No Exploits back-arc basin in the Iapetus suture zone of Ireland

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Abstract: A controversial aspect of the closure history of the Iapetus Ocean concerns the existence of the Exploits basin in Ireland and Britain. The Exploits–Tetagouche back-arc basin of the Canadian Appalachians opened during the Middle Ordovician as the Popelogan–Victoria volcanic arc migrated northwards from the Ganderian margin. The Bellewstown Terrane, within the Iapetus suture zone of Ireland, lies between the Ganderian–Avalonian Leinster Terrane and the Laurentian Grangegeeth Terrane. An early Ordovician ‘Celtic’ shelly fauna is hosted in volcanogenic breccia that we demonstrate is stratigraphically overlain by shales with no volcanic horizons. The lower 24 m of shale are unfossiliferous, but shale above this stratigraphic level has yielded a new graptolite fauna consistent with the upper part of the artus Biozone (Darriwilian, c. 464 Ma). U–Pb zircon dating of the volcanic horizon yields an age of c. 474 Ma. The shale, therefore, appears to represent c. 10 myr of deposition and a significant gap in volcanism. This, together with a Sandbian Anglo-Welsh fauna, suggests that the Bellewstown Terrane remained in a peri-Gondwanan position throughout the Ordovician. Hence, Exploits back-arc basin opening and Ganderian arc migration did not occur in the Irish sector of Iapetus.

Supplementary materials: The table of U–Pb zircon data, CL images of zircon grains, concordia plot of all U–Pb zircon analyses, and additional drawings and notes on the graptolite fauna are available at www.geolsoc.org.uk/SUP18858.

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Plate tectonic reconstructions indicate that several volcanic arcs were sequentially created and accreted during Ordovician to Silurian subduction and closure of Iapetus (van Staal et al. 1998, 2007; Chew et al. 2010; Hollis et al. 2012). The timing of volcanism in arc sequences, both flare-up and shut-off, is therefore an important constraint in reconstructing the closure history of Iapetus, especially when combined with faunal provincialism or other palaeogeographical indicators.

An element of the closure history of Iapetus that remains controversial in correlating sequences along the Caledonian–Appalachian orogeny concerns the existence of the Exploits basin in Ireland and Britain. The Exploits–Tetagouche (hereafter Exploits) back-arc basin of the Canadian Appalachians opened during the Middle Ordovician as the Popelogan–Victoria volcanic arc migrated northwards from the Ganderian margin above a retreating, southward subducting plate (van Staal et al. 1998; Zagorevski et al. 2010). This migration carried early Ordovician peri-Gondwanan sequences and faunas to the Laurentian margin by late Ordovician times (Williams et al. 1995), while a Middle Ordovician basin fill including basalts and volcaniclastic turbidites was accumulated (O’Brien et al. 1997). Van Staal et al. (1998) proposed that the Ordovician volcanic Grangegeeth Terrane and the late Ordovician to Silurian black shales–turbidite sequences of the Longford–Down Terrane of eastern Ireland were elements of the Exploits basin, placing the Gondwanan–Laurentian boundary in Ireland further north than previously recognized. McConnell et al. (2010), however, found that the Grangegeeth Terrane was Laurentian throughout its history. Furthermore, Waldron et al. (2014) found no Gondwanan detrital zircon provenance signal in the late Ordovician to early Silurian sedimentary rocks of the Southern Uplands of Scotland and argued against the model that a volcanic arc founded on Ganderian crust had migrated to the Laurentian margin by late Ordovician times.

The Bellewstown Terrane is an Ordovician volcanic arc fragment within the broad Iapetus suture zone of eastern Ireland (Fig. 1). The terrane is generally regarded as ‘intra-Iapetus’ in affinity; it lies tectonically between the Ganderian–Avalonian Leinster Terrane to the south (Murphy 1987) and the Laurentian Grangegeeth Terrane to the north (McConnell et al. 2010) and contains a synvolcanic early Ordovician ‘Celtic’ shelly fauna that is neither Laurentian nor Gondwanan (Harper et al. 1990). An overlying Sandbian Anglo-Welsh fauna is more typically Avalonian (Parkes & Harper 1996). Harper et al. (1990, 1992) compared the Bellewstown ‘Celtic’ fauna with those of some volcanic arc sequences in the Exploits Subzone of Newfoundland.

This paper presents new findings from recently created exposures in Bellewstown quarry. Study of these exposures has provided previously unknown stratigraphical constraints and yielded a new graptolite fauna that, together with a new U–Pb zircon date from a volcaniclastic sandstone, permits a detailed assessment of the timing of volcanism in the Bellewstown Terrane. Our new findings provide evidence against the existence of the Exploits basin in this sector of Iapetus.

Geological setting

The Bellewstown Terrane is bounded to the north by the Slane Fault against the Grangegeeth Terrane, and to the south by the Lowther Lodge Fault against the Leinster Terrane (Fig. 1; Murphy 1987; Vaughan & Johnston 1992). The oldest exposed rocks are early Ordovician slates and siltstones with slump breccias and coticules of the Prioryland Formation (Harper & Rast 1964; Murphy 1987). The formation is estimated to have a minimum thickness of 800 m. Possible Tremadoc acritarchs have been recovered from the lower part, which, together with the presence of coticules, suggest a correlation with the Ribband Group of SE Ireland (Kennan & Murphy 1998).
The Hilltown Formation is overlain by a 6 m thick unit of cal-

tuffaceous shales and dark mudstones of the Carnes Formation

Darriwilian) age (Harper & Rast 1964; Parkes & Harper 1996).

Paleontological collections from equivalent horizons (Rushton 1991) has found the

gnot be determined; conodonts suggest a late Llanvirn (late

Arenig (Floian–Dapingian) age from the Summerford Group of

Ordovician-Silurian accretionary

margin, Longford-Down terrane

Ordovician volcanic sequences (Carnes Fm. of early to mid-Ordovician felsic volcanic and fine-

grainer metasedimentary rocks (Harper & Rast 1964; Murphy

1987). Murphy (1987) suggested a calc-alkaline geochemical affin-

ity for the felsic volcanic rocks. Winchester & van Staal (1995)

instead proposed that the Hilltown Formation volcanic rocks are

tholeiitic, but their few analyses were of cross-cutting minor intru-

sions of uncertain relationship to the volcanic rocks.

An intra-Iapetus ‘Celtic’ brachiopod fauna (Paralenorthis sp.,

Jaanussonites sp., ‘Ahtiella’) has been documented from a volca-

nogenic breccia near the top of the Hilltown Formation at

Bellewstown (Harper et al. 1990). The fauna does not give a tight

age constraint, but suggests correlation with parts of the Dunnage

Zone of Newfoundland; it is most similar to faunas in rocks of

Arenig (Floian–Dapingian) age from the Summerford Group of

the Exploits Subzone (Harper et al. 1990, 1992). The Hilltown

Formation was, however, assigned by Harper & Rast (1964) to the

Bellewstown quarry

New exposures within the Hilltown Formation in Bellewstown

quarry (Fig. 2) reveal details of the brachiopod-bearing volcanogenic breccia described by Harper et al. (1990). The breccia unit is

stratified, with both normal and reverse grading and beds of vol-

caniclastic sandstone within the sequence. The upper breccia hori-

zon grades through bedded sandstone and siltstone to dark graptolitic shale. This upper transition has been investigated by
two cored boreholes through the section (Fig. 3), which demon-

strate a continuous fining-upward sequence from breccia to shale. Siltstone and shale in the transitional sequence contain wispy lam-

inae of reworked volcanicogenic sand, composed of feldspar crystals and

lithic grains of rhyolite, establishing a sedimentary link

between the volcanic rocks and shales (Fig. 3).

We interpret the breccia units as deposits of fluctuating volcanic mass flow, despite the occurrence of brachiopods in part of the

breccia matrix, because (1) clasts in the breccia are exclusively angular rhyolite, including some with jigsaw-fit shapes, or rip-ups of underlying volcanic sandstone; (2) both normal and reverse grading are present, and stratification is diffuse; (3) matrix and sandstone are composed of angular volcanic lithic grains and feld-

spar crystals in a devitrified glass matrix; (4) zircons extracted from sandstone (see below) are prismatic and magmatic in appearance.
Approximately 40 m of sulphide-rich shale are exposed in continuous quarry section above the volcaniclastic unit, without any further volcaniclastic beds or coarse sediment horizons. The lower 24 m of shale are unfossiliferous. The shale above 24 m has yielded a new graptolite fauna, preserved partly in pyrite.

**U–Pb zircon geochronology**

Zircons were separated from sandstone within the volcanogenic breccia, to obtain an age of the volcanism and to determine any provenance signal in inherited older grains (sample GSI10/220, collected adjacent to the drill site [Irish National Grid Ref. O 077 671], Fig. 2). U–Pb geochronology of the zircons was determined by laser ablation multi-collector inductively coupled plasma mass spectrometry (LA-MC-ICP-MS) at the NERC Isotope Geosciences Laboratory (NIGL), Nottingham, UK, using the methods as described by McConnell et al. (2009).

Analysis of 75 zircon grains in total from the Hilltown volcanoclastic sandstone (Fig. 4) yields a single age-probability peak at c. 474 Ma and a ‘TuffZirc’ age of 474.1 +1.0/–2.6 Ma. A single grain gave a late Precambrian age (c. 580 Ma).

We interpret the Ordovician age of c. 474 Ma as the age of volcanism at Bellewstown, which is consistent with the age of the associated brachiopods. The late Precambrian age of a single grain may indicate inheritance from an Avalonian crustal source (Pollock et al. 2009), but the paucity of older grains supports the interpretation that the volcanogenic breccia to sandstone unit is a primary volcanic deposit.

**New graptolite fauna**

The graptolites collected from cleaved dark grey mudrocks of the Hilltown Formation in Bellewstown quarry (Fig. 5) are from a level more than 24 m above the contact with the volcanic rocks. The fauna includes the following: (1) pendent didymograptid typical of Anglo-Welsh Llanvirn faunas from England and Wales; (2) the distinctive sinograptid *Nicholsonograptus fasciculatus* (Fig. 5a–c); (3) a variety of scendent biserial graptolites, most of them being early diplograptid forms. Many of the graptolites are pyritized and preserved in low or moderate relief, and whereas this may have lessened the effects of tectonic deformation, weathering has commonly caused the pyrite to oxidize, leaving the graptolites difficult to interpret.

The following have been identified: *Acrogrygraptus euodus* (Lapworth),? distal fragments; *Didymograptus cf. artus* Elles & Wood, several (Fig. 5f); *Nicholsonograptus fasciculatus* (Nicholson), 16 fragments (Fig. 5a–c); *Haddingograptus oliveri* (Bouéck), several (Fig. 5d and e); ‘Glyptograptid’ and ‘Climacograptid’, four or five specimens that represent forms of uncertain identity; *Cryptograptus* sp. indet., two scalariform views; *Pseudophyllograptus glossograptoides* (Ekström)?, two fragments.

This assemblage has features in common with Middle Ordovician (Llanvirn) faunas in England and Wales, especially with the graptolite fauna that Skevington (1970) described from mudrocks of the Skiddaw Group in the eastern Lake District; and also from equivalent strata in Sweden and Norway.

In England and Wales, the Abercricidian Stage (the lower part of the Llanvirn regional series; Forrey et al. 2000) is characterized by pendent *Didymograptus* species that have been used to divide the succession into the *artus* graptolite Zone, below, and the *murchisoni* Zone, above (Zalasiewicz et al. 2009, pp. 817–820). So far, no stratigraphical succession has been reported that is adequate to show details of the contact between these zones. However, there are descriptions of correlative successions in the Upper Didymograptus Shale of Scania, Sweden (Ekström 1937; Hede 1951) and in corresponding shales in Oslo Fjord, Norway (Maitz 1997) that show the succession of graptolites at around this level. Both Ekström (1937) and Hede (1951) recognized the short-ranging species *Azygograptus falciformis* Ekström that occurs somewhat above the base of the Upper Didymograptus Shale. Skevington (1966, p. 495) recorded Ekström’s species as a synonym of *N. fasciculatus*, and Maitz (1997, p. 36), in agreement with this, formalized a renaming of Ekström’s (1937) *falciformis* Subzone as the *fasciculatus* Zone.

Based on the ranges of graptolites in Scandinavia, the fauna from Bellewstown quarry is assigned to the *Nicholsonograptus fasciculatus* Zone of Maitz (1997). Furthermore, the presence of *Haddingograptus oliveri* (Fig. 5c and d), which appears in the *fasciculatus* Zone in Norway and ranges up through the overlying *Pterograptus elegans* Zone (Maitz 1997, fig. 2, p. 10), shows that the Bellewstown fauna is not older than the upper part of the British *artus* Zone (Loydell 2012). In terms of the Australasian graptolitic succession, the Bellewstown fauna may be correlated with the middle of the Darrwilian Series. The lowest division, Da1, is correlated with the upper part of the British regional Arenig Series, and Da2 approximates to the lower part of the *Didymograptus artus* Zone at the base of the Llanvirn Series. *Nicholsonograptus fasciculatus* is recorded from the subdivision Da3 (VandenBerg & Cooper 1992, p. 62).

**Discussion**

Our U–Pb zircon age of 474.1 +1.0/–2.6 Ma for the Hilltown volcanic breccia is significantly older than the upper *D. artus* Biozone age of...
the new graptolite fauna in the overlying shales (c. 464 Ma), with a
time gap of c. 10 myr on the timescale of Sadler et al. (2009) (Fig. 6).
We use the Sadler et al. (2009) timescale because the subsequent
Cooper & Sadler (2012) timescale includes a calibration point from
Slieve Gallion (Cooper et al. 2008) that has since been shown to be
unreliable (Hollis et al. 2013) and that distorts the position of the
stage boundaries in the section around the zircon age from
Bellewstown. Given that we have established a conformable strati-
graphical transition between the two, the simplest explanation
appears to be that the barren shale between the volcanic unit and the
graptolitic shale represents c. 10myr of deposition. This yields an
average sedimentation rate of 2.4 m Ma⁻¹, which is consistent with
rates for graptolitic shale in other Ordovician sequences (e.g. Churkin
et al. 1977) and deep-sea sedimentation generally (Stow et al. 1996).

Uninterrupted shale deposition for c. 10 myr, without any tuff or
bentonite layers, implies that volcanic activity in the Bellewstown

Fig. 3. Log of borehole GSI-14-04,
with photographs of core, showing (a)
laminae of reworked volcanic sand in
siltstone–shale transition, (b) graded base
and internal volcaniclastic breccia, and
(c) brecciated rhyolite.
Terrane ceased after emplacement of the c. 474 Ma volcaniclastic deposits. Volcanism in the Bellewstown sequence did not resume until after deposition of the Bellewstown Limestone Member, during early Sandbian deposition of the tuffaceous shales of the Carnes Formation. The section above the new graptolitic shale locality, through the Bellewstown limestone and into the Carnes Formation is poorly exposed, so it is not possible to be sure if volcanic horizons occur within that part of the sequence that would permit constraining the onset of renewed volcanism. The gap in volcanism is, however, at least throughout the upper Dapingian and lower Darriwilian (Fig. 6).

Upper Dapingian to lower Darriwilian volcanism is a feature of terranes of Laurentian affinity in Ireland (e.g. Dewey 1963; Graham et al. 1989; Hollis et al. 2012, 2013), and the Exploits back-arc basin of Newfoundland includes a Middle Ordovician basin fill including basalts and volcaniclastic turbidites (O’Brien et al. 1997). In contrast, the Hilltown Formation records a late Dapingian to Darriwilian gap in volcanism at Bellewstown. The overlying stratigraphy and fauna suggest a geological history shared with the Ganderian–Avalonian Leinster Terrane. At Bellewstown, the Llanvirn limestone member below renewed Sandbian volcanism and Anglo-Welsh fauna in the Carnes Formation is comparable with the situation in the Leinster Terrane, where the late Llanvirn Courtown–Tramore limestone at the base of the volcanic Duncannon Group rests unconformably on Floian to possibly Dapingian Ribband Group metasedimentary rocks (Fig. 6; Brenchley & Treagus 1970; McConnell 2000). Age control on the Ribband Group is poor (McConnell et al. 1999); a vari-corpus Biozone age for the Oaklands Formation (Rushiton 1996) suggests a correlation with the Prioryland Formation at Bellewstown, in agreement with correlation on lithological grounds (Murphy 1987; Kemman & Murphy 1993). Thus it appears that, in the southern part of Leinster, the sequence equivalent to the Hilltown Formation of Bellewstown is missing below the unconformity, which has been related to a Monian orogenic event to the south (Tietzsch-Tyler 1996). In the small Kildare inlier, in the northern part of the Leinster Terrane, the fine-grained metasedimentary Conlanstown Formation contains D. artus Biozone graptolites and
is overlain unconformably by the fossiliferous base of the volcanogenic mid-Sandbian Grange Allen Formation (Parkes & Palmer 1994). No volcanic rocks have been recorded from the Conlanstown Formation and it may be equivalent to the upper part of the Hilltown Formation at Bellewstown (Fig. 6). Sandbian volcanic rocks at Balbriggan and Lambay are correlated to the Kildare sequence as parts of a northern belt of the Upper Ordovician volcanic arc of SE Ireland (McConnell 2000), but no pre-Caradoc rocks are exposed in those places. The Lowther Lodge Fault separates the Balbriggan rocks from the Bellewstown Terrane to the north (Murphy 1987), but this fault records displacements within the active Ganderian margin of SE Ireland rather than accretion of exotic terranes.

After deposition of the early Ordovician rocks with ‘Celtic’ fauna, the Bellewstown Terrane became volcanically quiescent and remained in a peri-Gondwanan position, rather than migrating across Iapetus with the active Popelogan–Victoria volcanic arc sequences of the Exploits subzone of the Appalachians (see van Staal et al. 1998). The Bellewstown Terrane provides evidence that Exploits back-arc basin opening and arc migration did not occur in the Irish sector of Iapetus. Volcanic quiescence in the Hilltown Formation may equate to a pause in subduction related to initiation of Exploits basin extension. Renewed subduction produced abundant Upper Ordovician andesitic and felsic volcanism on the Ganderian margin in SE Ireland (McConnell 2000), which includes peralkaline rhyolites indicative of supra-subduction extension but no formation of basaltic crust (McConnell et al. 1991). Upper Ordovician volcanic rocks are absent from the equivalent margin to the south of the Exploits basin in Newfoundland because the active volcanic arc had migrated away. It is worth noting that extension-related peralkaline rhyolites at Avoca host the only significant economic volcanogenic massive sulphide deposit in the Ordovician rocks of SE Ireland, in contrast to the Central Mobile Belt of Newfoundland, where the Exploits back-arc basin hosts several such deposits (Rogers et al. 2007).

The Grangegeeth Terrane, to the north of Bellewstown, was formed at the Laurentian margin (McConnell et al. 2010) and so the Red Indian Line, the Laurentian–Gondwanan boundary, in eastern Ireland lies between Grangegeeth and Bellewstown along the Slane Fault and probably its extension along the Navan–Silvermines fault zone, the traditional ‘Iapetus suture’ in Ireland (Fig. 1; Phillips et al. 1976; Todd et al. 1991). Furthermore, because there was no Exploits back-arc basin, Silurian ocean closure in Ireland occurred along the same structure (Vaughan & Johnston 1992), unlike in the Canadian Appalachians where there are separate Ordovician and Silurian sutures.

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**Fig. 6.** Stratigraphical column for the Bellewstown sequence, showing new U–Pb zircon and graptolite ages for the Hilltown Formation, and comparative sequences in Kildare and south Leinster. Timescale from Sadler et al. (2009).

**Fig. 7.** Tectonic setting of the Ganderian margin of Ireland and Newfoundland, showing decoupling of Ireland from slab roll-back and Exploits basin formation in Newfoundland. It should be noted that the supra-subduction extension at Avoca in Ireland is later than Exploits basin formation.
Our interpretation from Bellewstown and the Ganderian margin of Ireland, that the Exploits back-arc basin is absent from that sector of Iapetus, is supported by the interpretation of Waldron et al. (2014), based on zircon provenance analysis, that a volcanic arc founded on Ganderian basement is not present in the Southern Uplands Terrane of the Scottish Laurentian margin. We conclude that Iapetus closure was not cylindrical along the orogen between Newfoundland and Ireland and that arc migration and Exploits back-arc basin opening did not occur along the Ireland and Britain sector of the Ganderian margin. We suggest that a hinge or an oceanic structure such as a transform fault allowed decoupling of the southern Iapetus subduction zone between Newfoundland and Ireland (Fig. 7), so that the active Ganderian margin in Ireland was isolated from slab roll-back and Exploits back-arc extension at the margin in Newfoundland.

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