of the Geological Society of London* 153, 625-635.
- Davidson, J., Tepley, F., III, Palacz, Z., Meffan-Main, S., 2001. Magma recharge, contamination and residence times revealed by in situ laser ablation isotopic analysis of feldspar in volcanic rocks: *Earth and Planetary Science Letters* 184, 427-442.
- Davidson, J., Charlier, B., Hora, J.M., Perloth, R., 2005. Mineral isochrones and isotopic fingerprinting: Pitfalls and promise. *Geology* 33, 29-32.
- Davidson, J., Morgan, D.J., Charlier, B.L.A., 2007. Isotopic microsampling of magmatic rocks. *Elements* 3, 253-259.

- Dewey, J.F., Dutton, B., Ryan, P.D., 1997. Transpression in the Irish Caledonides and the Silurian evolution of basins, plutons, fabrics and cleavage sequences. Abstracts: Continental Transpressional and Transtensional Tectonics. Tectonic Studies Group Meeting London.
- Dewey, J.F., Strachan, R.A., 2003. Changing Silurian-Devonian relative plate motion in the Caledonides: sinistral transpression to sinistral transtension. *Journal of the Geological Society, London* 160, 219–229.
- Dong, H., Hall, C.M., Halliday, A.N., Peacor, D.R., Merriman, R.J., Roberts, B., 1997. $^{40}\text{Ar}/^{39}\text{Ar}$ illite dating of late Caledonian (Acadian) metamorphism and cooling of K-bentonites and slates from the Welsh Basin, U.K. *Earth and Planetary Science Letters* 150, 337–351.
- Edmonds, M. and Wallace, P., 2017. Volatiles and exsolved vapour in volcanic systems. *Elements* 13, 29-34.
- Farina, F., Dini, A., Innocenti, F., Rocchi, S., Weternan, D.S., 2010. Rapid incremental assembly of the Monte Capanne pluton (Elba Island, Tuscany) by downward stacking of magma sheets. *Geological Society of America Bulletin* 122, 1463-1479.
- Farina, F., Stevens, G., Villaros, A., 2012. Multi-batch, incremental assembly of a dynamic magma chamber: the case of the Peninsula pluton granite (Cape Granite Suite, South Africa). *Contributions to Mineralogy and Petrology* 106, 193-216.
- Flinn, D., 1977. Transcurrent faults and associated cataclasis in Shetland. *Journal of the Geological Society* 133, 231-248.
- Freeman, B., Klemperer, S.L., Hobbs, R.W., 1988. The deep structure of northern England and the Iapetus Suture zone from BIRPS deep seismic reflection profiles. *Journal of the Geological Society* 145, 727-740.
- Fritschle, T., Daly, J.S., Whitehouse, M.J., McConnell, B., Buhre, S., 2017. Multiple intrusive phases in the Leinster Batholith, Ireland: geochronology, isotope geochemistry and constraints on the deformation history. *Journal of the Geological Society*. Doi:10.1144/jgs2017-034.
- Glazner, A.F., 1991. Plutonism, oblique subduction, and continental growth: An example from the Mesozoic of California. *Geology* 19, 784-786.
- Glazner, A.F., Bartley, J.M., Coleman, D.S., Gray, W., Taylor, R.Z., 2004. Are plutons assembled over millions of years by amalgamation from small magma chambers? *GSA Today* 14, 4-11.

- Gray, W., Glazner, A.F., Coleman, D., Bartley, J., 2008. Long-term geochemical variability of the Late Cretaceous Tuolumne Intrusive Suite, central Sierra Nevada, California, in Annen, C., and Zellmer, G., eds., *Dynamics of crustal magma transfer, storage and differentiation*. Geological Society of London, Special Publication 304, 183-201.
- Halliday, A.N. 1984. Coupled Sm-Nd and U-Pb systematics in late Caledonian granites and the basement under Northern Britain. *Nature* 307, 229-233.
- Halliday, A.N., Stephens, W.E., Harmon, R.S., 1980. Rb-Sr and O isotopic relationships in 3 zoned Caledonian granitic plutons, Southern Uplands, Scotland: evidence for varied sources and hybridization of magmas. *Journal of the Geological Society* 137, 329–348.
- Harmon, R.S., Halliday, A.N., Clayburn, J.A., Stephens, W.E., 1984. Chemical and isotopic systematics of the Caledonian intrusions of Scotland and Northern England – A guide to magma source regions and magma-crust interactions. *Philosophical Transactions of the Royal Society of London, Series A* 310, 709-742.
- Hersum, T., Hilpert, M., Marsh, B., 2005. Permeability and melt flow in simulated and natural partially molten basaltic magmas. *Earth and Planetary Science Letters* 237, 798-814.
- Hughes, R.A., Evans, J.A., Noble, S.R., Rundle, C.C., 1996. U-Pb chronology of the Ennerdale and Eskdale intrusions supports sub-volcanic relationships with the Borrowdale Volcanic Group (Ordovician, English Lake District). *Journal of the Geological Society, London* 153, 33-38.
- Jackson, M.D., Cheadle, M.J., Atherton, M.P. 2003. Quantitative modelling of granitic melt generation and segregation in the continental crust. *Journal of Geophysical Research* 108, B7, 2332.
- Jackson, M.D., Gallagher, K., Petford, N., Cheadle, M.J., 2005. Towards a coupled physical and chemical model for tonolite-trondhjemite-granodiorite magma formation. *Lithos* 79, 43-60.
- Johnson, B.R., and Glazner, A.F., 2009. Formation of K-feldspar megacrysts in granodiorite plutons by thermal cycling and late-stage textural coarsening. *Contributions to Mineralogy and Petrology* 159, 599-619.
- Kimbell, G.S., Young, B., Millward, D., Crowley, Q.G., 2010. The North Pennine batholith (Weardale Granite) of northern England: new data on its age and form. *Proceedings of the Yorkshire Geological Society* 58, 107–128.
- Le Bas, M.J., 1982. The Caledonian granites and diorites of England and Wales. In *Igneous Rocks of the British Isles* (ed. D.S Sutherland), Wiley, Chichester, pp 191-201.

- Lee, M.K., 1986. A new gravity survey of the Lake District and three-dimensional model of the granite batholith. *Journal of the Geological Society, London* 143, 425-435.
- Lee, M.K., 1989. Upper crustal structure of the Lake District from modelling and image processing of potential field data. *British Geological Survey Technical Report, WK/89/1*.
- Lee, M.R., Waldron, K.A., Parsons, I., 1995. Exsolution and alteration microtextures in alkali feldspar phenocrysts from the Shap granite. *Mineralogical Magazine* 59, 63-78.
- Kelly, N.M., Hinton, R.W., Harley, S.L., Appleby, S.K., 2008. New SIMS U-Pb zircon ages from the Langavat Belt, South Harris, NW Scotland: implications for the Lewisian terrane model. *Journal of the Geological Society* 165, 967-981.
- Kemp, A.E.S., 1987. Tectonic development of the Southern Belt of the Southern Uplands accretionary complex. *Journal of the Geological Society, London* 144, 827-838.
- Leggett, J.K., McKerrow, W.S., Eales, M.H., 1979. The Southern Uplands of Scotland: A Lower Palaeozoic accretionary prism: *Journal of the Geological Society of London* 136, 755-770.
- Lipman, P.W., 2007. Incremental assembly and prolonged consolidation of Cordilleran magma chambers: Evidence from the Southern Rocky Mountain volcanic field. *Geosphere* 3, 42-70.
- Lissenberg, C.J., Rioux, M., Shimizu, N., Bowring, S.A., Mevel, C., 2009. Zircon dating of oceanic crustal accretion. *Science* 323, 1048-1050.
- Marsh, B.D., 1996. Solidification fronts and magmatic evolution: *Mineralogical Magazine* 60, 5-40.
- Marsh, B.D., 2006. Dynamics of magma chambers: *Elements* 2, 287-292.
- Matzel, J., Miller, J.S., Munil, R., Paterson, S.R., 2006. Zircon saturation and the growth of the Cathedral Peak pluton, CA. *Geochimica et Cosmochimica Acta* 70, A403.
- Merriman, R.J., Rex, D.C., Soper, N.J., Peacor, D., 1995. The age of Acadian cleavage in northern England, UK: K-Ar and TEM analysis of a Silurian metabentonite. *Proceedings of the Yorkshire Geological Society* 50, 255-265.
- Matzel, J., Miller, J.S., Munil, R., Paterson, S.R., 2006. Zircon saturation and the growth of the Cathedral Peak pluton, CA. *Geochimica et Cosmochimica Acta* 70, A403.
- McKerrow, W.S., Leggett, J.K., Eales, M.H., 1977. Imbricate thrust model of the Southern Uplands of Scotland. *Nature* 267, 237-239.
- McKerrow, W.S., MacNiocaill, C., Dewey, J.T., 2000. The Caledonian Orogeny redefined. *Journal of the Geological Society, London* 157, 1149-1154.

- McNulty, B.A., Tong, W., Tobisch, O.T., 1996. Assembly of dike-fed magma chamber; the Jackass Lakes pluton, central Sierra Nevada, California. *Geological Society of America Bulletin* 108, 926-940.
- Memeti, V., Paterson, S., Matzel, J., Mundil, R., Okaya, D., 2010. Magmatic lobes as “snapshots” of magma chamber growth and evolution in large, composite batholiths: an example from the Tuolumne intrusion, Sierra Nevada, California, *Geological Society of America Bulletin* 122, 1912-1931.
- Miles, A.J., 2012. Genesis of Zoned Granite Plutons in the Iapetus Suture Zone: New Constraints from High-precision Micro-analysis of Accessory Minerals (PhD thesis). University of Edinburgh.
- Miles, A.J., Graham, C.M., Hawkesworth, C.J., Gillespie, M.R., Hinton, R.W., EIMF, 2013, Evidence for distinct stages of magma history recorded by the compositions of accessory apatite and zircon: *Contributions to Mineralogy and Petrology* 166, 1-19.
- Miles, A., Graham, C., Hawkesworth, C., Gillespie, M., Dhuime, B., Hinton, R., 2014. Using zircon isotope compositions to constrain crustal structure and pluton evolution: the Iapetus Suture Zone granites in Northern Britain. *Journal of Petrology* 55, 181–207.
- Miles, A.J., Woodcock, N.H., Hawkesworth, C.J., 2016. Tectonic controls on post-subduction granite genesis and emplacement: The late Caledonian suite of Britain and Ireland. *Gondwana Research* 39, 250-260.
- Miller, C.F. and Miller, J.S., 2002. Contrasting stratified plutons exposed in tilt blocks, Eldorado Mountains, Colorado River rift, Nevada, USA. *Lithos* 61, 209-224.
- Miller, J.S., Matzel, J.E.P., Miller, C.F., Burgess, S.D., Miller, R.B., 2007. Zircon growth and recycling during the assembly of large, composite arc plutons. *Journal of Volcanology and Geothermal Research* 167, 282-299.
- Moore, J.G. and Sisson, T.W., 2008. Igneous phenocrystic origin of K-feldspar megacrysts in granite rocks from the Sierra Nevada batholith. *Geosphere* 4, 387-400.
- Nebel, O., Scherer, E.E., Mezger, K., 2011. Evaluation of the ^{87}Rb decay constant by age comparison against the U-Pb system. *Earth and Planetary Science Letters* 301, 1-8.
- Neilson, J.C., Kokelaar, B.P., Crowley, Q.G., 2009. Timing, relations and cause of plutonic and volcanic activity of the Siluro-Devonian post-collision magmatic episode in the Grampian Terrane, Scotland. *Journal of the Geological Society* 166, 545–561.
- O’Brien, C., Plant, J.A., Simpson, P.R., Tarney, J., 1985. The geochemistry, metasomatism and petrogenesis of the granites of the English Lake District. *Journal of the Geological Society of London* 142, 1139-1157.

- Oberli, F., Meier, M., Berger, A., Rosenberg, C.L., Giere, R., 2004. U-Th-Pb and $^{230}\text{Th}/^{238}\text{U}$ disequilibrium isotope systematics: Precise accessory mineral chronology and melt evolution tracing in the Alpine Bergell intrusion. *Geochimica et Cosmochimica Acta* 68, 2543-2560.
- 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. doi:10.1144/0016-76492007-105
- Paterson, S.R., 2009. Magma tubes, pipes, troughs, diapirs, and plumes: Late-stage convective instabilities resulting in compositional diversity and permeable networks in crystal-rich magmas of the Tuolumne batholith, Sierra Nevada, California. *Geosphere* 5, 496-527.
- Paterson, S.R., 2016. Repeated, multiscale, magmatic erosion and recycling in an upper-crustal pluton: Implications for magma chamber dynamics and magma volume estimates. *American Mineralogist* 101, 2176-2198.
- Petford, N., Cruden, A.R., McCaffrey, K.J.W., Vigneresse, J.L., 2000. Granite magma formation, transport and emplacement in the Earth's crust. *Nature* 408, 669-673.
- Petford, N. and Gallagher, K., 2001. Partial melting of mafic (amphibolitic) lower crust by periodic influx of basaltic magma. *Earth and Planetary Science Letters* 193, 483-489.
- Pidgeon, R.G., Aftalion, M., 1978. Cogenetic and inherited zircon U-Pb systems in granites of Scotland and England, in: Bowes, D.R., Leake, B.E. (Eds.), *Crustal Evolution in Northwestern Britain and Adjacent Regions*, Geological Journal, Special Issue. pp. 183–220.
- Pitcher, W.S. and Berger, A.R., 1972, *The Geology of Donegal: A Study of Granite Emplacement and unroofing: Regional Geology Series*: New York, Wiley-Interscience, 435 p.
- Piwinski, A.J., 1968. Experimental studies of igneous rock series, central Sierra Nevada Batholith, California. *Journal of Geology* 76, 1787-1804.
- Plail, M., Edmonds, M., Woods, A.W., Barclay, j., Humphries, M.C.S., Herd, R.A., Christopher, T., 2018. Mafic enclaves record syn-eruptive basalt intrusion and mixing. *Earth and Planetary Science Letters* 484, 30-40.
- Ramos, F.C. and Reid, M.R., 2005. Distinguishing melting of heterogeneous mantle sources from crustal contamination: Insights from Sr isotopes at the phenocryst scale, Pisgah Crater, California: *Journal of Petrology* 46, 999-1012.

- Rock, N.M.S., Gaskarth, J.W., Rundle, C.C., 1986. Late Caledonian dyke-swarms in Southern Scotland: a regional zone of primitive K-rich lamprophyres and associated vents. *Journal of Geology* 94, 505–522.
- Samperton, K.M., Schoene, B., Cottle, J.M., Keller, C.B., Crowley, J.L., Schmitz, M.D., 2015. Magma emplacement, differentiation and cooling in the middle crust: integrated zircon geochronological-geochemical constraints from the Bergell Intrusion, Central Alps. *Chemical Geology* 417, 322–340.
- Scaillet., B., Holtz, F., Pichavant, M., 1997. Rheological properties of granite magmas in their crystallisation range. In Bouchez, J.L., et al. (Ed.), *Granite: From Segregation of Melt to Emplacement Fabrics*. Kluwer Academic Publishers, Netherlands, 11–29.
- Scaillet., B., Holtz, F., Pichavant, M., 1998. Phase equilibrium constraints on the viscosity of silicic magmas. *Journal of Geophysical Research* 103 (B11), 27,257–27,266.
- Schaltegger, U., Brack, p., Ovtcharova, M., Peytcheva, I., Schoene, B., Stracke, A., Marocchi, M., Bargossi, G.M., 2009. Zircon and titanite recording 1.5 million years of magma accretion, crystallisation and initial cooling in a composite pluton (southern Adamello batholith, northern Italy). *Earth and Planetary Science Letters* 286, 208–218.
- Schoene, B., Schaltegger, U., Brack, P., Latkoczy, C., Stracke, A., Gunther, D., 2012. Rates of magma differentiation and emplacement in a ballooning pluton recorded by U–Pb TIMS–TEA, Adamello batholith, Italy. *Earth and Planetary Science Letters* 355, 162–173.
- Selby, D., Conliffe, J., Crowley, Q.G., Feely, M., 2008. Geochronology (Re–Os and U–Pb) and fluid inclusion studies of molybdenite mineralisation associated with the Shap, Skiddaw and Weardale granites, UK. *Applied Earth Science: Transactions of the Institutions of Mining and Metallurgy: Section B* 117, 11–28.
- Sherlock, S.C., Kelley, S.P., Zalasiewicz, J.A., Schofield, D.I., Evans, J.A., Merriman, R.J., Kemp, S.J., 2003. Precise dating of low-temperature deformation: Strain-fringe analysis by 40Ar–39Ar laser microprobe. *Geology* 31, 219–222.
- Sisson, T.W., Ratajeski, K., Hanks, W.B., Glazner, A.F., 2005. Voluminous granitic magmas from common basaltic sources. *Contributions to Mineralogy and Petrology*, 148, 635–661.
- Smith, R.A., 1995. The Siluro-Devonian evolution of the southern Midland Valley of Scotland. *Geological Magazine* 132, 503–513.
- Solano, J.M.S., Jackson, M.D., Sparks, R.S.J., Blundy, J.D., Annen, C., 2012. Melt segregation in Deep Crustal Hot Zones: a Mechanism for chemical differentiation, crustal assimilation and the formation of evolved magmas. *Journal of Petrology* 53, 1999–2026.

- Solano, J.M.S., Jackson, M.D., Sparks, R.S.J., Blundy, J.D., 2014. Evolution of major and trace element composition during melt migration through crystalline mush: Implications for chemical differentiation in the crust. *American Journal of Science* 314, 895-939.
- Soper, N.J., Webb, B.C., Woodcock, N.H., 1987. Late Caledonian (Acadian) transpression in north-west England: timing, geometry and geotectonic significance. *Proceedings of the Yorkshire Geological Society* 46, 175–192.
- Soper, N.J. and Kneller, C., 1990. Cleaved microgranite dykes of the Shap swarm in the Silurian of NW England. *Geological Journal* 25, 161-170.
- Soper, N.J., Woodcock, N.H., 2003. The lost Lower Old Red Sandstone of England and Wales: a record of post-Iapetan flexure or Early Devonian transtension? *Geological Magazine* 140, 627–647.
- Soper, N.J. and Roberts, D.E., 1971. Age of cleavage in the Skiddaw Slates in relation to the Skiddaw aureole. *Geological Magazine* 108, 293-302.
- Spencer, C.J., Kirkland, C.L., Taylor, R.M., 2016. Strategies towards statistically robust interpretations of in situ U-Pb zircon geochronology. *Geoscience Frontiers* 7, 581-589.
- Szymanowski, D., Wotzlaw, J., Ellis, B.S., Bachmann, O., Guillong, M., von Quadt, 2017. Protracted near-solidus storage and pre-eruptive rejuvenation of large magma reservoirs. *Nature Geoscience* 10, 777-784.
- Thirlwall, M.F., 1989, Movement on proposed terrane boundaries in northern Britain: constraints from Ordovician-Devonian igneous rocks. *Journal of the Geological Society of London* 146, 373-376.
- Vernon, R.H., Paterson, S.R., 2008. How late are K-feldspar megacrysts in granites? *Lithos* 104, 327-336.
- Vernon, R.H., 2010. Granites really are magmatic: using microstructural evidence to refute some obstinate hypotheses. In: Forster M.A., Fitz Gerald, J.D. (eds) *Journal of the Virtual Explorer* 35: 1.g
- Villa, I.M., 1998. Isotopic closure. *Terra Nova-Oxford* 10, 42-47.
- Villars, a., Stevens, G., Buick, I.S., 2009. Tracking S-type granite from source to emplacement: clues from garnet in the Cape Granite Suite. *Lithos* 112, 217-235.
- Wadge, A.J., Gale, N.H., Beckinsale, R.D., Rundle, C.C., 1978. A Rb-Sr isochron for the Shap granite. *Proceedings of the Yorkshire Geological Society* 42, 297–305.
- Watson, E.B. and Harrison, T., 1983. Zircon saturation revisited: temperature and composition effects in a variety of crustal magma types. *Earth and Planetary Science Letters* 64, 295-304.

- Watson, J.V., 1984. The ending of the Caledonian Orogeny in Scotland. *Journal of the Geological Society, London* 141, 193–214.
- Walker, B.A., Jr., Miller, C.F., Claiborne, L.E., Wooden, J.L., Miller, J.S., 2007. Geology and geochronology of the Spirit Mountain batholith, southern Nevada: Implications for timescales and physical processes of batholith construction: *Journal of Volcanology and Geothermal Research* 167, 239-262.
- Wendt, I., Carl, C., 1991. The statistical distribution of the mean squared weighted deviation. *Chemical Geology Isotopes Geoscience Section* 86, 275-285.
- Wiebe, R. 1996. Mafic-silicic layered intrusions: The role of basaltic injections on magmatic processes and the evolution of silicic magma chambers. *Royal Society of Edinburgh Transactions, Earth Sciences* 87, 233-242.
- Wiebe, R.A. and Collins, W.J., 1998. Deposition features and stratigraphic sections in granite plutons: Implications for the emplacement and crystallisation of granite magma. *Journal of Structural Geology* 20, 1273-1289.
- Wiedenbeck, M., Alle P., Corfu, F., Griffin, W.L., Meier, M., Oberli, F., von Quadt, A., Roddick, J.C., Spiegel, W. 1995. 3 natural zircon standards for U-Th-Pb, LU-Hf, trace element and REE analyses. *Geostandards Newsletter* 19, 1-23.
- Woodcock, N.H., 2012. Ordovician volcanism and sedimentation on Eastern Avalonia, in: Woodcock, N.H., Strachan, R.A. (Eds.), *Geological History of Britain and Ireland* (2nd Edn). Wiley-Blackwell, Chichester, pp. 162–176.
- Woodcock, N.H., Soper, N.J., 2006. The Acadian Orogeny: the mid-Devonian phase that formed slate belts in England and Wales, in: Brenchley, P., Rawson, P.F. (Eds.), *The Geology of England and Wales*. Geological Society of London, p. 131–146.
- Wotzlaw, J., Schaltegger, U., Frick, D.A., Dungan, M.A., Gerdes, A., Gunther, D., 2013. Tracking the evolution of large-volume silicic magma reservoirs from assembly to supereruption. *Geology* 41, 867-870.
- Žák, J. and Klomínský J., 2007. Magmatic structures in the Krokonoše-Jizera Plutonic Complex, Bohemian Massif: Evidence for localized multiphase flow and small-scale thermal-mechanical instabilities in a granitic magma chamber: *Journal of Volcanology and Geothermal Research* 164, 257-267.

Table 1: Zircon U-Pb ages

Pluton	Zone	Sample	U ppm wt	Th ppm wt	Pb ppm wt	Th/U atomic	²⁰⁴ Pb ppb wt	f ₂₀₆ (%)	²⁰⁴ Pb/ ²⁰⁶ Pb	Corrected			Age			ρ	²⁰⁷ Pb/ ²³⁵ U			²⁰⁷ Pb/ ²⁰⁶ Pb			% discord		
										²⁰⁷ Pb/ ²⁰⁶ Pb	1σ	²⁰⁸ Pb/ ²⁰⁶ Pb	1σ	²⁰⁷ Pb/ ²³⁵ U	1σ		²⁰⁶ Pb/ ²³⁸ U	1σ	²⁰⁶ Pb/ ²³⁸ U	1σ	1σ	1σ		1σ	
Shap	1	23_1c	1458	857	108	0.60	0.76	0.02	8.7E-06	0.0545	0.003	0.1895	0.005	0.5160	0.000	0.0687	0.007	0.89	428	4	422	4	390	2	10
		23_7c	524	614	43	1.20	6.77	0.42	2.3E-04	0.0542	0.004	0.3787	0.005	0.4946	0.002	0.0662	0.007	0.84	413	4	408	4	380	5	9
Quarry		23_5c	589	251	41	0.44	0.59	0.03	1.7E-05	0.0547	0.005	0.1399	0.009	0.5056	0.002	0.0670	0.007	0.75	418	4	416	5	400	1	5
		23_10c	764	659	59	0.88	0.95	0.04	2.1E-05	0.0551	0.004	0.2736	0.008	0.5117	0.005	0.0674	0.007	0.82	420	4	420	4	415	6	1
		23_8c	561	352	40	0.64	1.60	0.09	5.0E-05	0.0547	0.005	0.2017	0.009	0.4993	0.001	0.0662	0.007	0.74	413	4	411	5	398	2	4
		23_18c	1324	673	93	0.52	0.86	0.02	1.1E-05	0.0552	0.002	0.1644	0.004	0.5087	0.007	0.0669	0.007	0.92	417	4	418	4	419	0	0
		23_4c	585	654	47	1.15	6.98	0.39	2.1E-04	0.0546	0.005	0.3524	0.004	0.4908	0.002	0.0652	0.007	0.74	407	4	405	5	396	2	3
		23_01r	1934	1399	140	0.74	11.34	0.19	1.0E-04	0.0548	0.001	0.2354	0.006	0.4919	0.003	0.0651	0.008	0.98	406	5	406	4	405	6	0
		23_05r	998	767	75	0.79	4.20	0.14	7.3E-05	0.0549	0.003	0.2375	0.004	0.5019	0.005	0.0663	0.009	0.95	414	6	413	5	408	0	1
		23_08r	684	326	46	0.49	6.26	0.30	1.6E-04	0.0549	0.003	0.1338	0.009	0.4887	0.004	0.0646	0.008	0.92	403	5	404	4	407	1	-1
		23_07r	1209	540	84	0.46	0.49	0.01	7.0E-06	0.0545	0.002	0.1428	0.007	0.5016	0.007	0.0667	0.008	0.96	416	5	413	5	393	9	6
		23_18r	1224	567	84	0.48	3.77	0.10	5.4E-05	0.0544	0.002	0.1497	0.006	0.4968	0.004	0.0662	0.008	0.95	413	5	410	4	389	9	6
Shap	2	32_22c	1039	699	75	0.69	0.91	0.03	1.5E-05	0.0549	0.002	0.2211	0.003	0.4939	0.006	0.0652	0.008	0.96	407	5	408	4	409	8	0

Quarry	32_11c	109	448	74	0.4	1.00	0.03	1.6E-05	0.054	0.0	0.132	0.0	0.50	0.05	0.06	0.0	0.9	413	4	412	4	404	1	2
		2			2			0.05	8	0.0	8	3	04	6	62	7	1							
	32_14c	929	512	66	0.5	0.00	0.00	2.0E-08	0.055	0.0	0.176	0.0	0.50	0.05	0.06	0.0	0.9	416	4	415	4	410	9	1
					7			0.0	0	0.0	1	7	52	6	67	7	3							
	32_16c	112	730	81	0.6	7.75	0.22	1.2E-04	0.054	0.0	0.209	0.0	0.49	0.05	0.06	0.0	0.8	413	4	411	4	402	1	3
		1			7			0.0	8	0.0	5	7	92	7	61	7	9							
	32_21c	114	729	83	0.6	1.19	0.03	1.8E-05	0.054	0.0	0.204	0.0	0.50	0.05	0.06	0.0	0.9	414	4	413	4	406	1	2
Shap	22r	793	254	52	0.3	0.63	0.03	1.4E-05	0.054	0.0	0.102	0.0	0.49	0.06	0.06	0.0	0.9	409	5	406	4	387	8	6
					3			0.0	4	0.0	2	3	15	4	55	8	6							
	32_26r	129	644	91	0.5	4.59	0.11	6.1E-05	0.055	0.0	0.160	0.0	0.50	0.06	0.06	0.0	0.9	416	5	415	4	414	4	0
		7			1			0.0	0	0.0	1	8	3	55	1	66	8	9						
	32_3r	193	795	129	0.4	10.02	0.17	9.2E-05	0.054	0.0	0.131	0.0	0.49	0.06	0.06	0.0	0.9	407	5	407	4	405	9	1
		0			2			0.0	8	0.0	8	4	32	6	52	8	5							
	06_09c	220	231	18	1.0	0.54	0.08	4.2E-05	0.055	0.0	0.342	0.0	0.50	0.08	0.06	0.0	0.8	413	6	413	6	415	1	0
Lonfell Gill	26c	493	774	45	1.6	0.55	0.04	1.9E-05	0.054	0.0	0.509	0.0	0.51	0.07	0.06	0.0	0.9	426	6	421	5	395	2	8
					1			0.0	6	0.0	0	7	36	5	83	9	2							
	06_17c	665	195	44	0.3	1.56	0.08	4.1E-05	0.053	0.0	0.090	0.0	0.49	0.08	0.06	0.0	0.9	416	6	407	5	358	5	16
					0			0.0	7	0.0	5	5	38	0	67	0	1							
	06_54c	375	542	33	1.4	0.73	0.06	3.3E-05	0.054	0.0	0.467	0.0	0.50	0.08	0.06	0.0	0.9	423	6	418	5	392	5	8
					8			0.0	5	0.0	4	7	92	1	77	0	1							
	06_09r	133	631	94	0.4	0.85	0.02	1.1E-05	0.054	0.0	0.153	0.0	0.50	0.07	0.06	0.0	0.9	420	5	416	5	398	8	5
Shap	26r	149	789	108	0.5	0.34	0.01	3.9E-06	0.054	0.0	0.171	0.0	0.51	0.07	0.06	0.0	0.9	426	6	423	5	406	7	5
		1			4			0.0	9	0.0	5	9	61	1	82	9	7							
	06_17r	617	194	41	0.3	1.64	0.09	4.6E-05	0.054	0.0	0.099	0.0	0.49	0.08	0.06	0.0	0.9	412	6	410	6	397	7	4
					2			0.0	6	0.0	4	7	70	5	60	0	0							
	06_61r	100	348	67	0.3	1.47	0.05	2.6E-05	0.054	0.0	0.111	0.0	0.50	0.07	0.06	0.0	0.9	414	5	412	5	401	9	3
		5			6			0.0	7	0.0	2	2	6	05	1	63	9	6						
	25_3c	739	752	59	1.0	8.89	0.39	2.1E-04	0.053	0.0	0.323	0.0	0.49	0.06	0.06	0.0	0.8	416	4	409	4	368	1	13

Quarry	25_	423	554	36	1.3			2.7E-	0.054	0.0	0.414	0.08	0.50	0.06	0.06	0.0	0.8						1	
	5c				4	0.66	0.05	05	5	3	2	4	49	1	72	7	8	419	4	415	4	390	2	8
Enclave	25_	126			0.5			1.2E-	0.054	0.0	0.165	0.0	0.50	0.05	0.06	0.0	0.9						1	
	20c	4	649	89	3	0.90	0.02	05	7	3	5	8	26	6	67	7	1	416	4	413	4	398	0	5
	25_				0.3			2.7E-	0.054	0.0	0.121	0.0	0.49	0.07	0.06	0.0	0.7						2	
	28c	395	151	27	9	0.61	0.05	05	7	5	9	7	92	2	62	7	2	413	4	411	5	399	2	4
	25_	142			0.5			1.7E-	0.054	0.0	0.162	0.0	0.51	0.06	0.06	0.0	0.8						1	
	25c	8	723	102	2	0.14	0.00	06	6	3	7	5	30	1	81	7	6	425	4	420	4	397	4	7
	25_	113			0.6			4.6E-	0.055	0.0	0.195	0.0	0.51	0.05	0.06	0.0	0.9						8	0
	32c	5	692	83	3	0.30	0.01	06	2	2	0	8	41	5	75	7	5	421	4	421	4	421	8	0
	25_	114			0.6			5.9E-	0.055	0.0	0.195	0.0	0.50	0.05	0.06	0.0	0.9						1	
	38c	3	702	82	3	3.85	0.11	05	1	2	7	7	52	6	65	7	2	415	4	415	4	416	0	0
Shap	26_				0.7			2.6E-	0.054	0.0	0.224	0.02	0.50	0.06	0.06	0.0	0.8						1	
	2c	591	415	44	2	0.91	0.05	05	8	4	9	0	95	4	74	7	5	420	4	418	4	405	5	4
Quarry	26_	138	128		0.9			6.0E-	0.055	0.0	0.296	0.01	0.50	0.06	0.06	0.0	0.8						1	
	7c	3	5	109	5	4.86	0.11	05	0	3	8	1	94	0	72	7	9	419	4	418	4	411	2	2
Enclave	26_				0.8			2.3E-	0.054	0.0	0.255	0.01	0.50	0.06	0.06	0.0	0.7						1	
	8c	718	576	54	2	9.70	0.43	04	9	5	4	1	54	8	68	7	8	417	4	415	5	407	9	2
	26_		119		2.1			2.8E-	0.054	0.0	0.672	0.02	0.49	0.06	0.06	0.0	0.8						1	
	15c	562	3	56	8	9.13	0.52	04	1	4	8	3	58	2	65	7	3	415	4	409	4	375	6	11
	26_				0.4			2.9E-	0.054	0.0	0.135	0.0	0.50	0.05	0.06	0.0	0.9						1	
	26c	917	388	63	3	15.30	0.54	04	9	3	0	7	11	7	62	7	0	413	4	412	4	407	1	2
Red Crag	03_	612		51.	1.1			1.8E-	0.054	0.0	0.367	0.04	0.50	0.07	0.06	0.0	0.9						1	
	03c	.8	702	1	8	0.63	0.03	05	6	3	9	0	99	6	78	9	3	423	6	418	5	394	1	7
	03_	238		18.	1.0			5.2E-	0.054	0.0	0.320	0.01	0.48	0.08	0.06	0.0	0.7						2	
	09c	.3	237	4	2	0.69	0.10	05	5	6	7	7	73	8	49	9	8	405	6	403	6	390	6	4

c = Core

r = Rim

From Miles et al.,
2014 (*italics*)

From this
study

STANDA
RDS

Miles et
al., 2014

915				0.3			4.2E-	0.074	0.0	0.0	0.0	0.0	0.0	0.0	0.7		1				1		
00	81	28	15	5	0.52	0.08	05	7	6	2	5	50	8	91	0	9	1062	1	1062	9	1060	7	0
									0.0	0.0	0.0	0.0	0.0	0.0	0.0								
915				0.3			6.3E-	0.074	0.0	0.105	0.0	1.87	24	0.18	02	0.8		1			1		
00	80	27	15	5	0.80	0.12	05	5	6	0	7	59	9	27	0	2	1081	1	1073	9	1054	6	3
									0.0	0.0	0.0	0.0	0.0	0.0	0.0								
915				0.3			9.3E-	0.075	0.0	0.108	0.0	1.88	29	0.18	02	0.7		1		1	2		
00	81	28	15	5	0.12	0.02	06	5	8	5	8	75	2	13	1	3	1074	1	1077	0	1082	1	-1
									0.0	0.0	0.0	0.0	0.0	0.0	0.0								
915				0.3			3.1E-	0.074	0.0	0.106	0.0	1.84	28	0.18	02	0.7		1		1	2		
00	81	28	15	6	0.38	0.06	05	3	8	1	9	64	2	03	0	2	1068	1	1062	0	1049	1	2
									0.0	0.0	0.0	0.0	0.0	0.0	0.0								
915				0.3			2.0E-	0.075	0.0	0.106	0.1	1.84	27	0.17	01	0.7		1		1	2		
00	83	29	15	5	0.25	0.04	05	7	7	8	0	66	2	70	9	4	1051	1	1062	0	1085	0	-3
									0.0	0.0	0.0	0.0	0.0	0.0	0.0								
915				0.3			2.4E-	0.075	0.0	0.106	0.0	1.87	27	0.17	02	0.7		1		1	2		
00	84	29	16	6	0.31	0.04	05	9	8	8	9	75	7	94	0	4	1064	1	1073	0	1092	0	-3
									0.0	0.0	0.0	0.0	0.0	0.0	0.0								
915				0.3			4.5E-	0.073	0.0	0.105	0.1	1.83	26	0.18	01	0.7		1			2		
00	84	29	16	5	0.59	0.08	05	3	7	7	3	76	6	18	9	3	1077	0	1059	9	1022	0	5
									0.0	0.0	0.0	0.0	0.0	0.0	0.0								
915				0.3			7.0E-	0.073	0.0	0.107	0.1	1.85	31	0.18	02	0.6		1		1	2		
00	84	29	16	6	0.93	0.13	05	9	9	0	0	50	2	22	1	8	1079	1	1065	1	1037	5	4
									0.0	0.0	0.0	0.0	0.0	0.0	0.0								
915				0.3			8.5E-	0.076	0.0	0.106	0.0	1.88	28	0.17	01	0.7		1		1	2		
00	84	29	15	6	0.00	0.00	08	0	8	6	6	15	0	95	9	3	1064	1	1075	0	1096	0	-3
									0.0	0.0	0.0	0.0	0.0	0.0	0.0								
915				0.3			2.0E-	0.074	0.0	0.108	0.0	1.83	25	0.17	02	0.8		1			1		
00	83	29	15	6	0.26	0.04	05	4	6	1	5	76	2	91	0	0	1062	1	1059	9	1052	6	1
									0.0	0.0	0.0	0.0	0.0	0.0	0.0								
915				0.3			2.9E-	0.073	0.0	0.105	0.0	1.80	28	0.17	02	0.7		1		1	2		
00	81	28	15	6	0.36	0.05	05	6	8	1	8	21	9	75	0	1	1053	1	1046	0	1031	3	2
									0.0	0.0	0.0	0.0	0.0	0.0	0.0								
915				0.3			4.0E-	0.074	0.0	0.105	0.0	1.79	25	0.17	01	0.7		1			1		
00	80	27	14	5	0.48	0.07	05	4	7	3	8	21	8	46	9	7	1038	1	1043	9	1053	8	-1
									0.0	0.0	0.0	0.0	0.0	0.0	0.0								
915				0.3			2.9E-	0.074	0.0	0.105	0.1	1.75	25	0.17	01	0.7		1			1		
00	80	28	14	6	0.35	0.05	05	0	7	0	0	46	3	21	8	4	1023	0	1029	9	1040	9	-2
									0.0	0.0	0.0	0.0	0.0	0.0	0.0								
915				0.3			7.9E-	0.075	0.0	0.107	0.1	1.82	28	0.17	01	0.6		1		1	2		
00	80	28	14	6	0.00	0.00	08	1	9	8	4	80	5	64	9	7	1047	0	1056	0	1072	3	-2
									0.0	0.0	0.0	0.0	0.0	0.0	0.0								
915				0.3			8.0E-	0.075	0.0	0.108	0.0	1.85	27	0.17	02	0.7		1		1	1		
00	82	28	15	6	0.00	0.00	08	2	7	4	8	36	4	88	0	5	1061	1	1065	0	1073	9	-1
915				0.3			3.2E-	0.075	0.0	0.106	0.0	1.88	0.0	0.18	0.0	0.8		1			1		
00	80	28	15	6	0.40	0.06	05	2	00	7	00	42	24	18	01	1	1077	0	1076	9	1072	5	0

										8	6	0	0											
										0.0	0.0	0.0	0.0											
915				0.3			3.3E-	0.074	0.0	0.106	0.0	1.84	0.17	0.0	0.8		1				1			
00	82	28	15	5	0.42	0.06	05	4	5	6	7	28	1	97	9	6	1065	1	1061	8	1051	3		
										0.0	0.0	0.0	0.0	0.0										
915				0.3			1.1E-	0.073	0.0	0.104	0.0	1.74	0.17	0.1	0.6		1		1		2			
00	80	27	14	5	1.33	0.21	04	8	9	4	9	62	8	15	8	5	1020	0	1026	1	1037	5		
										0.0	0.0	0.0	0.0	0.0										
915				0.3			3.9E-	0.074	0.0	0.107	0.0	1.75	0.16	0.1	0.8		1				1			
00	81	28	14	5	0.46	0.07	05	7	6	4	9	00	4	98	8	0	1011	0	1027	9	1061	6		
										0.0	0.0	0.0	0.0	0.0										
915				0.3			1.2E-	0.073	0.0	0.105	0.0	1.77	0.17	0.2	0.8		1				1			
00	77	27	14	6	1.36	0.21	04	0	5	1	8	26	3	62	0	6	1046	1	1035	8	1012	3		
										0.0	0.0	0.0	0.0	0.0										
915				0.3			8.2E-	0.073	0.0	0.107	0.0	1.81	0.17	0.1	0.7		1				1			
00	78	27	14	6	0.99	0.15	05	7	7	3	9	19	5	82	9	6	1057	0	1050	9	1034	8		
										0.0	0.0	0.0	0.0	0.0										
915				0.3			3.1E-	0.074	0.0	0.106	0.0	1.83	0.17	0.1	0.7		1				1			
00	79	28	14	6	0.37	0.06	05	2	7	9	8	74	5	96	9	4	1065	0	1059	9	1047	8		
										0.0	0.0	0.0	0.0	0.0										
915				0.3			4.0E-	0.075	0.0	0.108	0.0	1.86	0.17	0.1	0.7		1				1			
00	80	28	15	6	0.50	0.07	05	3	7	5	7	30	2	95	9	4	1064	0	1068	9	1076	9		
										0.0	0.0	0.0	0.0	0.0										
915				0.3			3.1E-	0.075	0.0	0.106	0.0	1.86	0.18	0.2	0.8		1				1			
00	80	28	15	6	0.38	0.06	05	2	6	2	7	76	2	02	0	0	1068	1	1070	9	1072	7		
										0.0	0.0	0.0	0.0	0.0										
915				0.3			9.5E-	0.075	0.0	0.110	0.0	1.89	0.18	0.2	0.6		1		1		2			
00	81	28	15	6	0.12	0.02	06	3	9	1	9	20	2	22	1	8	1079	1	1078	1	1076	4		
										0.0	0.0	0.0	0.0	0.0										
915				0.3			2.0E-	0.075	0.0	0.109	0.1	1.86	0.18	0.2	0.7		1		1		1			
00	80	28	15	6	0.25	0.04	05	1	7	7	0	72	5	04	0	6	1069	1	1070	0	1070	9		
										0.0	0.0	0.0	0.0	0.0										
915				0.3			1.1E-	0.074	0.0	0.104	0.0	1.86	0.18	0.2	0.8		1				1			
00	79	28	15	6	1.35	0.20	04	2	6	9	8	41	0	22	0	3	1079	1	1068	9	1047	5		
										0.0	0.0	0.0	0.0	0.0										
915				0.3			2.2E-	0.074	0.0	0.108	0.0	1.86	0.18	0.2	0.7		1		1		1			
00	79	28	15	6	0.27	0.04	05	8	7	2	8	74	2	10	0	6	1072	1	1070	0	1063	9		
										0.0	0.0	0.0	0.0	0.0										
915				0.3			8.7E-	0.075	0.1	0.109	0.1	1.83	0.17	0.1	0.6		1		1		2			
00	80	28	15	6	0.00	0.00	08	4	0	4	0	17	7	63	9	6	1047	1	1057	1	1077	5		
										0.0	0.0	0.0	0.0	0.0										
915				0.3			9.4E-	0.075	0.0	0.110	0.0	1.89	0.18	0.2	0.7		1				1			
00	79	28	15	6	0.12	0.02	06	7	7	1	8	14	4	12	0	8	1074	1	1078	9	1087	7		
										0.0	0.0	0.0	0.0	0.0										
915				0.3			4.2E-	0.074	0.0	0.107	0.1	1.80	0.17	0.2	0.8		1				1			
00	77	27	14	6	0.50	0.08	05	0	6	2	0	75	6	71	0	3	1051	1	1048	9	1041	5		
915				0.3			5.1E-	0.075	0.0	0.108	0.0	1.86	0.18	0.0	0.8		1				1			
00	80	28	15	6	0.64	0.10	05	2	00	5	01	67	23	00	02	6	1067	1	1069	8	1074	3		
										0.0	0.0	0.0	0.0	0.0										

Highlights

- A combination of geochronological methods is used to reveal a more complex and protracted evolution than indicated by application of any single dating method.
- The majority of zircon crystallisation occurs at deeper crustal levels and prior to final magma emplacement.
- The combination of geochronology and field relations provides a valuable insight into the longevity of magmatic systems within the crust.
- Final granite emplacement can only be indicated by the youngest zircon ages.

Figure 1

Figure 2

Figure 3

Stage I granite (AM0923)

Stage II granite (AM0932)

50 μ m

Figure 4

Figure 5

Figure 6

b)

	Bi	IIMg	Kfs	Kfs	Pl	Qtz	Ttn
Bi	14.9	1.7	9.8	0	10.9	6.3	1.1
IIMg		0	1.7	0	0.6	0.6	0
Kfs			4.0	0	10.3	11.5	2.9
Kfs				4.0	0	0	0.6
Pl					8.0	5.7	1.1
Qtz						2.9	0
Ttn							0.6

35.1% zircon grains as inclusions (diagonal cells)
 64.9% zircons in inter-grain sites (off-diagonal cells)

Figure 7

Figure 8