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

D.I. Schofield[1], J.A. Evans[2], I.L. Millar[2], P.R. Wilby[1] and J.A. Aspden[1]

[1]*British Geological Survey, Kingsley Dunham Centre, Nottingham, NG12 5GG, UK*

(e-mail: dis@bgs.ac.uk)

[2]*NERC Isotope Geoscience Laboratories, Kingsley Dunham Centre, Nottingham, NG12 5GG, UK*

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.

Introduction

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 pre-dated the mid-Devonian Acadian Orogeny often associated with terminal collision between Laurentia and the peri-Gondwanan continental fragments of Meguma and Avalonia (Fig. 1). While 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 synthesise 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 (MSFS), 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 supra-subduction zone volcanism preserved as scattered centres in Snowdonia, SW Wales and as fault-controlled tectonic inliers along the southeast margin of the basin. These vary in age and geographical distribution, but broadly comprise a Tremadoc age (ca. <488 to >478 Ma) episode, a mid-Arenig to Llanvirn (ca. <478 to >468 Ma) episode, and Llanvirn to Caradoc age (ca. 459 to 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 both 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 MSFS 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 characterised 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) (ca. <478 to >466 Ma), overstepping strata ranging in age from Neproterozoic (<604 Ma; Compston et al., 2002) up 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 Orodovician 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 syn-sedimentary fault movements that accommodated changing basin geometry during subsidence (e.g. Webb, 1983; Davies et al., 1997). Much of the penetrative structural development occurred during the mid-Devonian Acadian Orogeny, where 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±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 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 MSFS 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/. A hard copy can be obtained from the Society Library.

The Rb-Sr regression age for the Twt Hill 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 methodology is documented in

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. ^{87}Rb decay constant used was $1.42x10^{-11}a^{-1}$ Steiger & Jager (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 supra-subduction zone magmatism (Keppie at 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 dependant on mineral stability in the presence of water, and the presence of sufficient water to re-homogenise 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) indicating a close genetic link between the two and indicating that Greenly's (1944) interpretation that the tuffs overlie the granite cannot be ruled out.

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 Tremadocian, 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 MSFS at around 491 Ma may simply constrain the timing of orogen parallel movement along the Gondwanan margin (cf. Murphy & Nance, 1989), or even juxtapositioning of two discrete peri-Gondwanan fragments analogous to Ganderia and Avalonia of the northern Appalachians (cf. 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 supra-subduction volcanism in the Late Cambrian record of Wales means that, at present, validating either of the Penobsoctian 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 supra-subduction zone volcanism within the Harlech Dome and South Wales (Kokelaar et al., 1984), would support a diachronous Penobsct Orogeny as suggested by van Staal et al. (1998). However, elevated basin subsidence rates throughout much of southern Britain (Prigmore et al., 1998) 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 contstrain 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 as 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; Kawai et al., 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 (c.f. 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 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 through to 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 this manuscript. D. I. Schofield, J. A. Aspden and P. R. Wilby publish with the permission of the Executive Director, British Geological survey, NERC.

References

ASMERON, Y., DAMON, P., DICKINSON, W. R. & ZARTMAN, R. E. 1991. Resetting of Rb-Sr ages of volcanic rocks by low grade burial metamorphism. *Chemical Geology (Isotope Geoscience Section)*, **87**, 167-173.

BECKINSALE, R.D., EVANS, J.A., THORPE, R.S., GIBBONS, W. AND HARMON, R.S., 1984. Rb-Sr Whole-Rock Isochron Ages, Delta-O-18 Values and Geochemical Data for the Sarn Igneous Complex and the Parwyd Gneisses of the Mona Complex of Llyn, North Wales. Journal of the Geological Society, 141 701-709.

BELL, K. & BLENKINSOP, J. 1978. Reset Rb/Sr whole-rock systems and chemical control. *Nature*, **273**, 532-534.

BRENCHLEY, P. J., RUSHTON, A. W. A., HOWELLS, M. & CAVE, R. 2006. Cambrian and Ordovician: the early Palaeozoic tectonostratigraphic evolution of the welsh Basin, Midland and Monian Terranes of Eastern Avalonia. *In:* BRENCHLEY, P. J. & RAWSON, P. F. (eds), *The Geology of England and Wales.* The Geological Society, London, 25-74.

COLLINS, A.S. & BUCHAN, C. 2004. provenance and age constraints of the south Stack Group, Anglesey, UK: U-Pb SIMS detrital zircon data. *Journal of the Geological society, London*, **161**, 743-746.

COMPSTON, W., WRIGHT, A. E. & TOGHILL, P. 2002. Dating the Late Precambrian volcanicity of England and Wales. *Journal of the Geological Society, London*, **159**, 323-339.

DAVIES, J.R., FLETCHER, C. J. N., WATERS, R. A., WILSON, D., WOODHALL, D. G. & ZALASIEWICZ, J. A. 1997. *Geology of the country around Llanilar and Rhayader.*

Memoir of the British Geological Survey, Sheets 178 and 179 (England and Wales). British Geological Survey, Keyworth, Nottingham.

EVANS, J. A. 1991. Resetting of Rb-Sr whole-rock ages during Acadian low-grade metamorphism in North Wales. *Journal of the Geological Society, London,* **148**, 703-718.

EVANS, J.A., 1995. Mineral and isotope features related to resetting of Rb-Sr whole-rock isotope systems during low grade metamorphism. Bulletin of the American Geology Society, Special Paper, 296: 157-169.

FORTEY, R. A. 1984. Global earlier Ordovician transgressions and regressions and their biological implications. *In:* BRUTON, D. L. (ed), *Aspects of the Ordovician*. Universitetsforlaget, Oslo. 137-150.

GIBBONS, W. & HORÁK, J. M. 1996. The evolution of the Neoproterozoic Avalonian subduction system: evidence from the British Isles, *In:* NANCE, R. D. & THOMPSON, M. D. (eds), *Avalonian and Related Peri-Gondwanan Terranes of the Circum North Atlantic.* Geological Society of America, Special Papers, **304**, 269-280.

GREENLY, E. 1944. The Arvonian rocks of Arvon. Quarterly journal of the Geological Society, London, **100**, 269-287.

HOWELLS, M. F., REEDMAN, A.J. & CAMPBELL, S. D. G. 1991. *Ordovician (Caradoc) marginal basin volcanism in Snowdonia (north-west Wales).* HMSO, London for the British Geological Survey.

JAFFEY, A. H., FLYNN, G. K. F., GLENDENIN, L. E., BENTLEY, W. C. & ESSLING, A. M. 1971. Precision measurements of half-lives and specific activities of ^{235}U and ^{238}U. *Physical Reviews*, **C**, **4**, 1889-1906.

KAWAI, T., WINDLEY, B. F., TERABAYASHI, M., YAMAMOTO, H., MARUYAMA, S., OMORI, S., SHIBUYA, T., SAWAKI, Y. & ISOZAKI, Y. 2006. Geotectonic framework of the Blueschist Unit on Anglesey-Lleyn, UK, and its role in the development of a Neoproterozoic accretionary orogen. *Precambrian Research*, **153**, 11-28.

KAWAI, T., WINDLEY, B F., TERABAYASHI, M., YAMAMOTO, H., MARUYAMA, S. & ISOZAKI, Y. 2007. Mineral isograds and metamorphic zones of the Anglesey blueschist belt, UK: implications for the metamorphic development of a Neoproterozoic subduction-accretion complex. *Journal of Metamorphic Geology,* **7**, 591-602.

KEPPIE, J. D., NANCE, R. D., MURPHY, J. B. & DOSTAL, J. 1991. The Avalon Terrane. *In:* DALLMAYER, R. D. & LECORCHÉ, J. P. (eds), *The West African Orogens and Circum-Atlantic Correlatives.* Springer, New York, 315-333.

KEPPIE, J. D. DAVIS, D. W., MURPHY, J. B. & DOSTAL, J. 2003. Tethyan, Mediterranean, and Pacific analogues for the Neoproterozoic-Palaeozoic birth and development of peri-Gondwanan terranes and their transfer to Laurentia and Laurussia. *Tectonophysics,* **365**, 195-219.

KOKELAAR, B. P. 1988. Tectonic controls of Ordovician arc and marginal basin volcanism in Wales. *Journal of the Geological Society, London,* **145**, 759-775.

KOKELAAR, B. P., HOWELLS, M. F., BEVINS, R. E., ROACH, R. A. & DUNKLEY, P. N. 1984. The Ordovician marginal basin of Wales. *In:* KOKELAAR, B. P. & HOWELLS, M. F. (eds), *Marginal basin geology: volcanic and associated sedimentary and tectonic processes in modern and ancient marginal basins.* Geological Society, London Special Publication **16**, 245-269.

LUDWIG, K. R. 1993 PBDAT. A computer program for processing Pb-U-Th isotope data. version 1.24, *U.S. Geological Survey Open-file Report* **88-542**.

LUDWIG, K.R., 2003. Isoplot 3.00 A geochronological toolkit for Microsoft Excel. Special Publication, 4 (Berkley Geochronological Centre) 71pp.

MATTINSON, J.M., 2005. U-Pb inter-laboratory calibrations using zircon samples: Application of the new CA-TIMS technique. *Geochimica Et Cosmochimica Acta*, **69**, A319-A319.

MOLNAR, P. & ATWATER, T. 1978. Interarc spreading and cordilleran tectonics as alternatives related to the age of subducted oceanic lithosphere. *Earth and Planetry Science Letters*, **41**, 330-340.

MURPHY, J. B. & NANCE, R. D. 1989. Model of the Avalonian-Cadomian Belt. *Geology*, **17**, 735-738.

NOBLE, S. R., TUCKER, R. D. & PHARAOH, T. C. 1993. Lower Palaeozoic and Precambrian igneous rocks from eastern England and their bearing on Ordovician closure of the Tornquist Sea: constraints from U-Pb and Nd isotopes. *Geological Magazine*. **130**, 835-46.

PHARAOH, T. C. & CARNEY, J. N. 2000. Introduction to the Precambrian rocks of England and Wales. *In: Precambrian Rocks of England and Wales.* Geological Conservation Review Series, **20**, Joint Nature Conservation Committee, Peterborough, 1-18.

PRIGMORE, J. K., BUTLER, A. J. & WOODCOCK, N. H. 1997. Rifting during separation of Eastern Avalonia from Gondwana: Evidence from subsidence analysis. *Geology*, **25**, 203-206.

ROYDEN, L. H. 1993. The tectonic expression of slab pull at continental convergent boudaries. *Tectonics*, **12**, 303-325.

SMALLEY, C. F., FIELD, D. & RÅHEIM, A. 1983. Resetting of Rb-Sr whole-rock isochrons during Sveconorwegian low grade events in Gjerstad augen gneiss, Telemanrk, southern Norway. *Isotope Geosciences*, **1**, 269-282.

STACEY, J. S. & KRAMERS, J. D. 1975. Approximation of terrestrial lead isotope evolution by a two stage model. *Earth and Planetary Science Letters,* **26**, 207-221.

STRACHAN, R. A., COLLINS, A. S., BUCHAN, C., NANCE, R. D., MURPHY, J. B. & D'LEMOS, R. S. 2007. Terrane analysis along a Neoproterozoic active margin of Gondwana: insights from U-Pb zircon geochronology. *Journal of the Geological Society, London,* **164**, 57-60.

STEIGER, R.H. AND JAEGER, E. 1977. Subcommission on geochronology: convention is the use of decat-constatns in geo- and cosm chronology. *Earth and Planetry Science Letters*, **36**, 359-62.

TRAYNOR, J-J. 1988. The arenig in South Wales: sedimentary and volcanic processes during the initiation of a marginal basin. *Geological Journal*, **23**, 275-292.

TRAYNOR, J-J. 1990. Arenig sedimentation and tectonics in the Harlech Dome area (Dolgellau Basin), North Wales. *Geological Magazine,* **127**, 13-20.

TREAGUS, J. 2007. Metamorphic zones in the Anglesey blueschist belt and impications for development of a Neoproterozoic subduction-accretion complex: discussion. *Journal of Metamorphic Geology*, **25**, 507-508.

TUCKER, R. D. & PHAROAH, T. C. 1991. U-Pb zircon ages for Late Precambrian rocks in southern Britain. *Journal of the Geological Society, London*, **148**, 435-443.

VAN STAAL, C. R., DEWEY, J. F., MACNIOCAILL, C. & MCKERROW, W. S. 1998. The Cambrian-Silurian tectonic evolution of the northern Appalachians and British Caledonides: history of a complex, west and southwest Pacific-type segment of Iapetus. *In:* BLUNDELL, D. J. & SCOTT, A.C. (eds), *Lyell; the Past is the Key to the Present.* Geological Society, London Special Publication **143**, 199-242.

VAN STAAL, C. R. & DE ROO, J. A. 1995. Mid-Palaeozoic tectonic evolution of the Appalachian Central Mobile Belt in northern New Brunswick, Canada: Collision, extensional collapse and dextral transpression. *In:* HIBBARD, J. P., VAN STAAL, C. R. & CAWOOD, P. A. (eds), *Current Perspectives in the Appalachian-Caledonian Orogen.* Geological Association of Canada, Special Paper **41**, 367-389.

WASOWSKI, J. J. & JACOBI, R. J. 1985. geochemistry and tectonic significance of the mafic volcanic blocks in the Dunnage mélange, north central Newfoundland. *Canadian Journal of Earth Sciences,* **22**, 1248-1256.

WEBB, B. C. 1983. early Caledonian structures in the Cambrian Slate Belt, North Wales. *Institute of Geological Sciences report* **83/1**, 1-6.

WINCHESTER, J. A. & VAN STAAL, C. R. 1995. Volcanic and sedimentary terrane correlation between the Dunnage and Gander zones of the Canadian Appalachians and the British Caledonides reviewed. *In:* HIBBARD, J. P., VAN STAAL, C. R. & CAWOOD, P. A. (eds), *Current Perspectives in the Appalachian-Caledonian Orogen.* Geological Association of Canada, Special Paper **41**, 95-114.

WOODCOCK, N. H., SOPER, N. J. & STRACHAN, R. A. 2007. A Rheic cause for the Acadian deformation in Europe. *Journal of the Geological Society, London*, **164**, 1023-1036.

ZAGOREVSKI, A., VAN STAAL, C. R., MCNICOLL, V. & ROGERS, N. 2007. Upper Cambrian to Upper Ordovician Peri-Gondwanan island arc activity in the Victoria Lake Supergroup, Central Newfoundland: Tectonic development of the northeastern Ganderian margin. American journal of Science, **307**, 339-370.

Fig. 1. (a) Lower Palaeozoic, peri-Gondwanan tectono-stratigraphic zones of the northern Appalachians and British Isles (modified after Winchester & van Staal, 1995 and van Staal & de Roo, 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.

Fig. 2. U-Pb concordia plot showing data from three zircon fractions (solid 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.