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U-Pb zircon age constraints for the Ordovician Fishguard Volcanic Group and further evidence for the provenance of the Stonehenge bluestones

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New U-Pb zircon ages from rhyolite samples of the Fishguard Volcanic Group (FVG), southwest Wales, confirm a Middle Ordovician (Darriwilian) age for the group. One of the samples is from Craig Rhos-y-felin which has recently been identified on petrological and geochemical grounds as the source of much of the debitage at Stonehenge. Analysis of a Stonehenge rhyolite fragment yields an age comparable to the Craig Rhos-y-felin sample. Another Stonehenge fragment, thought to come from orthostat 48 and on petrographical grounds to be derived from the FVG (but not Craig Rhos-y-felin), yields an age also consistent with a FVG source.

Supplementary material: Details of analytical methods and a table of data are available at

For over 80 years, north Pembrokeshire has been thought to be the source of the majority of the so-called 'bluestones' used as orthostats (standing stones) in the world-renowned Stonehenge ancient monument, with specific outcrops in the Mynydd Preseli area being cited as source locations (Thomas 1923). Within the last decade the bluestones have been re-examined, petrographically and geochemically, and as a result these source locations have been challenged, with alternative, new sources being proposed (Bevins *et al.* 2011; Ixer & Bevins 2011a). This paper uses U-Pb zircon ages for samples from the FVG in north Pembrokeshire and from Stonehenge to test these recent proposals. The findings are supportive of one of the new Stonehenge sources proposed (the Craig Rhos-y-felin rhyolite) and strongly suggest that another of the Stonehenge rhyolites, as yet un-provenanced, is also from the Fishguard Volcanic Group. The precise location of the sources is critical for focussing archaeological investigations in order to take forward the long running debate

as to whether the Stonehenge bluestones were transported to Salisbury Plain by the actions of humans or by ice and by what route.

The Fishguard Volcanic Group (FVG) is a bimodal, acid-basic succession of Ordovician age which is exposed in north Pembrokeshire, southwest Wales (Fig. 1). It crops out from Porth Maen Melyn, to the southwest of Stumble Head, across the low ground north of Mynydd Preseli, to Crymych in the east. To date, its age has been determined on the basis of fossil evidence only, being ascribed to a Llanvirn (now Darriwilian) age on the presence of a fauna indicative of the *bifidus* (now *artus*) graptolite Biozone in black shales both above and below the volcanic succession exposed in cliffs at Fishguard Old Harbour (Thomas & Thomas 1956). However, more recent published (Burt *et al.* 2012) and unpublished investigations (C.J. Jenkins *pers. comm.* in Owens 2000) have re-described faunas from the area, with faunas below the volcanic succession being ascribed to the lower Abereiddian *artus* Zone and faunas from above the volcanic sequence being ascribed to a low level in the upper Abereiddian. The stratigraphic position of the FVG indicates eruption times close to the lower-upper Abereiddian boundary. According to Sadler *et al.* (2009) the Llanvirn, which includes both the Abereiddian and the Llandeilian, spans the period 465.60 Ma to 460.86 Ma, falling within the age range for the Darriwilian of 467.3 Ma to 458.4 Ma presented by Cooper & Sadler (2012).

In the area west of Dinas Cross the FVG has been sub-divided into three formations, namely the Porth Maen Melyn, Strumble Head, and Goodwick Volcanic formations (Bevins & Roach 1979) whilst to the east of Dinas Cross the group remains undivided (Burt *et al.* 2012). The Strumble Head Volcanic Formation comprises predominantly basaltic pillow lavas and associated hyaloclastites whilst the Porth Maen Melyn and Goodwick Volcanic formations are predominantly rhyolitic, comprising rhyolitic lavas (chiefly domes), rhyolitic ash-flow tuffs and volcaniclastic deposits. All of the FVG appears to have been erupted and emplaced in a subaqueous environment (Bevins & Roach 1979; Lowman & Bloxam 1981). Geochemical investigations have demonstrated that the dolerites (variably 'spotted') exposed in the adjacent region, in particular in the Mynydd Preseli area, are geochemically identical to the erupted basaltic lavas of the FVG and the whole volcanic assemblage has been termed the Fishguard Volcanic Complex (Bevins *et al.* 1989). Phillips *et al.* (2016) have recently presented a re-appraisal of the geochemistry of the FVG, confirming earlier suggestions that the sequence was emplaced in a back arc tectonic setting.

Stonehenge provenance studies. Essentially there are two lithological groups comprising Stonehenge, the larger 'sarsen' stones, which are a form of silcrete, and the smaller 'bluestones'. The former are thought to have been derived relatively locally, from the Marlborough Downs area (see Parker Pearson 2015), whilst it has long been recognised that the bluestones are exotic to the

region (see Bevins *et al.* 2011 for a summary of early studies). It was H.H. Thomas (1923), however, who identified source specific locations for the bluestones in the Mynydd Preseli area, citing Carn Alw as the source of the rhyolites, the northern slopes of Foel Drygarn for the 'calcareous ashes' and a number of outcrops, but mostly Carn Meini, as the source of the dolerites. Subsequent geochemical studies by Thorpe *et al.* (1991) supported the findings of Thomas (1923) but also added Carn Llwyd and Carn Clust-y-Ci, both in the Fishguard Volcanic Group, as additional sources for the rhyolites.

In a series of recent papers these sources have been called into question (see Ixer & Bevins 2010, 2016; Bevins *et al.* 2011, 2012, 2014; Bevins & Ixer 2013). In particular, the rhyolite outcrop of Craig Rhos-y-felin has been shown to be the major source of rhyolitic debitage (struck flakes) in the Stonehenge Landscape (Ixer & Bevins 2011a). Paradoxically, however, Craig Rhos-y-felin is not the source for any of the four rhyolitic and dacitic orthostats (stones 38, 40, 46 and 48) currently exposed at Stonehenge (Ixer & Bevins 2011b) although Bevins *et al.* (2012) have suggested, on petrographical grounds, that they too most probably have a source somewhere amongst the outcrops of the Fishguard Volcanic Group exposed in the north Pembrokeshire area. Specifically these recent studies have shown that Carn Alw, Carn Llwyd and Carn Clust-y-Ci are not sources of Stonehenge rhyolitic/dacitic bluestones (either extant orthostats or debitage).

Samples investigated. Five rhyolite samples were selected for investigation at the NERC Isotope Geoscience Laboratory based at the British Geological Survey. Laboratory procedures followed those described in Tapster *et al.* (2016). Inclusion free zircons were picked from the high density diamagnetic mineral fraction and chemically abraded following a protocol based on Mattinson (2005) in order to effectively eliminate Pb-loss. After cleaning and leaching the zircons were spiked with the (ET2535) EARTHTIME tracer solution, and dissolved in a pressure vessel (Condon et al., 2015; McLean *et al.* (2011). U and Pb separation was carried out using AG-1 1x8 ion exchange resin. Isotope ratio measurements were made using a Thermo-Electron Triton thermal ionisation mass spectrometer. Dates and propagated uncertainties were calculated based on algorithms of McLean *et al.* (2011), using decay constants of Jaffey *et al.* (1971), and the $^{238}U/^{235}U$ ratio of Hiess *et al.* (2012). Uncertainties reported in this paper are 'analytical only' as we are primarily interested in the differences between samples. Full details of the method including treatment of full uncertainties and the full data set are presented in the supplementary material.

Analysed samples included one rhyolite from the Craig Rhos-y-felin outcrop (sample SW52), two rhyolites from outcrops of the FVG at Fishguard Old Harbour (one from near the base and one from near the top of the succession; samples SW55 and SW54 respectively), one 'rhyolite with

planar fabric' debitage sample (SH08; identifying label: rhyolite with lensoidal fabric, STH08 Context2/3 FN636) from the 2008 excavations at Stonehenge by Tim Darvill and Geoff Wainwright (Darvill & Wainwright 2009), and one debitage fragment, a blocky rhyolitic ash-flow tuff sample (fully described in Ixer & Bevins 2013 as thin section TR45 Context 002/003 TR4548d) from the excavation at the Stonehenge Avenue (Trench 45) by Mike Parker Pearson and team, also in 2008, which Ixer & Bevins (2013) have determined as being petrographically identical with orthostat 48 (sample SH48d). The aims of the determinations were: i) to establish an age bracket for the FVG; ii) to see if an age comparison of a sample from Craig Rhos-y-felin and the 2008 rhyolitic debitage supported a common origin; and iii) to determine if a FVG source is plausible for the rhyolitic ash-flow tuff that comprises Stonehenge orthostat 48.

Results. Interpreted sample dates are discussed below and are presented as weighted mean $^{206}Pb/^{238}U$ dates based upon a coherent population which is identified using the mean standard weighted deviation (MSWD) as a guide. Three samples were collected to define and bracket the age of the Fishguard Volcanic Group (Fig. 1). The results from the samples from the top and bottom of the FVG produced non-reproducible zircon date populations. Zircons from the sample SW 55 from base of the Group describe a range of non-overlapping concordant data. The youngest 206Pb/238U date is 462.58 ± 0.81 Ma, (fraction z2, datatable) and the next youngest dates cluster around 464 Ma. Given the lack of reproducibility in a 'youngest date' we suggest that this sample has a maximum age of ~464 Ma. A weighted mean $^{206}Pb/^{238}U$ date of 462.64 ± 0.13 Ma (MSWD = 1.1) (supplementary section) was obtained from Craig Rhos-y-felin (SW52) and we consider this the best estimate for the age of the section at this sampled level. Zircons from the sample from the top of the Group (SW 54) describe a range of non-overlapping concordant data for which the weighted mean of the three youngest grains gives 465.33 ± 0.32 Ma (MSWD = 0.32) which is significantly older than the result from Craig Rhos y Felin, most likely from lower down the volcanic sequence (sample SW52), and hence cannot record the final eruptive event of the volcanic cycle. The debitage sample SH08 (Darvill and Wainwright 2008) gave a middle Darriwilian age of 462.20 ± 0.26 Ma (MSWD = 2.8, youngest 5 dates out of 6). The second debitage sample (SH48d) gave an older age of 463.88 ± 0.17 Ma (MSWD = 1.0 based upon 7 youngest dates out of 8).

Discussion. The FVG has been constrained, to date, using fossil evidence (see earlier) that indicate a late lower to early upper Abereiddian age which, according to Sadler *et al.* (2009), would suggest an age for the FVG somewhere in the range 465.60 Ma to 460.86 Ma, falling within the Darriwilian (467.3-458.4; see Cooper & Sadler 2012). The ages from Craig Rhos-y-felin provide the first

confirmed radiometric age for the FVG within the Darriwilian and the difference between the Craig Rhos-y-felin age and that of the age derived from the base of the group would suggest a minimum timespan of 2.5 to 3 Myr.

Two ages have been obtained for zircon crystals from Stonehenge debitage samples, one from sample SH08, thought to be derived from Craig Rhos-y-felin, and one thought to be derived from orthostat 48 (sample SH48d). The 2008 Darvill and Wainwright sample (SH08) yields a zircon age of 462.20 ± 0.26 Ma (Table 1). This places the origin of this sample of debitage from the same level within the Dariwillian as the Craig Rhos-y-felin rhyolite with which is shares fabric, petrographical and geochemical similarities (Bevins *et al.* 2011, 2012). The two samples (SH08 and SW 52) that have been considered to be from the same unit are similar, yet their weighted means are different by 0.44 ± 0.29 Ma. Figure 2 (lower Concordia plot) shows the U-Pb data for both plotted together and there is clear overlap between the two datasets. This similarity in the zircon data between these two samples is strengthened when the Th/U_{zircon} data are plotted (Fig. 2, Th/U plot) which shows complete overlap between samples SH08 and SW52, and a clear distinction from the other sample (SH48d). We suggest that the small difference in the weighted mean 206Pb/238U dates for the two samples could be due to the inclusion of data points with minor Pb-loss (sample SH08) and/or the inclusion of zircon that recorded pre-eruptive processes (sample SW52). These data suggest there is little significant difference between the zircon systematics (both dates and U/Th) derived from the two samples.

Sample SH48d, from the 2008 Avenue excavation by Parker Pearson and others, yields an age of 463.88 ± 0.17 Ma. It is older than SH08 and chemically different (U/Th ratio 0.73 ± 0.07, 1 SD, n=8) (Fig. 2). This sample, from orthostat 48, is a crystal-lithic-vitric ash-flow tuff, and has been considered by Bevins *et al.* (2012) to be derived from the FVG, although a source has yet to be determined. The age of the SH08 debitage sample is also significantly different from this other debitage sample (SH48d) which must come from stratigraphically lower down the Fishguard volcanic sequence because of its older age. The age determined in this study is consistent with the suggestion that indeed orthostat 48 (and by default because of similar arguments orthostats 38, 40 and 46) is likely to be derived from the Ordovician age Fishguard Volcanic Group outcrops exposed across the low ground to the north of the Mynydd Preseli in north Pembrokeshire, although the age obtained in this study supports the findings on the basis of petrography and geochemistry that its source is not Craig Rhos-y-felin. Nevertheless, this region provides an obvious target to search for further Neolithic quarry sites to add to those identified most recently by Parker Pearson *et al.* (2015).

Conclusions. Ages from two samples from the FVG confirm a middle Dariwillian age for the FVG, in agreement with available faunal evidence. Ages for samples SW52 and SH08 offer strong support, in terms of overlapping 'high-precision' zircon U-Pb dates and Th/U_{zircon} values, for the contention that the majority of the rhyolitic debitage in the Stonehenge Landscape is from Craig Rhos-y-felin, in the eastern part of the Mynydd Preseli area, in sympathy with other geological and archaeological evidence. In addition an age for SH48d, thought to be derived from Stonehenge orthostat 48, falls within the range determined for the FVG in this study (but not co-incident with the age for Craig Rhos-y-felin) and when combined with comparable lithological characteristics, is supportive of a north Pembrokeshire (FVG) origin for that orthostat and indeed likely therefore also for the three other similar rhyolitic and dacitic Stonehenge orthostats, namely orthostats 38, 40 and 46.

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Figure captions

Fig. 1. Map showing the outcrop of the Fishguard Volcanic Group across north Pembrokeshire, locations referred to in the text and the sampling sites for samples SW52 (Craig Rhos-y-felin) and SW54 and SW55 (both Fishguard Old Harbour). Based on compilation by British Geological Survey (2010).

Fig. 2. The top diagram in the figure presents a U-Pb Concordia diagram comparing data from the two debitage samples (SH08 and SH48d); the lower Concordia provides comparison of the data from SH08 debitage sample with the sample from Craig Rhos y Felin and the lower diagrams displays the Th/U_{zircon} vs mean $^{206}Pb/^{238}U$ age for the zircon fractions SH08 and its proposed source Craig Rhos y felin (sample SW 52), along with data from debitage sample (SH48d).