Age of the Acadian deformation and Devonian granites in northern England: a review

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Abstract: Field evidence shows that emplacement of Devonian granites in northern England overlaps in space and time with the end of the supposed Acadian deformation in their country rocks. The age of this Acadian event in England and Wales is in need of review because of revised Rb-Sr and K-Ar decay constants and recently acquired radiometric ages on the granites.

Published K-Ar and Ar-Ar cleavage ages recalculated to the new decay constants range from 404 to 394 Ma (Emsian, Early Devonian). Emplacement of the Skiddaw and Weardale granites at 398.8 ± 0.4 and 399.3 ± 0.7 Ma respectively is indicated by U-Pb zircon ages, and is compatible with the field evidence. However, emplacement of the Shap Granite at a Re-Os molybdenite age of 405.2 ± 1.8 Ma and at the youngest U-Pb zircon age of 403 ± 8 Ma matches the field evidence less well. The apparent paradox in these ages is resolved if the K-Ar ages record only the end of millions of years of cleavage formation. An earlier cluster of K-Ar and Ar-Ar cleavage ages at 426–420 Ma (Ludlow to Pridoli, late Silurian) dates a pre-Acadian resetting event soon after Iapetus closure, an event of uncertain significance.

Ion microprobe U-Pb zircon ages for the Shap Granite have a mean of 415.6 ± 1.4 Ma but a range of 428–403 Ma, compatible with a long magmatic history. Thermal considerations suggest that this history was not at the upper crustal emplacement site but in a mid-crustal mush zone, now preserved at about 10 km depth as a component of the Lake District and North Pennine batholiths.

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The Lower Palaeozoic rocks of northern England and Wales were mainly deformed by folds and cleavage assigned to the Acadian phase of the Caledonian Orogeny (Soper et al. 1987; McKerrow et al. 2000). When first applied in Britain, this name implied a time correlation with the type Acadian event of Devonian age in the northern Appalachians (van Staal et al. 1998). The age of the Acadian event in England and Wales has been constrained by a mid-Emsian to Givetian (Devonian) unconformity, by radiometric dating of cleavage-parallel micas, and by radiometric ages of granites shown to be emplaced during the later stages of deformation (reviews by Woodcock & Soper 2006; Woodcock et al. 2007; Woodcock 2012). An age range of 400–390 Ma (mid-Emsian to mid-Eifelian, Devonian) for the Acadian deformation event has been considered to fit the integrated evidence best.

Now, four developments prompt a revision of the Acadian age estimate.

1. Revised decay constants for the K-Ar and Rb-Sr systems require recalculation of existing cleavage ages and some granite ages.
2. Further radiometric ages on the Shap, Skiddaw and Weardale granites have become available.
3. Some of the recently acquired U-Pb ages on magmatic zircons in the Shap Granite pre-date the estimated age of its upper-crustal emplacement.
4. A pre-Devonian component to the main cleavage in northern England and Wales needs consideration in the light of late Silurian ages from the main cleavage in the English Midlands.

Dating the Acadian deformation in Britain and Ireland is also important in the light of continued attempts to correlate tectonic terranes between the Appalachians and the Caledonides. For instance, Waldron et al. (2014) have used detrital zircon ages to strengthen the correlation between the Leinster–Lakesman terrane and the Ganderia terrane in the Appalachians (Fig. 1b). Fritschle et al. (2018) have proposed a late Middle Ordovician rather than a Devonian age for the D1 cleavage in SE Ireland and the Isle of Man and, by implication, elsewhere in the Caledonian sector of Ganderia. Further SE, Waldron et al. (2011) and Pothier et al. (2015) have used detrital zircon dating to match components of the Avalon terrane of England and Wales with the Meguma terrane of Nova Scotia (Fig. 1b).

Despite these proposed long-range terrane correlations, all four of the above studies have recognized that the correlations are imperfect and require marked non-cylindricity in the terrane organization along the Appalachian–Caledonian orogen. Since the export of the term ‘Acadian’ from the Appalachians to the Caledonides, it has also become evident that Acadian events in the two sectors may correlate poorly both in time and by formation mechanism. So Woodcock et al. (2007) attributed the Acadian deformation in the Caledonides to collision of Iberia/Armorica with Avalonia at about 400–390 Ma. By contrast the Acadian event in the Appalachians is now ascribed to accretion of Avalonia to Ganderia at about 420–400 Ma (Fig. 1b), followed by a Neoacadian event due to accretion of Meguma with Ganderia at 395–350 Ma (van Staal et al. 2009; Wilson et al. 2017).
It is important to stress therefore that references in this paper to the Acadian event and its age apply to the England and Wales sector of the orogeny only unless otherwise specified. Correlation with other parts of the Caledonides will be discussed at the end of the paper, but better correlation with the Appalachians will not be attempted.

Regional geological setting

The pre-Upper Devonian geological context of northern England is shown in Figure 1a. This area is bisected by the Iapetus Suture, which separates terranes with Laurentian affinity to the NW from those to the SE derived from Gondwana. The intervening Iapetus Ocean closed in mid-to-late Silurian time. Bordering the suture on the Laurentian side is the Central–Southern Uplands terrane, mainly Lower Palaeozoic sedimentary rocks that formed a deep marine accretionary complex above the NW dipping Iapetus subduction zone (Leggett et al. 1979). On the Gondwanan side of the suture is the Leinster–Lakesman terrane, comprising Lower Palaeozoic sedimentary sequences that include Ordovician magmatic arc rocks. This terrane has been correlated with the Appalachian Ganderia domain (e.g. Waldron et al. 2014; Fritschle et al. 2018), as has the adjacent Monian composite terrane, which contains also Neoproterozoic basement rocks. Whether the Monian terrane continues eastward beneath the Upper Palaeozoic cover of northern England or wedges out in that direction is uncertain (Fig. 1a).

To the SE of the Monian terrane is the Avalon composite terrane, amalgamated with the Monian terrane in early Ordovician (Floian) time. On Avalonia, Cambrian to Lower

Fig. 1. (a) Geology of the Iapetus Suture zone, showing the Devonian granites of northern England in the context of the other Trans-Suture Suite granites. Most boundaries from British Geological Survey (1996); subsurface granite contours from Kimbell et al. (2010). (b) Palaeocontinental setting of map 1(a) showing the main Appalachian and Caledonian tectonics domains; modified from Waldron et al. (2014).
Devonian sedimentary rocks with Ordovician volcanic rocks rest on a Neoproterozoic basement. Detrital zircon and stratigraphic correlations have suggested to Waldron et al. (2011) that the Cambrian sequences in North Wales match those in the Meguma terrane of Nova Scotia. On this hypothesis, Megumia and Avalonia were also amalgamated by early Ordovician (Floian) time.

The Acadian deformation of Devonian (Emsian–Eifelian) age is recognized in the terranes SE of the Iapetus Suture (reviews by Woodcock & Soper 2006; Woodcock 2012). The deformation is dominated by upright folds trending between NE–SW and east–west, with a steep slaty cleavage that is axial planar or weakly clockwise-transsecting to the folds (Soper et al. 1987; review by Woodcock & Soper 2006). The main Acadian deformation is sporadically affected by a later, gently dipping crenulation cleavage and related folds, particularly in the Isle of Man and the northern part of the Lake District. The Acadian deformation can be traced into Ireland, but the deformation history there is complicated by recognition of a late Middle Ordovician event of uncertain extent (Fritschle et al. 2018). The Laurentian margin accretionary complex (the Scottish Southern Uplands terrane and the Central terrane in Ireland) was formed diachronously from late Ordovician to Wenlock time, although localized Devonian (possibly Acadian) deformation occurs on the Moniaive shear zone (review by Stone et al. 2012).

Granites of the Trans-Suture Suite were intruded in a zone about 100 km wide either side of the Iapetus suture (Fig. 1a) about 20 myr after Iapetus had closed (Brown et al. 2008). The debate about this spatial and temporal pattern has been summarized by Miles et al. (2016), who favoured an origin by crustal melting above a zone of delaminated lithosphere due to drop-off of the subducting Iapetus slab.

The field relations around an idealised Trans-Suture pluton are shown schematically in Figure 4. Key relations for most individual plutons are summarized by Brown et al. (2008) and for the Southern Uplands terrane by Hines et al. (2018), and are not repeated here. Rather, the main pluton attributes are discussed below with particular reference to the northern England examples. It must be emphasized that, of these examples, only the Shap and Skiddaw plutons are exposed at outcrop. The Ulpha and Crummock Water plutons are inferred from their exposed metasomatic aureoles. The plutons above the North Pennine batholith are known from gravity modelling and from two boreholes. Their original contact relations are not preserved because the plutons were partly unroofed during the post-Acadian uplift and were unconformably overlain by Carboniferous rocks.

Pluton size varies for the whole Trans-Suture suite with long-axis diameters of 1–75 km (Fig. 5a) and maybe up to 150 km for the unexposed Tweeddale pluton. The northern England plutons span the middle part of this size range, with Shap, Skiddaw and the smaller North Pennine plutons at the lower (3–12 km) end, and Weardale pluton in the mid-range (20–30 km).

Pluton shape is typically ovoid, with an axial ratio mostly in the range 1.5–2.5 (Fig. 5a). The northern England plutons follow this pattern, except for the highly ovoid (5:1) Crummock Water aureole.

Pluton orientation is shown in a rose diagram, scaled by the length of the pluton. The poorly known Tweeddale pluton is omitted (Fig. 5b). The long axis of each pluton tends to be sub-parallel to the regional strike of bedding and cleavage, where this can be determined. The Skiddaw pluton, along with the Crummock and Ulpha aureoles, is elongated along strike, but the long axis of the Shap pluton is clockwise.
oblique by 35° (Fig. 3). The strike-parallel geometry reflects emplacement into already folded and therefore anisotropic rocks, but some post-emplacement flattening is evident.

Internal foliation is seen in some plutons only. Where present, it parallels the pluton margin. It tends to be strongest at the margin and to weaken inwards, as well documented in the Rookhope borehole into the Weardale Granite (Dunham et al. 1965). This mica fabric is likely to be deformational, but the Shap Granite locally has a weak magmatic alignment of the pink K-feldspar phenocrysts that are such a distinctive feature of the pluton. The Skiddaw pluton has a marginal sheeting and mica-foliated greisen pods.

Xenoliths are only reported in a few Trans-Suture plutons, where they tend to parallel any magmatic foliation in the granite. At Shap, sparse xenoliths can carry the S₁ cleavage, disoriented with respect to country rocks (Soper & Kneller 1990), proving that a component of the cleavage pre-dated formation of part of the pluton. More common than xenoliths in some plutons are ovoid mafic enclaves (Fig. 6a), representing inclusions of coeval mafic melt that did not fully mix with the granitic magma. In the Shap pluton, these mafic enclaves are particularly common. The mafic melts entrained early-formed K-feldspar phenocrysts, proving that mafic and silicic melts co-existed.

Country rock fabric, comprising steep bedding and the S₁ cleavage, tends to be locally truncated, particularly at the NE and SW ends of each pluton (Fig. 6b), but elsewhere it is deflected to become parallel with and wrap the pluton (Fig. 3). This geometry is well seen at Shap (Fig. 3), where emplacement must be later than the folding of bedding to steep dips and formation of some component of the steep cleavage. However, shortening must have continued for the bedding and cleavage fabrics to wrap around the consolidating pluton. At Skiddaw, contact relations are only well

**Fig. 2.** Geological map of northern England showing the outcrop geology and main faults (modified from British Geological Survey 1996) overlain on thickness contours of subsurface granite (from Kimbell et al. 2010). Location of map shown on Figure 1.
exposed at the northern margin of the pluton. However, the Acadian cleavage did not develop here because the country rocks had previously been hornfelsed by the Ordovician emplacement of the Carrock Fell intrusive complex.

Apophyses to the pluton and cogenetic dykes may transect (Fig. 6c) or follow the composite bedding/cleavage fabric, showing that their intrusion post-dated some component of the Acadian deformation. However, some co-genetic dykes at Shap bear a weak cleavage in their margins (Soper & Kneller 1990) (Fig. 6f), showing that their intrusion pre-dated a component of the shortening. Aplite veins in the Weardale granite have a muscovite alignment of uncertain, but possibly deformational, origin (Dunham et al. 1965).

A metamorphic aureole is present around most Trans-Suture plutons. To the NW of the suture, the S1 fabric predates mineral growth in the aureoles. In northern England, the S1 cleavage, inferred to be Acadian, predates the metasomatic aureoles at Crummock and Ulpha. At Shap, micas overgrow this cleavage, first mimetically then randomly (Boulter & Soper 1973), and calcareous siltstones are randomly recrystallized (Soper & Kneller 1990) (Fig. 6e). At Skiddaw, andalusite porphyroblasts in the aureole

Fig. 3. Geological map of the area around the Shap pluton. Location marked on Figure 2. Based on British Geological Survey (2004, 2007), with granite thickness contours from Kimbell et al. (2010)

Fig. 4. Schematic map of the field relations in and around a typical Trans-Suture Suite pluton.
mostly post-date S1 (Fig. 6d), but porphyroblasts in the inner aureole zones are partly wrapped by the continuing development of the deformation fabric (Soper & Roberts 1971). The aureole minerals pre-date the sub-horizontal S2 crenulation cleavage.

In summary, the evidence from the exposed Trans-Suture plutons of northern England indicates that the plutons were emplaced during the later stages of Acadian S1 cleavage formation (Brown et al. 2008), but before that shortening deformation had ended completely. Consequently, radiometric ages from the granites are an important factor in constraining the age of the Acadian deformation event, for which radiometric ages are limited.

**Dating Acadian deformation**

**Stratigraphic constraints on the age of the Acadian deformation**

Soper et al. (1987) assembled the evidence that the angular unconformity marking syn- and post-Acadian uplift across England, Wales and Ireland is intra-Devonian rather than end-Silurian. The stratigraphic constraints on this unconformity are summarized on Figure 7.

The Acadian deformation is most intense in the former Lower Palaeozoic basinal rocks across Wales and throughout the Leinster–Lakesman terrane. Here, Mid-Devonian or later sedimentary units unconformably overlie folded and cleaved marine Cambrian to Silurian or Lower Devonian rocks. In northern England, the unconformity spans all of Early to Mid Devonian time, although the metamorphic grade below the unconformity implies a missing Lower Devonian cover at least 3.5 km thick (Soper & Woodcock 2003). The Midland Platform in SE Wales escaped intense Acadian deformation, but still preserves a gentle angular unconformity spanning at least intra-Emsian through Frasnian time, at most 395–372 Ma (Fig. 7). Unconformities in the Dingle area of SW Ireland may constrain the Acadian deformation more tightly, perhaps to at most mid-Emsian through Eifelian time (400–388 Ma, Fig. 7), but the ages and relationships of crucial units are debated (Richmond & Williams 2000; Meere & Mulchrone 2006; Todd 2015).

An unconformity that potentially includes the Acadian event also exists beneath East Anglia (Woodcock & Pharaoh 1993), but here it spans the whole of Early and Mid-Devonian time (419–383 Ma).

**Radiometric ages: presentation and decay constants**

The sections that follow review radiometric age determinations from the Trans-Suture granites and from their cleaved country rocks, both regionally then locally to northern England. Regionally aggregated ages for the relevant magmatic and tectonic events are shown as probability distribution functions (Fig. 8), mostly those of Miles et al. (2016), who detail their sources and derivation method.

There is ongoing discussion of the appropriate decay constants to be used for both the Rb-Sr and K-Ar/Ar-Ar dating methods. We have used revised constants for the main age spectra, but have shown the unadjusted spectra outlined by pecked lines for comparison (Fig. 8). The K-Ar ages that use the constant of $5.543 \times 10^{-10} \text{a}^{-1}$ (Steiger & Jäger 1977) have been adjusted upwards by the 1% suggested by Dickin (2005, pp. 275–276) and supported by comparisons with zircon U-Pb ages (Jourdan et al. 2009; Naumenko-Dezès et al. 2018). Rb-Sr ages have been adjusted upwards by 1.9% corresponding to a lowered decay constant of $1.393 \times 10^{-11}$ (Nebel et al. 2011). These adjustments are significant at the level of age resolution attempted in this paper.

**Radiometric age of the Acadian cleavage**

Merriman et al. (1995) have directly determined the radiometric age of the northern England cleavage from cleavage-parallel illite/mica in the Ribblesdale Inlier. These minerals gave a K-Ar age of 401 ± 7 Ma and an Ar-Ar total fusion age of 422 ± 3 Ma, both ages adjusted upwards by 1% (Fig. 8b). Merriman et al. (1995) concluded that these two ages bracketed the possible period of Acadian cleavage formation.
Fig. 6. Annotated field photographs, each with 5 cm scale bar. (a) Mafic enclave in K-spar porphyritic granite, Shap Pink Quarry [NY 558 084]. (b) Shap pluton truncating cleaved Borrowdale Volcanic Group country rock, Longfell Gill [NY 561 101]. (c) Granite vein cutting cleaved Borrowdale Volcanic Group country rock, Longfell Gill [NY 561 101]. (d) Randomly oriented andalusite in hornfelsed Skiddaw Group aureole to Skiddaw granite, Caldew Valley, Skiddaw [NY 320 320]. (e) Hornfelsed aureole to Shap Granite overprinting cleavage in Coldwell Formation, Packhorse Hill [NY 553 075]. (f) Parkamoor dyke with marginal foliation parallel to Acadian cleavage in country rock, Low Parkamoor [SD 305 924]. (g) Contact of Stage II granite against a phenocryst-poor schlieren zone of Stage I granite, Shap Pink Quarry [NY 558 084]. (h) Contact as (g) but with a vein of Stage II granite into the schlieren zone, seen in kerbstone in Settle (Yorkshire).
However, the same two age peaks occur (Fig. 8b) in Ar-Ar ages from five localities in Wales (Dong et al. 1997) suggesting that both age peaks have some discrete significance. The younger peak, at about 400 Ma (mid-Emsian, Early Devonian) is seen also in two other Welsh datasets: the K-Ar ages of Evans (1996) and the Ar-Ar ages of Sherlock et al. (2003). All authors agreed that the c. 400 Ma ages probably record the culmination of Acadian shortening.

The older peak at about 422 Ma (Prídolí, latest Silurian) is more problematic. Evans (1996) correctly pointed out that these ages substantially predate the time of maximum burial, which probably occurred after deposition of some kilometres of Lower Devonian rocks (Soper & Woodcock 2003). Dong et al. (1997) saw these Prídolí ages as the beginning of Acadian shortening and metamorphism, but both Evans (1996) and Merriman et al. (1995) suggested instead that the ages record the prograde transition from smectite to illite during burial. These early ages closely match the main 423 Ma peak of Ar-Ar ages (Fig. 8a) from the NW–SE-striking cleavage in the Charnwood inlier of the East Midlands (Carney et al. 2008). The latter authors linked the late Silurian ages to a pre-Acadian shortening event that was due to Iapetus closure, an event recognized as the Brabantian deformation in Belgium (Debacker et al. 2005).

Here we regard the 405–395 Ma peak as the best age estimate for the closure of the K-Ar system in cleavage-parallel illites or white micas as their host rocks were uplifted and cooled late in the Acadian shortening. It will be argued later that this shortening probably started earlier than 405 Ma, but not as early as 422 Ma. The cluster of earlier ages must mark a separate tectonothermal event, immediately after the soft closure of the UK sector of the Iapetus Ocean. It is unlikely that a strong component of the cleavage in northern England or Wales formed then, however, as there is no evidence for a two-stage history for the Acadian fabric.

The main slaty cleavage-forming deformation (D1) SE of the Iapetus Suture is sporadically affected by a later (D2), gently dipping crenulation cleavage and related folds, particularly in the Isle of Man and the northern part of the Lake District. This event has not been radiometrically dated.

**Dating Siluro-Devonian magmatism**

**Regional spectra of Trans-Siture granite ages**

Before focusing on the Devonian granites of northern England, it is helpful to review ages across the Trans-Suture suite as a whole (Fig. 8). Available ages for the granites and related lamprophyre dykes are shown as probability distribution functions on Figure 8c–g (from Miles et al. 2016 with added ages from Miles & Woodcock 2018 and Hines et al. 2018). To compensate for the different sizes of the plutons, the granite data have been weighted by the outcrop area of each pluton (or by the subsurface area for the North Pennine batholith). The coloured Rb-Sr and K-Ar distributions have been adjusted upwards by 1.9% and 1% respectively, in line with the revised decay constants discussed above. The unadjusted curves are also shown as pecked lines.
The U-Pb zircon ages for the granites have peaks between 414 and 399 Ma (Fig. 8g). Only the later half of this magmatic range overlaps with the Acadian shortening peak based on adjusted K-Ar cleavage ages (405–395 Ma).

Compared with the U-Pb ages, more of the Rb-Sr ages for the granites (Fig. 8f) are from older analytical studies, where doubts about reliability arise because of less sophisticated methods and higher analytical errors. However, the adjusted age spectrum is compatible with that from U-Pb ages, with similar peaks at 405 and 399 Ma, but with an even greater proportion of the ages pre-dating the Acadian event. By contrast, aggregated K-Ar ages from the granites are younger than ages from the other two methods, even after 1% adjustment (Fig. 8e). These ages might record the very end of granite cooling, resetting late in the Acadian event, or merely an unreliability of K-Ar ages in granite biotite.

Fig. 8. Probability distribution functions of radiometric ages from the Trans-Suture granites and related lamprophyre dykes and country rocks. Dashed curves are the unadjusted spectra for Rb-Sr and K-Ar ages. Curves a–c and f are from Miles et al. (2016), where data sources are specified. Curve (g) however incorporates new ages from Newry (Anderson 2015), Doon (Hines et al. 2018) and from Shap (Miles & Woodcock 2018). Curve (d) uses data from Hines et al. (2018) and curve (e) from Kulp et al. (1960); Brown et al. (1964, 1968); Shepherd et al. (1976) and Rundle (1982).

Fig. 9. Plots of radiometric age against closure temperature for the late Caledonian granites of northern England. Each data point is annotated with its source: Al87, Al Jawadi (1987); Co88, Cooper et al. (1988); Da05, Davidson et al. (2005); Ho70, Holland & Lambert (1970); Ki10, Kimbell et al. (2010); Mi18, Miles & Woodcock (2018); Pt78, Pidgeon & Aftalion (1978); Ru82, Rundle (1982); Ru87, Rundle (1987); Ru92, Rundle (1992); Se08, Selby et al. (2008); Sh76, Shepherd et al. (1976); Sh81, Shepherd & Darbyshire (1981); Wa78, Wadge et al. (1978).
The remaining probability distribution functions are for K-Ar biotite ages (Fig. 8c) and U-Pb zircon ages (Fig. 8d) in the suite of lamprophyre dykes that intrude much of the Trans-Suture zone. The field and petrological evidence, reviewed by Brown et al. (2008), suggests that these dykes are coeval with the Trans-Suture granites, probably representing the more mafic mantle melts that triggered the crustal melts for the granitic magmatism. This genetic link is supported by the similarity of the lamprophyre and granite age ranges. Miles et al. (2016) explain the lack of Acadian resetting of the lamprophyre K-Ar ages by the low Ar diffusion rates in Mg-rich biotite.

In summary then, the age spectra from both the granites and related lamprophyres suggest that magmatism first preceded then overlapped with the Acadian deformation peak. This result conflicts with the field evidence to be discussed below, which shows rather that most plutons were emplaced late in the Acadian deformation history. Two explanations will be developed later in this paper: (1) that Acadian deformation began some millions of years before the date recorded by the closure of the K-Ar system in the cleavage-parallel illite/mica; and (2) that some early zircon ages from granites are dating crystallisation in a mid-crustal mush zone, millions of years before upper crustal emplacement of that granite.

Detailed age analysis of the northern England Trans-Suture granites

This section looks in more detail at the available ages for the northern England plutons of the Trans-Suture suite. Because these ages derive from a range of isotopic systems, they have been plotted against the approximate closure temperature for the system concerned (Fig. 9). On these plots, error bars are given both for the age determination and for the closure temperature, using the estimates compiled by Dickin (2005). The plots contain relevant radiometric age determinations published since 1970, but caution must be exercised in interpreting ages from older studies, where analytical techniques were less sophisticated and less accurate.

Radiometric ages are available from two exposed plutons (Shap and Skiddaw), from a subsurface pluton (Weardale) and from the aureole of an inferred pluton (Crummock Water). There are no ages from the Ulpha pluton or the possible Haweswater pluton. The best estimate of emplacement age for each pluton, discussed below, is shown on the summary diagram (Fig. 7) and ranges from 408 to 399 Ma. It will be argued later that cooling and final solidification of most of the upper crustal plutons took place in less than a million years. Therefore, this age range shows that each pluton results from a discrete emplacement event rather than from a synchronous event across the whole of northern England.

The evidence for the emplacement age of each dated pluton is now reviewed.

The buried Weardale pluton has a U-Pb zircon age (isotope dilution thermal ionization mass spectrometry; ID-TIMS) of 399.3 ± 0.7 Ma (Kimbell et al. 2010). This age is within error of a Re-Os age of 398.3 ± 1.6 Ma on molybdenite in a hydrothermal quartz vein (Selby et al. 2008) that must post-date granite emplacement. An Rb-Sr whole rock age from an aplite vein of 397 ± 8 Ma (1.9% adjusted from Holland & Lambert 1970) is compatible with the U-Pb and Re-Os ages. An Rb-Sr age of 418 ± 10 Ma from the main granite published by the same authors might seem anomalously old were it not for the growing evidence from the Shap granite that the northern England magmas had a long pre-emplacement history in the mid-crust. We agree with Kimbell et al. (2010) that the U-Pb age of 399.3 ± 0.7 Ma is the best estimate of the emplacement age of the Weardale pluton.

The Skiddaw pluton had a very similar emplacement age to the Weardale pluton, based on a U-Pb ID-TIMS age on zircon of 398.8 ± 0.4 Ma (Selby et al. 2008) (Fig. 9b). The zircons picked for their analysis were small acicular grains that probably grew late in the magmatic history. Within error of the U-Pb age is an adjusted Rb-Sr age of 406 ± 8 Ma on granite K-feldspar (Rundle 1982) and adjusted K-Ar ages on granite biotite and muscovite of 396 ± 4 and 398 ± 8 Ma respectively (Shepherd et al. 1976; Rundle 1982). An adjusted Rb-Sr whole-rock age of 390 ± 4 Ma is anomalously young (Rundle 1982). Hydrothermal quartz veins that cross-cut granite and country rock give a significantly younger Re-Os age on molybdenite of 392 ± 3 Ma (Selby et al. 2008). This age is compatible with an Rb-Sr age on vein quartz fluid inclusions of 399 ± 5 Ma (Shepherd & Darbyshire 2001) and with a K-Ar age of 391 ± 2 Ma on muscovite in greisen marginal to the granite (Rundle 1982).

The Shap pluton has a more complex radiometric age record than the Weardale and Skiddaw plutons. The best direct estimate of its emplacement age is the Re-Os age on disseminated molybdenite of 405.2 ± 1.8 Ma (Selby et al. 2008) (Fig. 9c). An Rb-Sr whole-rock age of 402 ± 3 Ma (Wadge et al. 1978) and a K-Ar age on granite biotite of 401 ± 7 Ma (Rundle 1992) are both compatible with this emplacement age when recalculated to new decay constants. Nearly compatible are averaged Rb-Sr whole-rock ages on the comagmatic Devonian minor intrusive suite around Shap (Al Jawadi 1987; Rundle 1987), recalculated at 400 ± 3 Ma, but an early U-Pb zircon age of 390 ± 7 Ma (Pidgeon & Aftalion 1978) seems anomalously young. Also within the main granite, a more modern Rb-Sr age (Davidson et al. 2005) on the conspicuous K-feldspar phenocrys, recalculated at 413 ± 2 Ma, suggests that these grains started to grow up to 10 million years before the pluton was emplaced in the upper crust. This hypothesis is supported by U-Pb ages on single zircon grains analysed by ion microprobe (Miles et al. 2016; Miles & Woodcock 2018). These grains have a mean age of 415.6 ± 1.4 Ma and individual ages ranging from 428 ± 8 Ma to 403 ± 10 Ma, suggesting a protracted magmatic history in the lower and mid-crust before rapid upper crustal emplacement. Only the youngest of these grains puts any constraint on this emplacement age, and is compatible with the 405 Ma Re-Os age. The new zircon data therefore support the conclusion of Selby et al. (2008) that the Shap pluton was emplaced about 6 million years earlier than those at Skiddaw and Weardale.

The buried Wensleydale pluton has an Rb-Sr age that recalculates as 408 ± 10 Ma (Dunham 1974). This age is within error of the emplacement ages of the Shap, Skiddaw or Weardale plutons. However, a Devonian emplacement age...
for the Wensledale pluton has been questioned (e.g. by Millward et al. 2000) for several reasons: its cleaved margin, its low heat production and its geochemical similarity to the Ordovician plutons of the Lake District. A new U-Pb zircon age of $449 \pm 0.52$ Ma (C. Thomas et al. pers. comm. 2018) has verified this Ordovician age.

The Crummock Water pluton is postulated from its gravity signature and from the metasomatically bleached aureole in the overlying Skiddaw Group mudrocks (Millward 2002). This aureole gave an Rb-Sr age that recalculates to $409 \pm 3$ Ma (Cooper et al. 1988) (Fig. 9d), an age only just within error of the Shap pluton and significantly older than the Skiddaw and Weardale granites.

There are no radiometric ages available from the subsurface Ulpha and Haweswater plutons.

Discussion of the ages of Devonian plutons

The best estimate of emplacement age for each Devonian granite pluton in northern England is summarized on Figure 7 and ranges from 408 to 398 Ma. Comparing these ages with the cleavage ages highlights the paradox that emplacement of the Shap and Crummock Water plutons radiometrically predates the cleavage that the plutons physically truncate or metasomatise in the field. The reliability of the Crummock Water age might be doubted as an older Rb-Sr whole rock age, but the Shap age is based on more modern U-Pb, Re-Os and Rb-Sr mineral techniques. The age paradox therefore prompts consideration of what the radiometric ages mean in relation to a possibly protracted period of emplacement or cleavage formation. Estimates of the duration of emplacement and deformation are attempted in the next section.

The early U-Pb zircon ages from the Shap pluton have been discussed by Miles & Woodcock (2018). The large ($\pm 10$ Ma) errors on the ages of individual grains makes it statistically possible that all these grains form a single population with mean age of about 416 Ma. However, Miles & Woodcock (2018) considered it more likely that they record protracted crystallisation in a mid-crustal mush zone throughout much of Early Devonian time, as evidence from other granite plutons suggests (e.g. Coleman et al. 2004; Glazner et al. 2004). Miles & Woodcock (2018) envisaged that this mush reservoir was intersected by steep strike-slip faults at about 405 Ma and that a crystal-rich mush close to the solidus temperature was piped up into the upper crust at a releasing bend in the strike-slip system. The other pipe-shaped Devonian plutons in northern England were probably emplaced in a similar way (Kimbell et al. 2010), analogous to other Caledonide examples in Donegal (Hutton 1982), the Grampian terrane (Jacques & Reavy 1994) and more generally (Hutton & Reavy 1992). In northern England, the solidified mush zone is thought to be preserved at about 10 km depth as a component of the North Pennine and Lake District batholiths.

The exposed Shap pluton has three main textural varieties (Stages I, II and III, Grantham 1928). The abundance of orthoclase megacrysts increases from 1.5% in Stage I, to 30% in Stage II and up to 60% in Stage III. Contacts between Stages I and II are often diffuse, but rafts of Stage I granite within the younger Stage II granite suggested to Grantham that the Stage II variety post-dated Stage I. However, no significant difference in zircon ages has been found between the Stage I and II granite (Miles & Woodcock 2018, fig. 5) and we have found contacts where the darker Stage I variety locally post-dates Stage II (Fig. 6g and h). This evidence suggests that both varieties coexisted in the same melt body. The typically diffuse contacts suggest that juxtaposition of the two varieties happened in the mid-crustal mush zone or, less likely, in very quick succession in the upper crust. The Stage III granite is a minor constituent of the pluton and is found as 1 cm to 1 m wide dyke-like bodies that cross-cut Stages I and II with sharp margins.

Durations of emplacement and deformation

Duration of granite pluton emplacement

The likely duration of cooling of a cylindrical pluton can be estimated from conductive cooling models such as those explained by Best & Christiansen (2001, pp. 198–199), assuming that the pluton was emplaced into its final upper crustal site in one episode.

The characteristic time $\tau$ is the time for the temperature difference between the centre of the pluton and the far-field country rock to reduce to $1/e$ (36.8%) of its initial value. For a cylindrical pluton

$$\tau = \frac{\kappa t}{a^2}$$

where $\kappa$ is the thermal conductivity, $t$ = time and $a$ = pluton radius. Figure 10a shows the cooling times plotted against average pluton radius for various values of $\tau$ and for an appropriate thermal conductivity for the granite and the country rocks of $10^{-6} \text{ m}^2 \text{s}^{-1}$. Apart from the large Weardale pluton, the cooling times for the northern England plutons are low; they would be 95% cooled within 2.5 myr and 63% cooled within a million years. Even Weardale would be 63% cooled in less than 6 myr.

For Shap specifically, the average radius at 2 km depth is about 2 km and the cooling time is given by $\tau = 0.127 t$ myr. In the area to the west of Shap, illite crystallinity studies (British Geological Survey 1998) show that the country rock had reached mid-anchizone grade by the time of granite emplacement, corresponding to a temperature of 250°C (Kisch 1987). The Shap magma probably intruded at a temperature of about 650°C, close to solidus temperature, giving an initial temperature difference with respect to the country rock of 400°C. As the pluton cooled and the local wall rocks heated, the temperature difference with the far-field country rock would have reduced to 37% of its initial value at $\tau = 1$, corresponding to a duration of 127 000 years. Thirty-seven percent of 400°C is 147°C, implying that the centre of the pluton would then have cooled to 397°C, well below solidus temperatures. Cooling equivalent to $\tau = 3$, when the differential temperature would have reduced to 5% of its initial value, would have been achieved in only 300 000 years.

The rapid cooling times for the Shap pluton require a very short time gap between the upper crustal intrusion of the Stage I and Stage II magmas, or require that these two textural varieties were brought together in the mid-crustal mush zone, to be emplaced together into the upper crust.
Acadian deformation and northern England granites

Duration of the Acadian deformation

The likely duration of the Acadian deformation can be estimated by dividing the accumulated finite strain by a plausible strain rate based on modern contractional or transpressional orogens.

The best indicators of the amount of Acadian shortening in northern England are the accretionary lapilli shapes in the Borrowdale Volcanic Group measured by Bell (1981). These lapilli suggest shortening perpendicular to the cleavage of 50–70%, a result very similar to wider compilations of cleavage in the Caledonian belt (Ramsay & Wood 1973).

Strain rates in contractional orogens vary from $10^{-12}$ to $10^{-16}$ s$^{-1}$ but in strike-slip orogens have a narrower range from $10^{-14}$ to $10^{-15}$ s$^{-1}$ (Campbell-Stone 2002). Some strain rates that are well constrained by GPS measurements are shown on Figure 10b, and fall within the range from 1.5 to $6.5 \times 10^{-15}$ s$^{-1}$. At these rates, 60% Acadian shortening in northern England would have taken between 3 and 10 myr to accumulate (Fig. 7).

Significance of the emplacement and deformation rates

The estimates of the duration of emplacement and deformation (Fig. 7) are helpful in clarifying that the Acadian deformation was more protracted than the emplacement of any one late Devonian pluton. The modelling suggests that the Acadian folding and cleavage probably developed over 3 to 10 myr, whereas all plutons except for Weardale appear to have been emplaced in the upper crust and solidified in less than a million years. Even Weardale was 63% cooled in less than 6 myr (Fig. 10a).

The rate estimates therefore suggest an explanation for the paradox that the K-Ar ages on the Acadian cleavage, locally and regionally, are younger than the emplacement age of the Shap pluton, even though the pluton truncates the cleavage in the country rocks. The paradox is resolved if the Acadian cleavage took as long as 10 myr to evolve, with the K-Ar age recording only the end of this deformation, when overburden was eroded, the deformed rocks cooled, and the K-Ar system closed. The local K-Ar age on the cleavage of 401 ± 7 Ma allows deformation to have started as early as 411 Ma and to have been in progress for 6 myr before the emplacement of the Shap pluton at about 405 Ma (Fig. 7).

The cooling estimates above assume that each cylindrical pluton was emplaced in one event, with the textural and geochronological complexity of a pluton such as Shap being inherited from the mid-crustal mush zone (Miles & Woodcock 2018). If, alternatively, such plutons were built up incrementally in the upper crust by a series of sill or dyke intrusions, then the cooling time of each magma batch would be an order of magnitude shorter; tens of thousands of years only (e.g. Barboni et al. 2015). The spread of the U-Pb zircon ages in the Shap pluton could then be interpreted as upper crustal emplacement of successive magma batches over 10 million years or more, comparable with larger granitic plutons such as the Tuolumne Suite in California (Coleman et al. 2004; Glazonet et al. 2004).

This incremental emplacement model is implausible because of the paucity of sharp chilled contacts between different magma batches in the Shap pluton. Figure 6g and h shows local examples of sharp contacts, which would conventionally be interpreted as chilling of a later phenocryst-poor batch (‘Stage I’) against an earlier phenocryst-rich batch (‘Stage II’). However the veining in Figure 6h suggests that the Stage II facies was indeed the later component. We therefore reinterpret the apparent chills as mica-rich schlieren formed by filter-pressing at the margin of the Stage I melt (Weinberg et al. 2001; Paterson et al. 2018), probably because it still contained substantial interstitial melt. Both magma batches probably coexisted as crystal-rich mushes in the mid-crust, not in the upper crust.

Discussion

This review has considered the dating of the Acadian deformation in northern England and of the Devonian granites that overlapped with that deformation in both space and time. The central conclusion is that the cluster of K-Ar and Ar-Ar ages recalculated at 404–394 Ma (Emsian, Early Devonian; Figs 7 and 9) provides a good estimate of the end of the Acadian deformation. However, that deformation must already have been in progress for some millions of years in order to satisfy the observed field relations wherein the Acadian cleavage is truncated at the margins of the Shap and other granites. The granitic plutons themselves were rapidly
emplaced and cooled into these country rocks, mostly in less than a million years.

There is, however, a second hypothesis that needs to be considered: that the main cleavage-forming ‘Acadian’ deformation is dated by the earlier cluster of K-Ar and Ar-Ar ages at about 419–426 Ma (late Ludlow and Přidolí, late Silurian). This hypothesis naturally satisfies the field relations that the cleavage is truncated and thermally overprinted at the margins of the Shap and Skiddaw granites and in the Crummock and Ulpha metasomatic aureoles. However, a late Silurian age for the Acadian deformation presents the following problems:

a) The late Silurian does not correspond to the regional Acadian unconformity: the gap in deposition during which pre-Acadian rocks were deformed, uplifted and eroded. Where it is best constrained, in South Wales and the Welsh Borderland (Avalonia), this unconformity spans intra-Emsian through Frasnian time, at most 407–372 Ma (Figs 7 and 9). It therefore begins at least 12 myr after the end of the late Silurian radiometric resetting episode.

b) It might be argued that the unconformity in northern England (Leinster–Lakesman terrane or Ganderia) is wider, and begins in Přidolí time. However, illite crystallinity data show that at the time the Acadian cleavage developed, the Silurian rocks in northern England had an overburden of at least 3.5 km of uppermost Silurian and lower Devonian rocks (Soper & Woodcock 2003), so a late Silurian cleavage age is implausible.

c) A late Silurian age for the Acadian deformation conflicts with the evidence around the Shap and Skiddaw plutons that shortening continued after emplacement of the plutons and whilst their metamorphic aureoles developed (Soper & Roberts 1971; Boulter & Soper 1973; Soper & Kneller 1990).

For these reasons, the Emsian (Early Devonian) age is preferred here for the main Acadian deformation in northern England and Wales. The cause of the end-Silurian cluster of ages is still debatable. The suggestion of Evans (1996) and Merriman et al. (1995) that the ages record the prograde transition from smectite to illite during burial is appealing. However, a late Silurian cluster of Ar-Ar ages with a peak at 423 Ma has been obtained from the NW–SE striking cleavage in the Charnwood inlier of the East Midlands (Carney et al. 2008). These ages seem to record substantial late Silurian shortening in the Anglian Basin on the northeast margin of the Midland Platform. The possibility that this shortening also affected the Welsh Basin and the basins of the Lakes-Leinster terrane cannot be discounted. However, any late Silurian shortening seems not to have been enough to terminate deposition, only to have reduced subsidence rates in these basins and to promote a facies change from marine to non-marine (Soper & Woodcock 2003). Eastward from the Anglian Basin, the Brabant Massif was also deformed in late Silurian and Lower Devonian time (426–393 Ma; Debacker et al. 2005), in the event termed the Brabantian.

The D1 and D2 deformation sequence in the Lake District Massif, supposed here to be Acadian, was correlated by Simpson (1963, 1967) with the similar sequence on the Isle of Man, a structural correlation broadly supported by more recent studies (Fitches et al. 1999; Morris et al. 1999; Power & Barnes 1999). The most recent mapping of the Isle of Man (Chadwick et al. 2001) regards D1 and D2 as ‘Acadian’ but of late Silurian or early Devonian age. D1 and D2 must pre-date the weakly deformed Peel Sandstone Group, then thought to be about 400–410 Ma (Pragian to Emsian), on the basis of its 29 ± 5 palaeolatitude estimated palaeomagnetically (Piper & Crowley 1999). This age for the Peel Group would be compatible with the 404–394 Ma age for the Acadian deformation in northern England if the Peel Group was at the later Emsian end of the palaeomagnetically allowable range. However, whilst a subsequently identified Scoyenia ichnofacies assemblage indicates a latest Silurian to Early Devonian age, a spore microflora suggests a more specific late Lochkovian to Pragian age for the Peel Group (Crowley et al. 2009). This age is incompatible with the evidence from northern England, and the necessary conclusion is that D1 and D2 in northern England and the Isle of Man are not time correlates. The northern England ‘Acadian’ deformation is 404–394 Ma (Emsian) whereas the Isle of Man deformation is pre-end Pragian, so at least 408 Ma, possibly equivalent to the 419–426 Ma (late Ludlow and Přidolí, late Silurian) radiometric ages from England and Wales already discussed.

Interpretation of deformation timing in the Isle of Man has recently been further complicated by a Late Ordovician U-Pb zircon age of 457.2 ± 1.2 Ma from the Dhoon Granodiorite (Fritschle et al. 2018). These authors quote Power & Barnes (1999) as concluding that this granite was intruded during or after the D1 deformation, implying that D1 must be an Ordovician event. In fact, Power & Barnes (1999) observed that porphyroblasts in the aureole to the Dhoon pluton, flattened in the S1 cleavage and replaced by chlorite and biotite, suggest that ‘...the Dhoon Granodiorite was formed pre- or possibly syn-D1. ’ So a late Silurian or Early Devonian age for D1 is still compatible with the new age for the Dhoon pluton. Furthermore, Fritschle et al. (2018) do not mention that the D1 to D2 structural sequence in the Ordovician Manx Group is also present in the Wenlock (mid-Silurian) Dalby Group, precluding a pre-late Silurian age for the main deformation on the Isle of Man.

A late Silurian or Early Devonian ‘Acadian’ deformation can be traced into the Balbriggan inlier of eastern Ireland (Murphy 1987), through the Slieve Phelim and Galtse Mountains inliers of central Ireland (Phillips 2001) to the Dingle Peninsula of the west coast (Todd 2015). To the SW, in the Leinster Massif, U-Pb zircon ages (Fitches et al. 2018) show that the D1 deformation in the Ribband Group is about 460 Ma (late Middle Ordovician) in age rather than Acadian as previously thought. Deformation in the unconformably overlying Duncannon Group may still be Acadian.

Conclusions

a) A review of the field evidence shows that the Devonian plutons in northern England were intruded after most – but not all – of the Acadian folding and cleavage formation had occurred.

b) U-Pb zircon and Re-Os molybdenite ages (Selby et al. 2008; Kimbell et al. 2010) suggest that the
Skiddaw and Weardale plutons were emplaced at about 399 Ma, but the Shap pluton earlier at about 405 Ma.

c) The K-Ar age on the Acadian cleavage in northern England of 397 ± 7 Ma (Merriman et al. 1995) and K-Ar and Ar-Ar ages from Wales ranging from 400 to 390 Ma are just compatible with the emplacement ages of Skiddaw and Weardale, but incompatible with emplacement of Shap at 405 Ma. Adjustment of these ages upwards by 1% in line with the revised decay constant increases the local K-Ar age to 401 ± 7 Ma and the regional range from 404 to 394 Ma (Emsian, Lower Devonian); this is still younger than the Shap emplacement age, but is more compatible with it within error.

d) Assessment of the thermal history of the northern England plutons show that they mostly cooled within a million years, with only the Weardale pluton having a more protracted cooling history.

e) By contrast, the Acadian deformation probably lasted from 3 to 10 myr, offering a solution to the age paradox around the Shap pluton. Folds and cleavage may have been forming for as much as 10 myr before the closure of the K-Ar isotopic system at about 401 Ma.

f) An earlier cluster of K-Ar and Ar-Ar cleavage ages at 426–420 Ma (Ludlow to Pridoli, late Silurian) is problematic, as it falls before the regional unconformity marking Acadian deformation, uplift and erosion.

g) A cluster of U-Pb zircon ages from the Shap pluton averaging 415.6 ± 1.4 Ma is thought not to relate to pluton emplacement. Rather, these ages are considered to record zircon crystallisation in a mid-crustal mush zone kept near solidus temperature for much of Early Devonian time, and which was eventually the source for the upper crustal plutons

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