Geol. Mag. **147** (*1*), *2010, pp. 145–150.* © *Cambridge University Press 2009*
doi:10.1017/S001675680999063X

RAPID COMMUNICATION

A new, high precision U–Pb date from the oldest known rocks in southern Britain

D. I. SCHOFIELD*†, I. L. MILLAR‡, P. R. WILBY* & J. A. EVANS‡

*British Geological Survey, Kingsley Dunham Centre, Nottingham, NG12 5GG, UK
‡NERC Isotope Geoscience Laboratories, Kingsley Dunham Centre, Nottingham, NG12 5GG, UK

(*Received* 27 July 2009; *accepted* 8 September 2009; First published online 27 October 2009)

Abstract

A new high precision U–Pb zircon age of 710.8 ± 1.5 Ma for granophyric granitic rock from the Stanner Hanter Complex of the Welsh Borderland lies just within error of an older Rb–Sr isochron age. εNd values of −0.3 and −1.2 combined with T_{DM} of 1394 Ma and 1468 Ma indicate that the magma incorporated an older crustal source component. The Nd data highlight differences with western Avalonia, the widely considered Late Neoproterozoic north American counterpart to southern Britain, and point toward a closer similarity with other Peri-Gondwanan terranes that incorporate older, cratonic source material.

Keywords: Late Neoproterozoic, Avalonia, U–Pb dating, Gondwana.

1. Introduction

The Stanner Hanter Complex of the Welsh Borderland represents one of a small number of fault-bounded units that make up the record of exposed crystalline basement of Britain, south of the Iapetus Suture. An Rb–Sr isochron age of 702 ± 8 Ma presented by Patchett *et al.* (1980) suggested the complex to be the oldest of these tectonic inliers. This paper presents a new, high resolution U–Pb age on zircon from the complex which, in combination with accompanying new Sm–Nd data, has resulted in a greater understanding of the affinities of basement terranes in southern Britain.

2. Regional tectonic framework

The Neoproterozoic basement of England and Wales is generally considered to comprise a collage of terranes that formed in close proximity to each other as component parts of the peri-Gondwanan eastern Avalonia microcontinent (e.g. Keppie *et al.* 2003; Strachan *et al.* 2007). Individual terranes described by Pharaoh *et al.* (1987) and Pharaoh & Carney (2000) include, from west to east, the Monian Composite Terrane, the Cymru Terrane, the Wrekin Terrane, the Charnwood Terrane and the Fenland Terrane (Fig. 1). Their existence as discrete tectonostratigraphic entities is largely predicated on the presence of a series of significant structural lineaments, interpreted as terrane boundaries, supported by contrasts in the geochemical characteristics of volcanic successions entrained as tectonic inliers within them (Pharaoh *et al.* 1987). The upper crustal expressions of the structural lineaments are marked by broad zones of faulting, including the Menai Straits Fault Zone, Welsh Borderland Fault System and Malvern Lineament (Fig. 1). Neoproterozoic basement rocks have also been proven in a limited number of deep boreholes (e.g. Allen & Jackson, 1978; Noble, Tucker & Pharaoh, 1993; Barclay *et al.* 1997; Pharaoh *et al.* 1991).

The terranes themselves are thought to have formed during cycles of arc-related magmatism and sedimentary deposition. Together these make up part of the record of assembly of West Gondwana at around 765–660 Ma and 635–550 Ma (Nance, Murphy & Keppie, 2002; Nance *et al.* 2008 and references therein). This included accretion of Avalonian-type and Ganderean-type terranes against a composite West Africa–Amazonia–Baltica margin of Gondwana (Murphy *et al.* 2004; Nance *et al.* 2008), recorded in southern Britain as the *c.* 667–650 Ma metamorphic event (Strachan *et al.* 1996, 2007). Available isotopic data suggest that the Avalonian terranes of southern Britain were assembled together by latest Precambrian to Early Cambrian times (Gibbons & Horák, 1996; Strachan *et al.* 2007).

However, the data from southern Britain in support of this tectonic assembly model are very limited, both in terms of paucity and distribution of exposure and antiquity of some of the isotopic studies. Indeed, the terrane boundaries in southern Britain, within which many of the Late Neoproterozoic rocks are entrained, are understood to be long-lived structures influenced by several accretionary cycles (e.g. Woodcock & Gibbons, 1988; Kawai *et al.* 2007; Schofield *et al.* 2008). Consequently, considerable scope exists for a more complex assembly process in which disparate geological elements may have been combined and intercalated over a long period of geological time. Accordingly, this study, based on new isotopic data from the Stanner Hanter Complex, represents part of an ongoing reappraisal of the terrane affinities of southern Britain.

3. Geology of the Stanner Hanter Complex

The Stanner Hanter Complex forms an inlier of intrusive igneous rocks cropping out west of the village of Kington in the Welsh Borderland (Fig. 1). It is contained within splays of the Church Stretton Fault, part of the Welsh Borderland Fault System (WBFS), and was considered an exposure of the basement to the Wrekin Terrane by Pharaoh *et al.* (1987). Although contacts are poorly exposed, the inlier is interpreted to be overstepped by strata of Silurian age on its southern

†Author for correspondence: dis@bgs.ac.uk

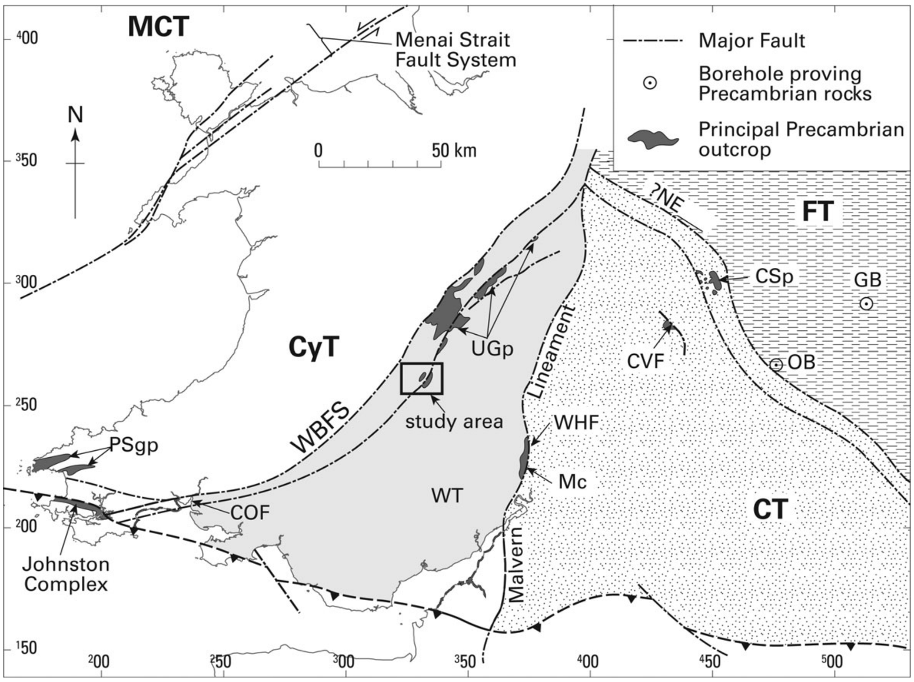

Figure 1. Terrane map of southern Britain after British Geological Survey (1996) and Pharaoh & Carney (2000). MCT – Monian Composite Terrane; FT – Fenland Terrane; CT – Charnwood Terrane; WT – Wrekin Terrane; CyT – Cymru Terrane; CSp – Charnian Supergroup; CVF – Caldecote Volcanic Formation; WHF – Warren House Formation; Mc – Malverns Complex; UGp – Uriconian Group; COF – Coombe Volcanic Formation; PSgp – Pebidian Supergroup; NECBF – NE Charnwood Boundary Fault; WBFS – Welsh Borderland Fault System; GB – Glinton borehole; OB – Orton borehole. Box shows approximate location of Stanner Hanter Complex as illustrated in Figure 2. Co-ordinates are British National Grid.

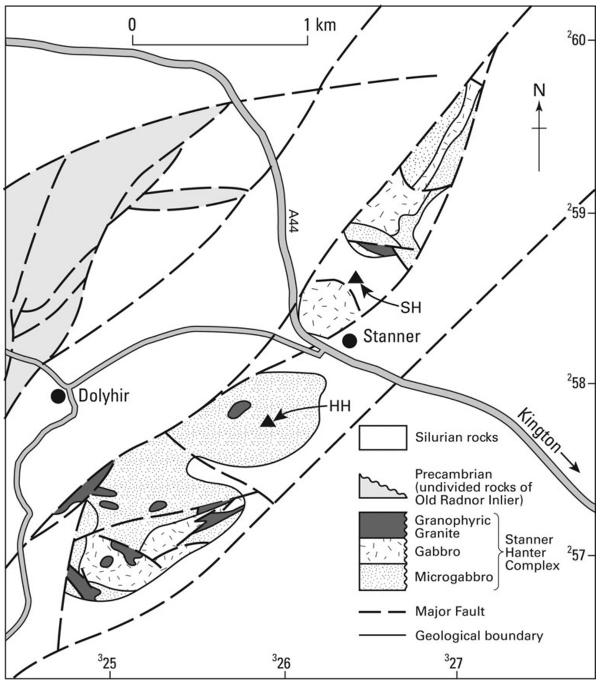

Figure 2. Geological map of the Stanner Hanter Complex (after Holgate & Hallowes, 1941; Woodcock, 1988). Filled triangles indicate the summits of Hanter Hill (HH) and Stanner Hill (SH). Co-ordinates are British National Grid.

and eastern margin, but faulted along its northern contact (Holgate & Hallowes, 1941; Fig. 2).

The Church Stretton Fault makes up the easternmost strand of the Welsh Borderland Fault System, part of a plexus of structures that mark the transition from thick basinal deposits of the Lower Palaeozoic Welsh Basin to the west to the condensed sequences of the Midland Platform to the east (Woodcock & Gibbons, 1988). The fault is thought to preserve a long history of movement, including a significant inferred component of transcurrent displacement (Woodcock, 1988). Fault reactivation during the Early Palaeozoic appears to have strongly influenced sedimentation in the region; indeed the angular unconformity between Longmyndian and overlying Cambrian rocks of the nearby Wrekin hills (see below) provides evidence for probable Late Neoproterozoic movements (Greig *et al.* 1968), while an angular sub-Wenlock unconformity has been taken to indicate an episode of pre-Acadian (Early- to Mid-Devonian), probably Late Ashgill-age, tectonism (Woodcock, 1988; Woodcock & Gibbons, 1988).

Along strike to the northeast, the Church Stretton and Pontesford Linley faults (or Pontesford Lineament, a basinward strand of the Welsh Borderland Fault System) enclose additional Neoproterozoic to Early Cambrian age inliers (Fig. 3), which along with the Malvern Complex to the east make up the entire exposure of the proposed Wrekin Terrane (Fig. 1). Recent interpretations (Pharaoh & Carney, 2000) treat the units enclosed by the Welsh Borderland Fault System as a single tectonostratigraphic succession in which the Stanner Hanter Complex preserves the oldest isotopic age. The nearby Rushton Schist is reported to have a younger Rb–Sr whole rock isochron age of 667 ± 20 Ma (Thorpe *et al.* 1984), which along with the Primrose Hill Gneiss have been interpreted as metamorphosed sedimentary remnants of unknown protolith age.

Adjacent to these, also located within splays of the Church Stretton Fault, are a succession of acid, intermediate and basic tuffs and lavas of the Uriconian Group and intrusive Ercall Granophyre (Fig. 3). Rhyolite from the former has yielded a

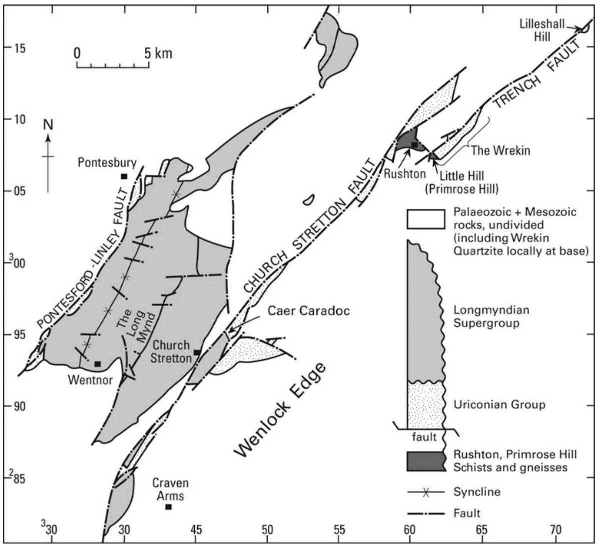

Figure 3. Geological map of the Wrekin terrane inliers after Pauley (1991) and Pharaoh & Carney (2000). Co-ordinates are British National Grid.

U–Pb age of 566 ± 2 Ma, while the Ercall Granophyre has been dated at 560 ± 1 Ma (Tucker & Pharoah, 1991). The Uriconian Group is overlain by a 6500 m thick succession of the Longmyndian Supergroup which has yielded a U–Pb age from tuff and bentonite within the succession of 555.9 ± 3.5 Ma (Compston, Wright & Toghill, 2002). Although the nature of their relationship has been the matter of some debate, James (1952, 1956) argued that the presence of volcanic clasts similar to Uriconian lithologies demonstrated an unconformable relationship between the two. The youngest rocks of the Wrekin Terrane are represented by a succession of Early to Middle Cambrian sedimentary rocks, the Wrekin Quartzite and Lower and Upper Comley sandstones. The Wrekin Quartzite comprises approximately 50 m of indurated shoreface sands (Wright *et al.* 1993), which were recognized by Callaway (1879) and Cope & Gibbons (1987), on the basis of derived volcanic pebbles, as unconformably overlying the Uriconian Group. The age of the Wrekin Quartzite is poorly constrained to a Placentia Series age (approximately 543–520 Ma) on the basis of a sparse shelly fauna (Brasier, 1989), while the overlying Lower and Upper Comley sandstones have yielded a more extensive fauna spanning Branch to St David's series ages (approximately 520–510 Ma; Rushton, Hamblin & Strong, 1988; Greig *et al.* 1968).

The Stanner Hanter Complex comprises an assemblage of igneous rocks, dominated by basic lithologies but containing significant intermediate and acid components. Lithologies are generally highly altered and the complex itself is dissected by numerous faults (Fig. 2). Pocock & Whitehead (1935) recognized similarities with the nearby Uriconian Group, although subsequent dating (Tucker & Pharoah, 1991) has shown it to be significantly younger than the Stanner Hanter Complex. Holgate & Hallowes (1941) recognized a fourfold division of sequentially emplaced lithologies, whereas Jones (2000) identified the importance of magma mixing in the assembly of the complex. The oldest component, a fine-grained microgabbro, is interpreted as having intruded into an unspecified host rock as a series of sills (Jones, 2000) and forms the majority of the exposure of the inlier. These were intruded by an array of coalesced, dyke-like gabbro sheets with prominent chilled margins. A larger gabbro body, exposed on Hanter Hill, has a low-angled basal contact, preserves compositional layering which becomes considerably more leucocratic toward the top, and was considered by Jones (2000) as a remnant section through a small magma chamber. Jones (2000) also interpreted interaction of the gabbroic facies with the final phase of narrow sheets of locally porphyritic, biotite microgranite containing abundant microgabbro xenoliths with strongly cuspate margins to indicate magma mixing and mingling. A phase of tourmaline mineralization within the main gabbro body has also been linked to the intrusion of the final granitic intrusive phase (Holgate, 1977). Hydrous alteration of all the magmatic facies is widespread.

4. Isotope analysis

Zircon grains were separated from a sample of granophyric granitic rock from the Stanner Hanter Complex. The sample was collected from a small unit of the intrusive biotite microgranite facies exposed on the flanks of Hanter Hill [325253 257860]. The separated zircons were chemically abraded (Mattinson, 2005) and analysed at the NERC Isotope Geoscience Laboratories (NIGL), following the procedures of Noble, Tucker & Pharaoh (1993). Chemistry blanks were ~ 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 Isoplot/Ex (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). Sm–Nd whole-rock analyses were also carried out at NIGL on two further samples from the complex, one of granitic rock sampled from Hanter Hill [324791 256845] and one of gabbro collected from nearby Stanner Rocks [32617 3258282]. Data for both U–Pb and Sm–Nd analyses are presented in Appendix Tables A1 and A2, respectively, available as supplementary material online at http://www.cambridge.org/journals/geo.

5. Discussion

Of six analysed zircon fractions, one is highly discordant, with a $^{207}Pb/^{206}Pb$ model age of *c.* 1035 Ma, indicating the presence of an inherited component. The remaining five grains lie on concordia, and give a weighted mean $^{206}Pb/^{238}U$ age of 710.8 ± 1.5 Ma (95 % confidence limits), which is interpreted to reflect the crystallization age of the latest, granitic facies of the complex (Fig. 4). This age is similar to, and just within error of, the 702 ± 8 Ma Rb–Sr isochron age of Patchett *et al.* (1980), yielded from granitic rocks collected from the adjacent Stanner Hill, and suggests that the latter age also approximates to the age of crystallization of that facies.

The new zircon age confirms that the Stanner Hanter Complex therefore remains the oldest known outcrop of the crystalline basement of southern Britain. The complex also appears to have largely been unaffected by subsequent thermal events within the Wrekin Terrane, such as the *c.* 667 Ma metamorphic event preserved in the Rushton Schist, and 667–650 Ma metamorphic event preserved in the nearby Malverns Complex (Strachan *et al.* 1996, 2007).

Much of both western and eastern Avalonia is dominated by arc magmatic rocks ranging between 635 and 550 Ma in age (Nance, Murphy & Keppie, 2002). Importantly, the new age data from the Stanner Hanter Complex confirms that it represents one of a dispersed number of magmatic relicts that together record an older, *c.* 765 to 650 Ma, cycle of arc magmatism (Nance, Murphy & Keppie, 2002) that

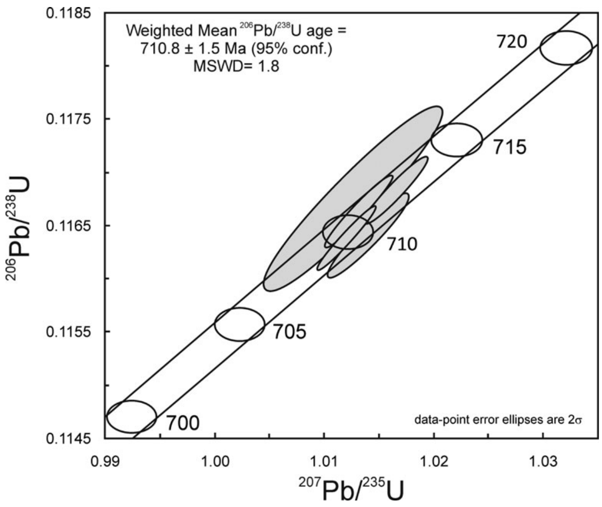

Figure 4. U–Pb concordia plot showing data from six zircon fractions. The error quoted on the age includes decay constant errors and the MSWD incorporates concordance and equivalence.

critically relates the basement of southern Britain to other Avalonian-type terranes preserved along the Caledonian–Appalachian Orogen. Examples from the Avalonian terrane of southern Newfoundland include: *c.* 687–670 Ma calc-alkaline volcanic rocks of the Tickle Point Formation and Furbys Cove Intrusive Suite (Swinden & Hunt, 1991; O'Brien *et al.* 1995); the *c.* 680 Ma Cinq Cerf–Grey River gneiss terrane (Dunning & O'Brien, 1989; Valverde-Vaquero, Dunning & O'Brien, 2006); the *c.* 760 Ma Burin Group (Murphy *et al.* 2008); and *c.* 730 Ma felsic magmatic rocks of the Holyrood Horst on the Avalon Peninsula (O'Brien *et al.* 2001). Early arc complexes of Nova Scotia include: the *c.* 676 Ma Stirling Belt (Bevier *et al.* 1993); the *c.* 700–630 Ma volcanic rocks of the Creignish Hills (Keppie & Dostal, 1998); the *c.* 734 Ma calc-alkaline Economy River Gneiss (Doig, Murphy & Nance, 1993); and the proposed back-arc basin succession of the Gamble Brook Formation (Murphy, 2002). Beyond Avalonia, this phase of arc magmatism has been recorded by the *c.* 746 Ma Pentevrian Complex of the Cadomian Terrane in France (Egal *et al.* 1996).

εNd values of −0.3 (gabbro) to −1.2 (granitic rock) from the complex are slightly lower than estimated bulk earth compositions. Because ancient crustal material evolves toward negative εNd, the implication of these data is that the Stanner Hanter magmas were generated either by reworking of pre-existing crust, or mixing of contemporary mantle-derived magma with much older crustal material. In the first case, T_{DM} of 1393 Ma and 1469 Ma, respectively, for the two samples would approximate to the age for that source material. However, when taken together with analyses from the Orton and Glinton boreholes of the Fenland Terrane, which have yielded εNd values of −4.03 to −4.46 and T_{DM} ranging from 1614 Ma to 1644 Ma (two-stage depleted mantle model ages, recalculated from Noble, Tucker & Pharaoh, 1993), the Sm–Nd data suggest that mixing of *c.* 700 Ma mantle-derived magmas with a more ancient, Palaeoproterozoic or Archaean, source component is more likely. The analysed sample from the Stanner Hanter Complex contained one highly discordant zircon grain (online Appendix Table A1), which, if regressed through the intrusion age of 710.8 ± 1.5 Ma, yields an upper intercept age of *c.* 1648 Ma. Clearly, little weight can be placed upon such highly discordant data, but this at least confirms the presence of more ancient crustal material in the Stanner Hanter granite.

These data contrast with typical values for Neoproterozoic igneous rock from the western Avalonian terranes of Newfoundland and Nova Scotia, which typically have positive εNd values and $T_{DM} < 1.0$ Ga (e.g. Murphy *et al.* 2000). Previous studies (e.g. Nance & Murphy, 1994; Murphy *et al.* 2000) have argued against the presence of ancient basement as a source component to the Avalonian terranes, favouring derivation from relatively juvenile 'Grenvilian' age, *c.* 1 Ga, island arcs or ocean plateaux formed during the assembly of the supercontinent of Rodinia. A more detailed study of the age distribution of inherited zircon in the Stanner Hanter granite would be required to test for the presence of such Grenville-aged material.

Some Late Neoproterozoic palaeogeographic reconstructions (e.g. Murphy *et al.* 2000) indicate that eastern Avalonia formed adjacent to the West African Craton. The latter is largely characterized by magmatic rocks formed during the *c.* 2.1 Ga Eburnean orogenic cycle as well as older, Archaean phases of crustal growth and accretion. Continental crust of this age is therefore the most likely potential source component contributing to the evolved Sm–Nd characteristics of the Late Neoproterozoic magmas of eastern Avalonia. Although not exposed in southern Britain, remnants of cratonic basement are preserved in other peri-Gondwanan terranes also thought to have originated adjacent to the West African Craton terranes. These include the *c.* 2.1 Ga Icartian Gneiss and Svetlik Gneiss of Cadomia (Samson & D'Lemos, 1998) and Bohemia (Wendt *et al.* 1993), respectively. Indeed, the Stanner Hanter rocks lie within the range of isotopic compositions for mixed source granitic magmas from Cadomia (εNd values of +1.6 to −1.9 and T_{DM} ranging from 1.0 to 1.9 Ga; D'Lemos & Brown, 1993) and illustrate the potential input of an ancient crustal source of similar age. Alternative palaeogeographic reconstructions (e.g. Samson *et al.* 2005; Strachan *et al.* 2007) suggest that Avalonia was further around the Gondwanan margin, adjacent to the Amazon Craton, during Late Neoproterozoic times. This region is in part distinguished from the West African Craton by the presence of Mesoproterozoic belts ranging from around 1.6 to 1.0 Ga in age (e.g. Tassinari & Macambira, 1999), which overlap with the T_{DM} values from eastern Avalonia and provide another potential crustal source region to the Stanner Hanter Complex.

In conclusion, it should be noted that apparent fundamental isotopic differences in source composition between eastern and western Avalonia highlighted by these new data are balanced against similar, bi-partite cycles of arc magmatism and accretion that distinguish the Avalonian type from other peri-Gondwanan terranes (Keppie *et al.* 1991). These data show that a more thorough investigation of the terrane and palaeogeographic affinities of eastern Avalonia is called for, requiring a more comprehensive isotopic dataset than is currently available.

Acknowledgements. D. I. Schofield and P. R. Wilby publish with the permission of the Executive Director, British Geological Survey.

References

ALLEN, P. M. & JACKSON, A. A. 1978. Bryn-Teg Borehole, North Wales. *Bulletin of the Geological Survey of Great Britain* **61**, 51 pp.

BARCLAY, W. J., AMBROSE, K., CHADWICK, R. A. & PHARAOH, T. C. 1997. *Geology of the country around*

Worcester. Memoir of the British Geological Survey, Sheet 199 (England and Wales). Keyworth, Nottingham: British Geological Survey, 156 pp.

BEVIER, M. L., BARR, S. M., WHITE, C. E. & MACDONALD, A. S. 1993. U–Pb geochronologic constraints on the volcanic evolution of the Mira (Avalon) terrane, southeastern Cape Breton Island, Nova Scotia. *Canadian Journal of Earth Sciences* **30**, 1–10.

BRASIER, M. D. 1989. Sections in England and their correlation. In *The Precambrian–Cambrian Boundary* (eds J. W. Cowie & M. D. Brasier), pp. 82–104. Oxford University Press.

BRITISH GEOLOGICAL SURVEY. 1996. *Tectonic map of Britain, Ireland and adjacent areas.* 1:1 500 000 scale. Keyworth, Nottingham: British Geological Survey.

CALLAWAY, C. 1879. The Precambrian Rocks of Shropshire – Part 1. *Quarterly Journal of the Geological Society of London* **35**, 643–62.

COMPSTON, W., WRIGHT, A. E. & TOGHILL, P. 2002. Dating the Late Precambrian volcanicity of England and Wales. *Journal of the Geological Society, London* **159**, 323–39.

COPE, J. C. W. & GIBBONS, W. 1987. New evidence for the relative age of the Ercall Granophyre and its bearing on the Precambrian–Cambrian boundary in southern Britain. *Geological Journal* **22**, 53–60.

D'LEMOS, R. S. & BROWN, M. 1993. Sm–Nd isotope characteristics of late cadomian granite magmatism in northern France and the Channel Islands. *Geological Magazine* **130**, 797–804.

DOIG, R., MURPHY, J. B. & NANCE, R. D. 1993. Tectonic significance of the Late Proterozoic Economy River Gneiss, Cobequid Highlands, Avalon composite terrane, Nova Scotia. *Canadian Journal of Earth Sciences* **30**, 474–9.

DUNNING, G. R. & O'BRIEN, S. J. 1989. Late Proterozoic–Early Palaeozoic crust in the Hermitage flexure, Newfoundland Appalachians: U–Pb ages and tectonic significance. *Geology* **17**, 548–51.

EGAL, E., GUERROT, C., LE GOFF, D., THIEBLEMONT, D. & CHANTRAINE, J. 1996. The Cadomian orogeny revisited in northern France. In *Avalonian and Related Peri-Gondwanan Terranes of the Circum North Atlantic* (eds R. D. Nance & M. D. Thompson), pp. 281–318. Geological Society of America, Special Paper no. 304.

GIBBONS, W. & HORÁK, J. M. 1996. The evolution of the Neoproterozoic Avalonian subduction system: evidence from the British Isles, In *Avalonian and Related Peri-Gondwanan Terranes of the Circum North Atlantic* (eds R. D. Nance & M. D. Thompson), pp. 269–80. Geological Society of America, Special Paper no. 304.

GREIG, D. C., WRIGHT, J. E., HAINS, B. A. & MITCHELL, G. H. 1968. *Geology of the Country around Church Stretton, Craven Arms, Wenlock Edge and Brown Clee*. Memoir of the Geological Survey of Great Britain, England and Wales Sheet 166. London: HMSO.

HOLGATE, N. 1977. Tourmaline from amphibolized gabbro at Hanter Hill, Radnorshire. *Mineralogical Magazine* **41**, 124–7.

HOLGATE, N. & HALLOWES, K. A. K. 1941. The igneous rocks of the Stanner-Hanter district, Radnorshire. *Geological Magazine* **78**, 241–67.

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.

JAMES, J. H. 1952. Notes on the Relationship of the Uriconian and Longmyndian rocks near Linley, Shropshire. *Proceedings of the Geologist's Association* **63**, 198–200.

JAMES, J. H. 1956. The structure and stratigraphy of part of the Pre-Cambrian outcrop between Church Stretton and Linley, Shropshire. *Quarterly Journal of the Geological Society, London* **112**, 315–37.

JONES, K. A. 2000. *Hanter Hill.* In *Precambrian Rocks of England and Wales* (eds J. N. Carney, J. M. Horák, T. C. Pharaoh, W. Gibbons, D. Wilson, W. J. Barclay & R. E. Bevins), pp. 118–22. Geological Conservation Review Series 20. Peterborough: Joint Nature Conservation Committee.

KAWAI, T., WINDLEY, B. F., TERABAYASHI, M., YAMAMOTO, H., MARUYAMA, S., OMORI, S., SHIBUYA, T., SAWAKI, Y. & ISOZAKI, Y. 2007. 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.

KEPPIE, J. D. & DOSTAL, J. 1998. Birth of the Avalonian arc in Nova Scotia, Canada: geochemical evidence for 700–630 Ma back-arc rift volcanism off Gondwana. *Geological Magazine* **135**, 171–81.

KEPPIE, J. D., NANCE, R. D., MURPHY, J. B. & DOSTAL, J. 1991. The Avalon Terrane. In *The West African Orogens and Circum-Atlantic Correlatives* (eds R. D. Dallmayer & J. P. Lecorché), pp. 315–33. New York: Springer.

KEPPIE, J. D., NANCE, R. D., 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.

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.* Berkley Geochronological Centre, Special Publication no. 4, 71 pp.

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.

MURPHY, J. B. 2002. Geochemistry of the Neoproterozoic metasedimentary Gamble Brook Formation, Avalon Terrane, Nova Scotia: evidence for a rifted arc environment along the West Gondwanan margin of Rodinia. *Journal of Geology* **110**, 407–20.

MURPHY, J. B., MCCAUSLAND, P. J. A., O'BRIEN, S. J., PISAREVSKY, S. & HAMILTON, M. A. 2008. Age, geochemistry and Sm–Nd isotopic signature of the 0.76 Ga Burin Group: compositional equivalent of Avalonian basement? *Precambrian Research* **165**, 37–48.

MURPHY, J. B., PISAREVSKY, S. A., NANCE, R. D. & KEPPIE, J. D. 2004. Neoproterozoic–Early Palaeozoic evolution of peri-Gondwanan terranes: implications for Laurentia–Gondwana connections. *International Journal of Earth Sciences* **93**, 659–82.

MURPHY, J. B., STRACHAN, R. A., NANCE, R. D., PARKER, K. D. & FOWLER, M. B. 2000. Proto-Avalonia: a 1.2–1.0 Ga tectonothermal event and constraints for the evolution of Rodinia. *Geology* **28**, 1071–4.

NANCE, R. D. & MURPHY, J. B. 1994. Contrasting basement isotopic signatures and the palinspastic restoration of peripheral orogens: Example from the Neoproterozoic Avalonian–Cadomian belt. *Geology* **22**, 617–20.

NANCE, R. D., MURPHY, J. B. & KEPPIE, J. D. 2002. Cordilleran model for the evolution of Avalonia. *Tectonophysics* **352**, 11–32.

NANCE, R. D., MURPHY, J. B., STRACHAN, R. A., KEPPIE, J. D., GUTIÉRREZ-ALONSO, G., Fernández-Suárez, QUESADE, C., LINNEMANN, U., D'LEMOS, R. & PISAREVSKY, S. A. 2008. Neoproterozoic-early

Palaeozoic tectonostratigraphy and palaeogeography of the per-Gondwanan terranes: Amazonian v. West African connections. In *The Boundaries of the West African Craton* (eds N. Ennih & J.-P. Liégeois), pp. 345–83. Geological Society of London, Special Publication no. 297.

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

O'BRIEN, S. J., DUNNING, G. R., DUBÉ, B., O'DRISCOLL, C. F., SPARKES, B., ISRAEL, S. & KETCHUM, J. 2001. New insights into the Neoproterozoic geology of the central Avalon Peninsula (parts of map areas 1N/6 and 1N/3), Eastern Newfoundland. *Current Research (2001), Newfoundland Department of Mines and Energy, Geological Survey Report* **2001–1**, 169–89.

O'BRIEN, S. J., O'DRISCOLL, C. F., GREENE, B. A. & TUCKER, R. D. 1995. Pre-Carboniferous geology of the Connaigre Peninsula and the adjacent coast of fortune bay, Southern Newfoundland. *Current Research (1995), Newfoundland Department of Natural Resources, Geological Survey Report* **1995–1**, 267–98.

PATCHETT, P. J., GALE, N. H., GOODWIN, R. & HUMM, M. J. 1980. Rb–Sr whole-rock isochron ages of late Precambrian to Cambrian igneous rocks from southern Britain. *Journal of the Geological Society, London* **137**, 649–56.

PAULEY, J. C. 1991. A revision of the stratigraphy of the Longmyndian Supergroup, Welsh Borderland, and its relationship to the Uriconian volcanic complex. *Geological Journal* **26**, 167–83.

PHARAOH, T. C. & CARNEY, J. N. 2000. Introduction to the Precambrian rocks of England and Wales. In *Precambrian Rocks of England and Wales* (eds J. N. Carney, J. M. Horák, T. C. Pharaoh, W. Gibbons, D. Wilson, W. J. Barclay & R. E. Bevins), pp. 1–18. Geological Conservation Review Series 20. Peterborough: Joint Nature Conservation Committee.

PHARAOH, T. C., MERRIMAN, R. J., EVANS, J. A., BREWER, T. S., WEBB, P. C. & SMITH, N. J. P. 1991. Early Palaeozoic arc-related volcanism in the concealed Caledonides of southern Britain. *Annales de la Société Géoloqique de Belgique* **114**, 63–91.

PHARAOH, T. C., WEBB, P. C., THORPE, R. S. & BECKINSALE, R. D. 1987. Geochemical evidence for the tectonic setting of late Proterozoic volcanic suites in central England. In *Geochemistry and Mineralization of Proterozoic Volcanic Suites* (eds T. C. Pharaoh, R. D. Beckinsale & D. Rickard), pp. 541–52. Geological Society of London, Special Publication no. 33.

POCOCK, R. W. & WHITEHEAD, T. H. 1935. *British Regional Geology: The Welsh Borderland*. London: H. M. Geological Survey and Museum, 84 pp.

RUSHTON, A. W. A., HAMBLIN, R. J. O. & STRONG, G. E. 1988. *The Croft borehole in the Lilleshall inlier of north Shropshire.* Report of the British Geological Survey no. 19.

SAMSON, S. D. & D'LEMOS, R. S. 1998. U–Pb geochemistry and Sm–Nd isotopic composition of Proterozoic gneisses, Channel Islands, U.K. *Journal of the Geological Society, London* **156**, 47–54.

SAMSON, S. D., D'LEMOS, R. S., MILLER, B. V. & HAMILTON, M. A. 2005. Neoproterozoic palaeogeography of the Cadomia and Avalon terranes: constraints from detrital zircon U–Pb ages. *Journal of the Geological Society, London* **162**, 65–71.

SCHOFIELD, D. I., EVANS, J. A., MILLAR, I. L., WILBY, P. R. & ASPDEN, J. A. 2008. New U–Pb and Rb–Sr constraints on pre-Acadian tectonism in North Wales. *Journal of the Geological Society, London* **165**, 891–4.

STACEY, J. S. & KRAMERS, J. D. 1975. Approximation of terrestrial lead isotope evolution by a two stage model. *Earth and Planetary Science Letters* **26**, 207–21.

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.

STRACHAN, R. A., NANCE, R. D., DALLMEYER, R. D., D'LEMOS, R. S., MURPHY, J. B. & WATT, G. R. 1996. Late Precambrian tectonothermal evolution of the Malverns Complex. *Journal of the Geological Society, London* **153**, 589–600.

SWINDEN, S. & HUNT, P. A. 1991. A U–Pb age from the Connaigre Bay Group, Southwestern Newfoundland: Implications for regional correlations and metallogenesis. *Radiometric and isotopic studies, Report 4. Geological Survey of Canada Special Paper* **90–2**, 3–10.

TASSINARI, C. C. G. & MACAMBIRA, M. J. B. 1999. Geochronological provinces of the Amazonian Craton. *Episodes* **22**, 174–82.

THORPE, R. S., BECKINSALE, R. D., PATCHETT, P. J., PIPER, A., DAVIES, G. R. & EVANS, J. A. 1984. Crustal growth and late Precambrian-early Palaeozoic plate tectonic evolution of England and Wales. *Journal of the Geological Society, London* **141**, 521–36.

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**, 435–43.

VALVERDE-VAQUERO, P., DUNNING, G. R. & O'BRIEN, S. J. 2006. Polycyclic evolution of Late Neoproterozoic basement in the Hermitage Flexure region (southwest Newfoundland Appalachians): New evidence from the Cinq-Cerf gneiss. *Precambrian Research* **148**, 1–18.

WENDT, J. I., KRÖNER, A., FIALA, J. & TODT, W. 1993. Evidence from zircon dating for existence of approximately 2.1 Ga old crystalline basement in southern Bohemia, Czech Republic. *Geologische Rundschau* **82**, 42–50.

WOODCOCK, N. H. 1988. Strike-slip faulting along the Church Stretton Lineament, Old Radnor Inlier, Wales. *Journal of the Geological Society, London* **145**, 925–33.

WOODCOCK, N. H. & GIBBONS, W. 1988. Is the Welsh Borderland Fault System a terrane boundary? *Journal of the Geological Society, London* **145**, 915–33.

WRIGHT, A. E., FAIRCHILD, I. J., MOSELEY, F. & DOWNEY, C. 1993. The lower Cambrian Wrekin Quartzite and the age of its unconformity on the Ercall Granophyre. *Geological Magazine* **130**, 257–64.