Journal of the Geological Society, London, Vol. **165**, 2008, pp. 891–894. Printed in Great Britain.

SPECIAL

New U–Pb and Rb–Sr constraints on pre-Acadian tectonism in North Wales

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A new U–Pb date of 615.2 ± 1.3 (2σ) Ma for the Twt Hill Granite, North Wales, contrasts with an Rb–Sr isochron age of 491 ± 12 (2σ) Ma from the same body. The latter age is thought to result from isotope resetting during regional low-grade metamorphism or fault reactivation. The Rb–Sr age also coincides with the onset of latest Cambrian to Early Tremadoc regression and is taken to reflect tectonic uplift prior to the Arenig overstep at around 478 Ma. It is proposed that this in turn reflects plate-scale processes along the contemporary peri-Gondwanan continental margin.

Evolution of the peri-Gondwanan margin of the Iapetus Ocean during the Ordovician involved complex patterns of subduction and accretion. In the northern Appalachians of New England and Atlantic Canada, this included emplacement of the Penobscot (513–486 Ma) and Victoria (478–455 Ma) arcs and accretionary complexes of the Central Mobile Belt onto a composite Ganderia–Avalonia continental margin (van Staal *et al*. 1998, and references therein; Zagorevski *et al*. 2007). The resulting tectonism significantly predated the mid-Devonian Acadian Orogeny often associated with terminal collision between Laurentia and the peri-Gondwanan continental fragments of Meguma and Avalonia (Fig. 1). Although these events are well preserved in the tectonically active outboard part of the Gondwanan margin, which overlies Ganderian basement, their far-field effects, and evidence for inboard transfer of orogenic stress, remain largely cryptic. In southern Britain evidence for pre-Acadian deformation is relatively sparse, and cannot be easily related to a larger palaeotectonic framework. Indeed, even the assignment of the Acadian Orogeny to the collision between Laurentia and Avalonia is being questioned (e.g. Woodcock *et al*. 2007).

In an attempt to synthesize Iapetus evolution throughout the transposed remnants of the belt, van Staal *et al*. (1998) suggested that deformation in the ensialic Welsh Basin during the Tremadoc, and subsequent formation of a late Tremadoc–Early Arenig arc, was related to diachronous Penobscotian collision and a renewed cycle of suprasubduction-zone magmatism equivalent to the Victoria arc. In this paper we re-examine this hypothesis and consider the importance of pre-Acadian deformation in the Welsh Basin in the light of new U–Pb and Rb–Sr geochronology from the Twt Hill Granite of North Wales (Fig. 1). This pluton was intruded within one of the main bounding fault systems of the Welsh Basin, the Menai Straits Fault System, and as such was considered a likely candidate to record an isotopic record of fault reactivation.

Geodynamic framework. During much of the Ordovician the Welsh Basin represented a site of enhanced subsidence and sedimentary deposition, and formed as an ensialic marginal basin above an approximately SE-facing subduction zone (Kokelaar *et al*. 1984; Kokelaar 1988). Evidence for continental basement to the basin is provided by remnants of Neoproterozoic igneous complexes preserved around the basin margin and proven in the Bryn Teg borehole of the Harlech Dome (e.g. Pharaoh & Carney 2000).

The Neoproterozic basement of Wales comprises a collage of fault-bounded terranes that evolved as component parts of the peri-Gondwanan Avalonia microcontinent (Keppie *et al*. 1991; Strachan *et al*. 2007). These formed during cycles of arc-related magmatism and deposition that record the assembly of Gondwana by latest Precambrian to Early Cambrian times (e.g. Gibbons & Horák 1996; Strachan *et al*. 2007).

Detachment of Avalonia from Gondwana during the Early Palaeozoic was accompanied by the onset of subduction and contraction of the Iapetus Ocean, intervening between Avalonia and the North American palaeocontinent of Laurentia. In the Welsh Basin, subduction is most dramatically marked by cycles of Ordovician suprasubduction-zone volcanism preserved as scattered centres in Snowdonia, SW Wales and as fault-controlled tectonic inliers along the SE margin of the basin. These vary in age and geographical distribution, but broadly comprise a Tremadoc age (*c*. <488 to >478 Ma) episode, a mid-Arenig to Llanvirn age (*c*. <478 to >468 Ma) episode, and a Llanvirn to Caradoc age (*c*. 459–454 Ma) episode (e.g. Kokelaar *et al*. 1984; Howells *et al*. 1991).

Initiation of basin subsidence recorded by the sedimentary record of the northern Welsh Basin during the Cambrian is marked by marine transgression and local overstep of Neoproterozoic basement units. This is thought to have been controlled by coincidence of global eustatic sea-level rise (Fortey 1984) and onset of the Iapetus cycle (e.g. Murphy & Nance 1989), and was followed by rapid subsidence. Movement along the Menai Straits Fault System at that time brought about development of contrasting sequences in the Arfon sub-basin and Harlech Dome (Prigmore *et al*. 1997). Regression during the Early Tremadoc was manifest in the Harlech Dome by deposition of a shelf succession recorded by the Dol-cyn-afon Formation (e.g. Brenchley *et al*. 2006).

Deposition during the Arenig was characterized by dramatic overstep of nearshore sedimentary facies passing up into basinal mudstones (e.g. Traynor 1988, 1990). The unconformity is strongly diachronous, with basal units ranging in age from the early Arenig (Moridunuan) to late Arenig (Fennian) (*c*. <478 to >466 Ma), overstepping strata ranging in age from Neproterozoic (<604 Ma; Compston *et al*. 2002) to Tremadoc (<489 Ma; Landing *et al*. 2000) on the flanks of the Harlech Dome (Brenchley *et al*. 2006).

Following volcanic shut-down in the Caradoc, Late Ordovician and Silurian deposition in the basin occurred in a transtensional setting, influenced by terminal collision of Laurentia and Avalonia, which is thought to have ended in the Late Ordovician (Woodcock *et al*. 2007).

The structural record of the Welsh Basin provides evidence for weak intrabasinal deformation throughout its history; in particular, synsedimentary fault movements that accommodated changing basin geometry during subsidence (e.g. Webb 1983;

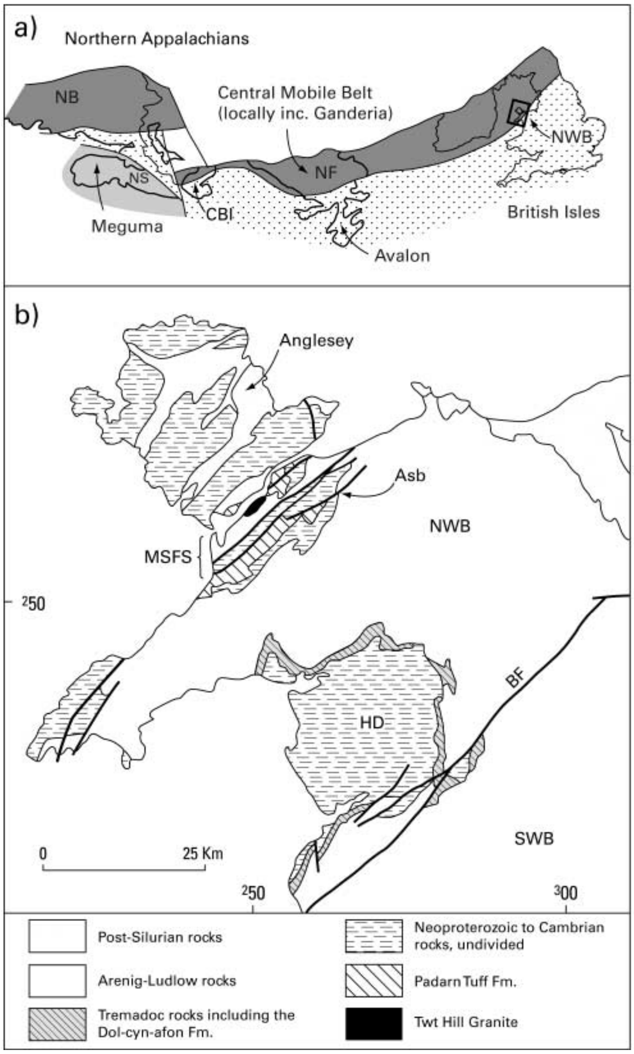

Fig. 1. (**a**) Lower Palaeozoic, peri-Gondwanan tectonostratigraphic zones of the northern Appalachians and British Isles (modified after van Staal & de Roo 1995; Winchester & van Staal 1995). CBI, Cape Breton Island; NWB, northern Welsh Basin; NF, Newfoundland; NB, New Brunswick; NS, Nova Scotia. (**b**) Simplified geology of the northern Welsh Basin. Asb, Arfon sub-basin; BF, Bala Fault; HD, Harlech Dome; MSFS, Menai Straits Fault System; NWB, northern Welsh Basin; SWB, southern Welsh Basin.

Davies *et al*. 1997). Much of the penetrative structural development occurred during the mid-Devonian Acadian Orogeny, when folding and pervasive slaty cleavages were developed throughout the basin (e.g. Davies *et al*. 1997). However, the penetratively deformed Cambrian–Early Ordovician strata of the Holyhead Formation of the Monian Terrane of Anglesey ($<501 \pm 10$ Ma; Collins & Buchan 2004) are overstepped by Arenig strata indicating an episode of Tremadoc to Arenig age deformation. In contrast, contemporary tectonic uplift of the Harlech Dome prior is thought to have been achieved by reactivation of earlier basement fractures (Kokelaar 1988).

The Twt Hill Granite is enveloped by the Neoproterozoic Padarn Tuff Formation of the Arfon sub-basin within the Menai Straits Fault System and is overstepped by transgressive basinal sediments of Arenig age. Although the exact relationship is unclear, the granite was considered by Greenly (1944) to be the lower 'member' of his Arvonian 'formation'. It largely comprises a relatively homogeneous pale micro-syenogranite and is well exposed in crags and quarries around Twt Hill in the town of Caernarfon.

Geochronology. Zircon grains were separated from a sample of the Twt Hill Granite that was collected from outcrops at Twt Hill [248301 363138], chemically abraded (Mattinson 2005) and analysed following the procedures of Noble *et al*. (1993). Chemistry blanks were *c*. 2 pg, and uranium blanks were <0.1 pg U. All results and errors were calculated following the methods of Ludwig (1993) and plotted using IsoplotX (Ludwig 2003). Pb isotope ratios were corrected for initial common Pb in excess of laboratory blank using the model of Stacey & Kramers (1975). Results were calculated using the decay constants of Jaffey *et al*. (1971). Data are available online at http://www.geolsoc.org.uk/SUP18317.

The Rb–Sr regression age for the Twt Hill Granite was determined in 1981 on samples of microgranite collected from the same locality as that used for the U–Pb sample, but the data were not published at that time. The methods were described by Beckinsale *et al*. (1984). The Rb–Sr age was calculated using IsoplotX (Ludwig 2003) using 0.01% (1σ) error for the $^{87}Sr/^{86}Sr$ ratios. The ^{87}Rb decay constant used was 1.42×10^{-11} a^{-1} (Steiger & Jäger 1977).

Discussion. The Twt Hill Granite gives a concordia age of 615.2 ± 1.3 (2σ) Ma (Fig. 2), and is interpreted as dating emplacement during the Avalonian cycle of suprasubduction-zone magmatism (Keppie *et al*. 2003). However, the U–Pb age is clearly at odds with the Rb–Sr isochron age of 491 ± 12 (2σ) Ma (Fig. 3) and suggests that the Rb–Sr isotopic system has been thoroughly reset. Previous studies have shown that this resetting is likely to record water–rock interaction and is largely dependent on mineral stability in the presence of water, and the presence of sufficient water to rehomogenize Rb and Sr (Evans 1995).

The U–Pb date is within error of that yielded by the surrounding Padarn Tuff Formation at 614 ± 2 Ma (Tucker & Pharaoh 1991), suggesting a close genetic link between the two and indicating that the interpretation by Greenly (1944) that the tuffs overlie the granite cannot be ruled out.

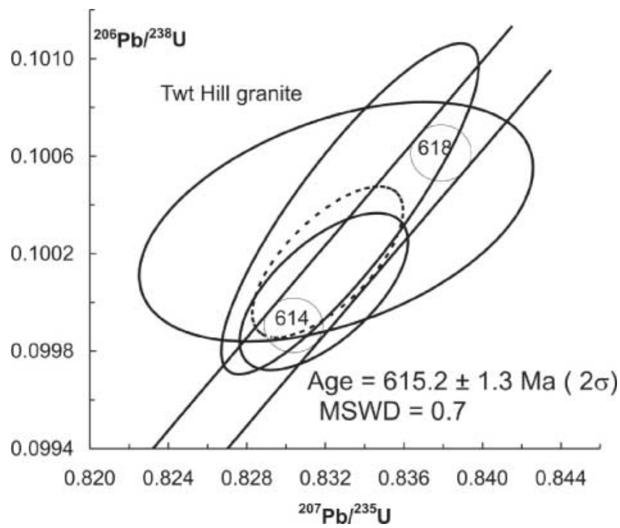

Fig. 2. U–Pb concordia plot showing data from three zircon fractions (continuous lines) and the concordia age (dashed line). The error quoted on the age includes decay constant errors and the MSWD incorporates concordance and equivalence.

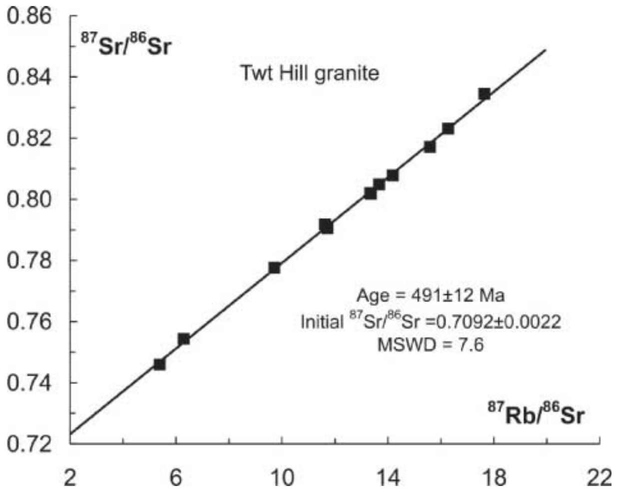

Fig. 3. York–Williamson least-squares $^{87}Sr/^{86}Sr$–$^{87}Rb/^{86}Sr$ regression diagram.

A number of studies have shown that Rb–Sr resetting generally coincides with regional low-grade metamorphism under diagenetic to epizone facies conditions (e.g. Bell & Blenkinsop 1978; Smalley *et al*. 1983; Asmeron *et al*. 1991; Evans 1991). As the Rb–Sr isochron approximately coincides with the onset of marine regression, tectonic uplift in the Harlech Dome and more penetrative deformation on Anglesey, we propose that isotopic resetting records low-grade metamorphism associated with a tectonic episode of similar age to Tremadoc, Penobscotian collision in the northern Appalachians. Several hypotheses can be proposed to explain the plate-scale processes controlling tectonic activity at that time; these are briefly described in the remainder of this discussion.

One possibility is that deformation in the Menai Straits Fault System at around 491 Ma may simply constrain the timing of orogen-parallel movement along the Gondwanan margin (see Murphy & Nance 1989), or even juxtapositioning of two discrete peri-Gondwanan fragments analogous to Ganderia and Avalonia of the northern Appalachians (see van Staal *et al*. 1998). Alternatively, it may reflect changes in subduction dynamics equivalent to those that gave rise to obduction of the Penobscot arc (van Staal *et al*. 1998).

A conventional interpretation of the Penobscot Orogeny is that it records obduction onto Ganderia of island arc, ophiolitic and olistrostromal fragments formed during the mid- to Late Cambrian and Tremadoc above a NW-dipping subduction zone. This was followed by a polarity reversal to SE-dipping subduction and the onset of a new phase of ensialic subsidence and back-arc magmatism developed on the composite Gander margin during the Arenig (van Staal *et al*. 1998, and references therein). The age of this event is well constrained by stitching plutons to between around 485 and 474 Ma (van Staal *et al*. 1998, and references therein).

A more recent interpretation of Early Ordovician accretionary tectonics in the Newfoundland Appalachians places the Penobscot arc adjacent to the Gander margin above a SE-dipping subduction zone. In this model, a short-lived compressional event led to obduction of the intervening back-arc as the subducting front stepped outboard of the continental margin (Zagorevski *et al*. 2007).

The absence of suprasubduction-zone volcanism in the Late Cambrian record of Wales means that, at present, validating either of the Penobscotian accretionary models is problematic as subduction-zone polarity prior to the Tremadoc cannot be clearly constrained. On the one hand, this could support a NW-dipping subduction model by allowing for the excision or dispersal of Late Cambrian island arc successions formed outboard of the preserved Gondwanan margin. Polarity reversal, marked by the *c*. 491 Ma resetting event, prior to the onset of Tremadoc age suprasubduction-zone volcanism within the Harlech Dome and South Wales (Kokelaar *et al*. 1984), would support a diachronous Penobsoct Orogeny as suggested by van Staal *et al*. (1998). However, on the other hand, elevated basin subsidence rates throughout much of southern Britain (Prigmore *et al*. 1997) could argue for the onset of ensialic back-arc extension above a SE-dipping subduction zone during the Late Cambrian and provide evidence in support of the more recent interpretation of the orogeny by Zagorevski *et al*. (2007). In this case, *c*. 491 Ma tectonism could constrain obduction of an adjacent back-arc, followed by renewed, inboard, subsidence within the continental margin during the Tremadoc.

Some elements of the geological succession of Anglesey may ultimately be demonstrated to be part of a Penobscotian age accretionary assemblage and could shed light on the Early Palaeozoic subduction polarity. However, at present there is insufficient constraint on age and provenance and little consensus regarding overall facing direction of this assemblage (e.g. van Staal *et al*. 1998; Kawai *et al*. 2006, 2007; Treagus 2007).

Although the underlying causes for the Penobscot Orogeny are poorly understood (e.g. Zagorevski *et al*. 2007), one scenario that satisfies both NW- and SE-facing models could involve a change from a retreating to an advancing plate boundary brought about by an increase in the rate of overall convergence (Royden 1993). This would have led to a change from horizontal extension and basin subsidence to compression and inversion of the continental margins including the Welsh Basin.

A similar change of plate boundary conditions could also be induced by subduction of increasingly buoyant oceanic lithosphere (see Molnar & Atwater 1978). Through the Cambrian and Early Ordovician, as the peri-Gondwanan plate boundaries migrated toward the Iapetan spreading centre, increasingly young and warm oceanic crust was being subducted. This may have led to a decrease in the subduction angle and an inevitable change from a retreating to an advancing plate margin. This, in turn, would have led to inversion of ensialic basins such as the northern Welsh Basin. Conversely, during the Arenig, waning convergence rates or subduction of cooler, older oceanic lithosphere, possibly following on from ridge subduction, may have led to roll-back and a renewed cycle of basin subsidence and back-arc magmatism that persisted until volcanic shut-down in the Caradoc. Support for this latter model is provided by evidence for subduction of a segment of the Iapetan spreading ridge during the Arenig, recorded in the northern Appalachians by formation of the Summerford Seamount (Wasowski & Jacobi 1985; van Staal *et al*. 1998).

The authors would like to thank A. Wood and A. Sumner for technical support; and R. D. Beckinsale, with whom the original Rb–Sr study was undertaken. T. C. Pharoah and J. R. Davies are thanked for reviewing an earlier version of the manuscript. D. I. Schofield, J. A. Aspden and P. R. Wilby publish with the permission of the Executive Director, British Geological Survey, NERC.

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Received 10 April 2008; revised typescript accepted 9 May 2008.
Scientific editing by Rob Strachan