Reconstructing extraction techniques at Stonehenge's bluestone megalith quarries in the Preseli hills of west Wales

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Abstract

Excavations at two of the sources of Stonehenge's bluestones in Mynydd Preseli, west Wales, have led to the discovery of stone tools associated with megalith quarrying in the final centuries of the fourth millennium BC, shortly before the suspected date of the bluestones' erection at Stonehenge, 240km away. Among the most plentiful of these tools were stone wedges, three of which were found *in situ* at the rhyolite bluestone quarry of Craig Rhos-y-felin. Two of these were positioned in the joints of a rhyolite pillar adjacent to a recess left by a removed pillar. Geochemical analysis reveals that these and the third wedge are of compositions different to the rock on either side of the cracks into which they had been driven, confirming their identification as quarrying tools. This research sheds new light on the methods used to extract the stones for Stonehenge.

Keywords

Megalith quarries, Dolerite, Rhyolite, Stonehenge, Mynydd Preseli, Neolithic

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CRediT author statement

Parker Pearson: conceptualisation, methodology, writing – original draft, investigation, visualisation. **Bevins:** investigation, formal analysis, writing – original draft, visualisation. **Pearce:** investigation, formal analysis, writing – original draft, visualisation. **Ixer:** writing – review & editing. **Pollard:** investigation. **Richards:** investigation. **Welham:** investigation.

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Introduction

Quarries for megaliths have received considerably less attention from archaeologists than the megalithic monuments that constitute their finished products. This is, in part, due to the difficulty of finding and excavating these quarry sites as much as to overriding interest in the often dramatic character of megaliths and similar prehistoric monuments. Yet quarries provide evidence for some of the technological and social processes through which monument construction was achieved (*e.g.* Mens 2008). In the case of Stonehenge, the distance from quarry to eventual destination is the maximum known for megalithic monuments anywhere in the world (Parker Pearson *et al*. 2020a). Whilst its enormous sarsen stones are mostly provenanced to a locality 24km north of Stonehenge (Nash *et al*. 2020), the majority of the 43 bluestones have their origins in the Preseli hills of north Pembrokeshire in west Wales, 240km away (Ixer and Bevins 2011; 2017; Bevins *et al*. 2014; 2021; Ixer *et al*. 2017; Pearce *et al*. 2022). In addition, Stonehenge's 5m-long Altar Stone is likely to derive from younger strata elsewhere in western Britain (Bevins *et al*. 2020).

Stonehenge's bluestones

Stonehenge's bluestones mainly weigh between an estimated 1 ton and 3.75 tons and the tallest stand to just above 2m tall with the smaller ones being not much larger than 1m in height (Field *et al*. 2015). Nine have been worked down to stumps and remain buried beneath Stonehenge's turf (Cleal *et al*. 1995: 29). The term 'bluestone' is used for a variety of rock types for these 'foreign stones' other than the Altar Stone: 27 or 28 are of spotted dolerite, three are of unspotted dolerite, three are of rhyolitic tuff, two are of dacitic tuff, five are of andesitic tuff, and two are of possibly non-micaceous sandstone. The full lengths of the tallest bluestones of spotted dolerite are about 2.90m long (Cleal *et al*. 1995: fig. 296).

Geological analysis has led to the provenancing of several of these types of bluestone to specific outcrops within Preseli. The dominant source of spotted dolerite is Carn Goedog on the north flank of the hills (Figure 1; Bevins *et al*. 2014). Bluestone monoliths at Stonehenge identified as coming from Carn Goedog are Stones 33, 37, 49, 65 and 67. These represent half of the nine spotted dolerite monoliths that have been geologically analysed, though the remaining 20 or so spotted dolerite bluestones are still not chemically characterised. Other sources of Stonehenge's spotted dolerite are thought to lie to the east of Carn Goedog and south of Carn Alw.

A source of rhyolite (Rhyolite Group A–C) is at Craig Rhos-y-felin within the Brynberian tributary of the River Nevern to the north of the Preseli hills (Ixer and Bevins 2011). While some 1,200 fragments of Rhyolite Group A–C have been identified among the lithic debris from Stonehenge, no extant bluestone monolith has been identified as being of this type although we suspect that these fragments may derive from Stone 32d, a buried stump as yet unanalysed (Ixer and Bevins 2022).

The sandstone monoliths (not including the Altar Stone) derive from Lower Palaeozoic strata in west Wales, largely east or northeast of the Preseli ridge (Ixer *et al*. 2017). Finally, sources of Stonehenge's unspotted dolerite have been identified along the Preseli ridge at Cerrigmarchogion in the west (Bevins *et al*. 2021) and Garn Ddu Fach in the east (Pearce *et al*. 2022).

Evidence for megalith extraction at Carn Goedog

Archaeological excavations at Carn Goedog revealed a stone extraction area on the outcrop's south side where its pillar-like blocks are easily accessible amongst the surrounding clitter and scree that otherwise blocks access to its north, east and west sides (Parker Pearson *et al*. 2019; Parker Pearson 2020). The western end of this south side had been subjected to stone extraction and breakage in the post-medieval period, as indicated by the presence of drill holes and broken, small stone blocks and dated by a heavily worn copper-alloy token dating to *c*. AD 1800.

In the central part of the south side, large natural pillars occur together in near-vertical positions, leaning northwards at about 75° from horizontal, and separated by joints between each pillar. Many recesses or gaps amongst and between them reveal where pillars once stood but have been removed. The largest of these recesses has been formed by the removal of probably four pillars, lying two abreast and two deep. Excavation of the debris at the base of this recess uncovered a stony sediment containing charcoal dated to 2130–1900 cal BC (OxA-31681; 3629±29 BP) and cal AD 1690–1940 (OxA-31866; 116±24 BP).[1] The recess is blocked by a large boulder which has become detached from a large pillar to its east and, below the recess, a large pillar lies east–west on a ledge, having fallen from its upright position. Its former upper end lies to the east and has a cleft which is one end of an incomplete joint. This cleft has been artificially widened to form a small indentation c. 0.05m x 0.03m and 0.02m deep (Figure 2). This is an artificial quarrying feature though it is very different to the drill holes and other vestiges of post-medieval quarrying with metal tools. A second indentation, 0.09m x 0.025m and 0.02m deep, can be found at the top of a near-vertical pillar 19m west of the large recess. These two indentations are interpreted as attempts to widen joints in order to insert wedges which could be hammered into the joint in order to free the pillar from the outcrop.

At the foot of these pillars lay a crude, level platform, 10m north–south by at least 8m east–west, formed of over 50 large dolerite slabs. Scrape marks on the side of one of these slabs reveal where it had been scratched by the tip of a second slab being manoeuvred into position. The southern edge of the platform had a vertical edge 0.9m above the ground surface. Fragments of charcoal from the earliest layer of sediment in between and beneath the slabs contained two pieces of roundwood charcoal of Pomoideae and one of *Corylus avellana* dating to 3350–3100 cal BC (OxA-31820; 4502±31 BP), 3350–3040 cal BC (OxA-31821; 4490±31 BP) and 3350–3040 cal BC (OxA-31822; 4491±31 BP; Parker Pearson *et al*. 2019). After abandonment of the platform, one of its slabs was removed and the resulting void used as a fire pit, charcoal from which is dated to 2890–2630 cal BC (OxA-31824; 4164±30 BP). The latest date on charcoal from sediments within the platform is 3020–2880 cal BC (OxA-35182; 4316±32 BP) on roundwood of *Quercus* sp. (*ibid*.).

The position of the stone platform at the foot of the outcrop would have enabled quarry workers to lower detached pillars onto its surface and then pivot them, using long poles as levers, to the edge of the platform where they could be lowered onto a wooden sledge and dragged away. The relatively level area on top of the outcrop could have served as a position on which a team of rope-pullers could stand, paying out rope while maintaining its tension as a group on the platform hauled on other ropes also tied to the top of the pillar to raise it to the vertical axis. From this point, the group on top of the outcrop could control the pillar's gradual descent onto the platform.

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[1] All radiocarbon dates are quoted at 95% probability.

South of the platform, a shallow ditch, 2.05m wide x 12m long and 0.40m deep, had been dug and packed with large dolerite blocks and boulders, the tops of which formed an upstanding linear feature. Although five of the six radiocarbon dates on charcoal recovered from this ditch fill are of Mesolithic age, the sixth dates to 3080–2920 cal BC (OxA-35154; 4307±30 BP), the same as a final radiocarbon date from within the platform. Set along the foot of the platform, this stone-filled ditch would have provided an impediment to any attempts to remove pillars from the outcrop and presumably was constructed after prehistoric quarrying had ended.

South of the stone-filled ditch, a handful of cut features included a small, circular, flat-bottomed pit which included a worked stone artefact which can be interpreted as a wedge (Figure 3). This has a wide blade at its distal end, narrowing to a thick-butted proximal end, providing a triangular cross-section which is narrowest at its blade and widest at its butt. Two scrape marks (75mm long x 13mm wide and 32mm long x 10mm wide) down the middle of one face are likely to have been caused by the wedge’s contact with another stone, presumably from having been driven into a joint between pillars.

Evidence for megalith extraction at Craig Rhos-y-felin

Whilst spotted dolerite monoliths are the most numerous at Stonehenge, rhyolite from Craig Rhos-y-felin is thought to be represented by just a single pillar, Stone 32d, or less likely Stone 32e, a buried stump in the northeast sector of the outer bluestone circle. In contrast, Craig Rhos-y-felin rhyolite (referred to as Rhyolite Group C or rhyolite-with-fabric; Ixer and Bevins 2011) is represented in Stonehenge’s lithic assemblage by over 1,200 flakes. Other flakes of this rhyolite-with-fabric have been recovered from various parts of the Stonehenge landscape, such as south of the Greater Cursus (Stone 1947; Parker Pearson *et al*. 2020b: 192–6) and within Durrington village (Harding and Ixer 2018: 53–6).

It is likely that just one bluestone pillar was extracted from the outcrop at Craig Rhos-y-felin (Figure 4). This striking outcrop is situated in the bottom of a steep-sided valley along which flows a stream that rises close to Carn Goedog and forms a tributary of the River Nevern (Parker Pearson *et al*. 2015; 2019). Initial geological sampling at 19 locations around this outcrop through the stratigraphy of rhyolitic body revealed just one location, close to the northern tip of the outcrop, where the ‘Jovian’ micro-structure of spherical to lensoidal features (named after the famous ‘spot’ on Jupiter’s surface) within the rhyolite matches the fabric identified within some of the flakes from Stonehenge and its environs (Ixer and Bevins 2011).

A recess immediately north of this location but along its strike length appears to be the result of removal of a pillar 2.50m high, up to 0.45m wide and 0.40m thick. As at Carn Goedog, the natural pillars here lie at an angle of about 75° so as to rest against the bedrock behind them. A slight indentation in the bedrock’s near-vertical face close to what would have been the top of the pillar on its north side could be one half of a hammered-out depression to open the joint, like the two complete ones identified at Carn Goedog but it is too faint to be certain.

The base of the recess sits at 0.15m above the Neolithic ground surface (itself buried at a depth of about 1m below the ground level as encountered at the start of excavation). This Neolithic surface is dated to 3500–3120 cal BC (SUERC-46205; 4590±30 BP) and 3620–3360 cal BC (OxA-30502; 4667±30 BP) by determinations on carbonised hazelnut shells from a hearth at this level 2m to the northeast. This hearth was surrounded on its north, east and west sides by a deposit of dark brown sediment containing small quantities of burnt stones. Among the artefacts from this layer were a single flint chip and flaked rhyolite tools.

A vertically set rhyolite block in front of the recess may have served as a pivot stone onto which the detached monolith could have been lowered and then moved with other stone fulcrums and wooden levers across a stony surface onto a platform of artificially made-up ground 2.50m northeast–southwest by 5m northwest–southeast. This platform terminated on its north side at a near-vertical drop of 0.9m down to the clay bed of a palaeochannel, against which its near-vertical side was revetted by a crude stone wall of up to three courses of drystone masonry. Charcoal fragments from the sediment filling the platform and packed behind the wall gave dates in the Mesolithic period and the only artefact, other than burnt stones, from this deposit was a rhyolite end-scraper (Parker Pearson *et al*. 2019).

At the foot of the stone wall, a 2.20m-wide sunken surface or hollow way within the top of the clay deposit led northeast and curved round to the north where it was followed for 7m to the edge of the excavation trench, evidently continuing beyond it to the north. Whilst charcoal from the clay deposit beneath the hollow way produced Mesolithic dates, charcoal of *Corylus avellana* roundwood from the silt filling the hollow way provided dates of 3330–2920 cal BC (OxA-35151; 4434±31 BP) and 3520–3340 cal BC (OxA-35412; 4627±34 BP; *ibid*.). This hollow way, leading from the foot of the retaining wall at the north end of the platform is interpreted as a trackway along which the monolith taken from the outcrop was hauled, presumably having been lowered onto a wooden sledge.

Later activity at Craig Rhos-y-felin included the construction of a second platform further to the south, on which a large monolith was propped up by a number of large rhyolite slabs. Two radiocarbon dates of 2200–1950 cal BC on roundwood charcoal from the platform's sediment suggests that this monolith was the product of a later phase of quarrying in the Early Bronze Age or later (Parker Pearson *et al*. 2015).

Materials and methods

Stone wedges in situ at Craig Rhos-y-felin

Three stone wedges (SF135, SF136, SF137) were found within joints in the bedrock at Craig Rhos-y-felin. In addition, the joint containing SF137 also had a large, thin sheet of rhyolite within it. The aim of the analysis was to establish whether these three wedges and the thin sheet were indeed artificially introduced intrusions or were fortuitously fractured pieces of bedrock within the jointing. Whilst two of the wedges exhibited flake-removal consistent with having been hammered into place, geochemical analysis was carried out to establish whether the wedges were indeed different in composition to the surrounding rock.

Wedge SF 135 was jammed between two slabs just west of the hearth and its surrounding occupation layer at the northern tip of the outcrop. On the western edge of this layer, the two sides of a 1m-wide by 1m-high split boulder were held apart by this large stone wedge (SF135; 175mm x 110mm x 165mm; Figure 5). This was formed from a large, weathered, triangular-sectioned rhyolite block of trapezoidal shape, tapering from its top to its base. A large chunk (30mm x 32mm x 150mm) has been detached from its upper right corner (as viewed from the south while *in situ*) but there is no other definitive evidence of the wedge's having been hammered into the joint in which it was found.

Beneath this wedge, lying in the same sediment as that formed around the Neolithic hearth, lay the broken tip of another stone wedge and a hammerstone. This wedge-sectioned rhyolite blade (SF134; 127mm x 78mm x 33mm) had a flake bed on one of its flat sides and edge damage, including four indentations, along its tongue-shaped tip. Fifty millimetres above it, in the same sediment and also within the gap created by the split slabs, lay an ovate-shaped hammerstone (SF133; Figure 6).

The two halves of this split boulder would not have made very impressive standing stones, being much more squat and stubby than the elegant, tall pillar that must have once stood in the recess 2m to the south, discussed earlier. The split boulder could have been a practice piece, for example, opened up just to prove the technique. The large wedge (SF135) must have been driven in at some point before the accumulation of colluvium around and above it in AD 810–1030 (OSL sample X5456; 1080±110 BP; Parker Pearson *et al*. 2015: table 1). The wedge's base lay 0.10m above the top of the ground surface associated with the Neolithic hearth.

Two further wedges left *in situ* within joints close to the recess, however, provide more definitive evidence of attempts to open up the joints around a rhyolite pillar in the process of pillar extraction (Figure 7). The south side of the recess is formed by the north side of a large pillar, 2.60m tall, up to 1m wide and 0.60m thick, slightly set back (eastwards) from the back of the recess. A rhyolite wedge (SF 136) remained in position within the top of the joint and, 0.30m away on the pillar's east side, a second wedge (SF 137) also sat *in situ* within the top of the joint on that side. Their positions on the tops of two joints reveal that the quarry workers had identified the pillar next to the recess for removal but had either failed to set it free from the parent rock or had decided that it was surplus to requirements having successfully removed the pillar immediately to its north.

Lithic analysis of impact damage to the stone wedges

Whilst one of the wedges (SF 135) had no definitive trace of damage caused by hammering it into the joint in which it was wedged, the other two wedges exhibited multiple flake scars on their upper sides below the platform at their upper, broad end.

The rhyolite wedge (SF136; 198mm x 71mm x 54mm) in the joint on the north side of the pillar was formed from a large rectangular-sectioned flake of trapezoidal shape, in which the basal 100mm narrows to a point (Figure 8). The very tip of the point has broken off and there is damage from this tip along the 40mm-long edge on the wedge's narrower face. At the proximal end or top of the wedge, two lines of flake scars are visible along the tops of the two wider faces. Five flake scars are visible on one side and four on the other side, one of them larger (32mm long x 45mm wide) than the rest. These are the result of percussion on the top of the wedge, no doubt as it was hammered into the joint in which it was found.

The rhyolite wedge (SF137; 246mm x 282mm x 36mm) in the joint on the east side of the pillar was formed from a large sub-rectangular-sectioned flake of sub-triangular shape, in which the basal 60mm narrows to a pointed, sharp edge and tip. The wedge has split longitudinally (the smaller fragment is 148mm x 107mm x 21mm) which was how it was found within the joint, already in two separated, non-touching pieces, the smaller one to the south). Five large, crude flake scars (from 20mm x 70mm to 135mm x 50mm in extent) are visible on one face at the top of the wedge and down the side furthest from the smaller piece. Their crudeness is largely a result of this stone's highly laminated fabric. The other face has no such damage. The flakes were detached from the proximal end of the wedge as the result of percussion on the top of the wedge, no doubt as it was hammered into the joint in which it was found.

The removal of flakes from the butts of the two wedges was not accompanied by any crushing of the striking platform as might be expected if they had been struck with a hard hammer of stone. The actions which led to the flakes' detachment must have been performed with a soft hammer of wood or antler – perhaps a large wooden mallet or club, or an upended tree trunk.

Geochemical analysis of the stone wedges in situ at Craig Rhos-y-felin

Whilst the majority of the stone wedges at Carn Geodog were of a different lithology to the spotted dolerite of that outcrop, the wedges found *in situ* at Craig Rhos-y-felin were of the same foliated rhyolite as the outcrop (considered to be an intensely-welded ash-flow tuff showing a parataxitic texture; REB's unpublished observations). To establish whether these were genuine artefacts hammered into place, rather than accidental, naturally shattered components within the rock face, we carried out a series of geochemical analyses to determine whether their compositions were the same as the margins of the crack from which they had been removed, or whether they were compositionally different.

Two sets of portable X-ray fluorescence analyses (henceforth pXRF) of the stone wedges and the rhyolites making up their host cracks were conducted during November 2021. The first (10th November 2021) consisted of six analyses on either side of two of the cracks and six on each of the four wedges. This was followed up with four more analyses on the second visit (23rd November 2021) to make a total of ten analyses for each wedge and crack, except SF137 which has only six analyses each for the wedge and crack margins. There was no difference between the two sets of analyses as confirmed by the comparison of the rhyolite analyses on different days, and from repeated analyses of our "in-house" reference material, a 5 x 4 x1.5cm flake of the Newberry Big Obsidian Flow, used to check reproducibility. Instrument calibrations and operating conditions remained the same between analyses sets, and weather conditions were similar (dry and cool).

Analysis was also carried out on a thin sheet of rhyolite within a joint immediately north of SF137 which was about 5 cm wide and 60 cm long, and appeared to be a natural flake produced by frost shattering of the margins of the crack. The positions of the analyses at the north-eastern end of Craig Rhos-y-felin are shown on Figure 9. The pXRF analytical methods are described in detail elsewhere (Bevins et al. 2022, Pearce et al. 2022) All analyses were performed using a Thermo Fisher Scientific™ Niton™ XL3t GOLDD+ handheld XRF analyser (pXRF). The Niton pXRF uses a 2 W Ag anode X-ray tube, which can operate at between 6-50 kV and 0-200 µA, with operating conditions being varied during the "TestAllGeo" analysis method. Analyses of the wedges (November 2021) were performed for 100 seconds. Table 1 gives the operating conditions for the pXRF for the analyses of the stone wedges.

Results

Previously (April 2021) we had conducted a series of approximately 140 analyses at Craig Rhos-y-felin to determine the range of composition of the rhyolite eruptive unit there, here excluding analysis of the relatively poorly-determined light elements (Si, Al, Mg) in an 80 second analysis. All analyses are included in Supplementary Table 1 "pXRF analyses". In all cases, analyses performed in the field were undertaken on the weathered surface of the rock.

Figure 10 presents a series of bivariate plots of the composition of the individual wedges and their host rocks either side of the cracks, as well as the data from Craig Rhos-y-felin (which in some of these extends outside the margins of the plots so as to show the wedge and crack compositions more clearly). The elements considered here - Ba, Sr, K and Rb - are abundant, have low detection limits by pXRF, and are determined with good accuracy and precision (see Frahm 2014 and Frahm 2019 for general accuracy and calibration issues and Bevins *et al*.2022 and citations therein for the accuracy and methods applied for the instrument used here). These are also compatible elements in the mineral phases which are likely to form in rhyolitic magmas (notably feldspars), and may thus vary during an eruption. Within the Craig Rhos-y-felin rhyolites there is vertical variation in composition through the thickness of eruptive sheet, which is associated with changes in the proportions of glass, minerals and lithics originally ejected during different eruptive phases, this leading to some small-scale vertical and horizontal heterogeneity in these bodies. Incompatible element ratios (e.g. ratios between Zr, Nb, Th and U) remain broadly constant throughout the body of rhyolite, indicating the source of magma does not change during deposition of this eruptive unit. Potts et al. (2006) noted a rather inconsistent behaviour in the enrichment or leaching of trace elements in rhyolitic compositions between the fresh interior of the sample and the weathered exterior. Notably any changes of the compatible elements studied here were <15% relative (average of all rhyolitic data in Potts et al., 2006) suggesting that there is no particularly significant change between weathered and fresh surfaces.

It is clear from Figure 10 that all of the analysed wedge compositions fall within the compositional space occupied by the rhyolites of Craig Rhos-y-felin, confirming the local source for these.

Crack compositions – how much variation is their either side of an open crack?
Figure 10 shows that, whilst there can be some compositional variation across an open crack, the different sides of each crack form a broad compositional continuum, with no pronounced gap either side of the crack (see the dotted fields marked on Figure 10). This reflects the heterogeneity within the rhyolite and can be expected in a complex ash deposit made up of different amounts of lithics, crystals and glass from a complex eruption. If each wedge retrieved from the cracks was material derived from the walls of the crack, we would expect it to have a composition that was within the range shown by the margins of the crack.

Are the wedges of the same composition as the cracks which host them?
For reference to the sample locations referred to below, see Figure 9.

“Thin flake” to the north of SW 137: This flake is too long and thin to be an effective wedge and has the appearance of a thin sheaf of rock spalled from one face by frost shattering. Analyses of this, and the margins of its enclosing crack show that they occupy essentially the same compositional space, with the flake sitting in the middle of the compositional range of the enclosing crack margins. This confirms the expectation of similar, overlapping compositions which would be expected if this was *in situ* material.

Stone wedges SF134 and SF135: These wedges were retrieved from the same crack, SF135 wedged tightly in the crack, SF134 appears to be the broken end of a wedge found in sediment at the base of the crack. SF134 is similar to its host crack in terms of Rb, Sr, K and Ba, and sits within the compositional range of the crack’s margins, and is not clearly different in composition. In contrast, SF135, which was tightly wedged in the crack is markedly different from its host crack in terms of Rb, Sr, K and Ba, and is clearly not derived from material adjacent to the crack.

Stone wedge SF136: This wedge differs from its host crack in its Rb, Sr, K and Ba concentrations, and is clearly of a different composition to the margins of the crack.

Stone wedge SF137: This wedge occupies a compositional space which largely differs from the material in the cracks either side of it for Rb, Sr, K and Ba, and whilst there is a marginal overlap of the fields of data, they do not form a continuum, and the wedge does not sit within the compositional range of the crack margins. Again, the wedge is of a different composition to the margins of the crack.

Student T-tests (2-tailed, equal variances) were performed on those elements which are reliably determined by pXRF (see Bevins et al., 2022, Pearce et al., 2022, Bevins et al., 2022 submitted) to compare the average wedge compositions with their host cracks, and to compare the average compositions from either side of the cracks. These are presented in Table 2. Where $p < 0.05$, the samples can be considered to be significantly different for that element at a 95% probability. The great majority of the elements in the stone wedges SF135, SF136 and SF137, are statistically different (at $p < 0.05$) from the mean of the compositions of the material at the margins of the crack, and thus statistical analysis confirms the compositional plots and shows these wedges to have different compositions from their host cracks (see also discussion above) and are not material derived from the cracks in which they sit. SF134 has many compositional similarities to the material at the crack margins, despite some subtle differences (in Zr, Rb and Sr; see above and Figure 10) and seems likely to be material derived from the crack margins. The thin flake in the crack near SF137 is essentially identical in composition to the material at the margins, and this is not surprising given its morphology and possible origin as a frost-shattered flake. Comparison of the T-test results for different sides of the host crack shows some similarities and some differences in compositions, and this relates to the variation in composition of the rhyolites. Note that the host rhyolite adjacent to wedges SF135 and SF137 are parallel to the layering of the tuff and hence they are at the same height in the tuff unit whilst SF136 lies in a crack which is perpendicular to the layering and hence the continuous range of composition seen may relate to variations in height through the tuff unit resulting from variations in magma composition during eruption of the tuff unit.

Principal component analysis (PCA) performed on the same elements (*viz.* Rb, Ba, Sr and K; Figure 11) also clearly shows the compositional similarity of the thin flake with its surroundings, and that marked differences in composition exist for Stone Wedges SF135, SF136 and SF137 from the material making their host cracks. Stone Wedge SF134 cannot be confidently separated from the composition of its host crack using PCA.

Discussion

Until recently there has been relatively little research into the methods and equipment used by Neolithic quarry-workers to extract megalithic stones. This may be partly because interest in the complete chain of operations from extraction to erection has developed only recently (e.g. Mens 2008) and partly because megalith quarries are unlikely to yield much in the way of conventional archaeological artefacts and materials such as pottery or food remains. Furthermore, ethnographic studies reveal that much of the equipment is likely to have been in the form of timbers and ropes that rarely survive from prehistory (Steimer Herbert 2018; Wunderlich 2019) whilst the acidic soil conditions encountered in rocky locales such as the Preseli Hills prevent the survival of animal bone or antler. We are fortunate that Carn Goedog and Craig Rhos-y-felin have preserved good evidence in the form of stone tools as well as features such as artificial platforms, the recesses left by extracted monoliths and, especially, the cracks into which stone wedges were hammered.

Stone tools at Carn Goedog and Craig Rhos-y-felin

Excavations of these two bluestone megalith quarries have yielded assemblages of stone tools of varying form, function and lithology. Those from Carn Goedog are the most numerous and varied, including nine wedges, a hammerstone and a variety of flaked implements and stone flakes (Table 3). Apart from the numerous stone flakes, stone wedges and wedge fragments are the most common tools, most of them recovered from features dating to the late 4th millennium BC, including the stone-filled ditch across the entrance to the quarry (Table 1). Most of the wedges are of fine-grained mudstone and are thus manuports to this dolerite outcrop. The rarity of hammerstones at Carn Goedog is interesting, raising questions about how the wedges might have been hammered into the joints. Artefacts in materials other than mudstone or dolerite were virtually absent, other than a small flint blade. Most of the large dolerite flakes came from post-Neolithic layers.

The worked stone assemblage from Craig Rhos-y-felin has a similar composition to that from Carn Goedog, with wedges being the most common tools. However, there is an equivalent number of hammerstones to wedges (Table 4). Whilst the wedges are mostly from late 4th millennium BC contexts, only one hammerstone (SF 133) is of this date. The other four (SF 2, SF 17, SF 19 and SF 21) are all from post-Neolithic contexts. Whilst it is possible that some or even all were re-used Neolithic tools, a parsimonious approach should exclude them from consideration as originally used in Neolithic quarrying. The evidence for soft-hammer percussion on wedges SF 136 and SF 137 indicates the use of wooden (or antler) hammers at Craig Rhos-y-felin and the small numbers of stone hammerstones at both quarries would suggest that organic materials provided the most common form of percussive tool.

Use of wooden hammers in the British Neolithic

A handful of waterlogged Neolithic contexts within Britain have produced wooden tools that could have been used in percussive activities, and are generally classed as clubs. Substantial Neolithic wooden clubs are known from Ehenside Tarn, Cumbria (Darbishire 1874: 288, plate 9, fig. 1 ; Coles *et al*. 1978 : fig. 5.1), the Sweet Track, Somerset Levels (Coles *et al*. 1978: fig. 3.2) and from the Thames at Chelsea, London (Webber with Ganiaris 2004).

The Ehenside Tarn club is 470mm long and 70mm wide, and made of beech, while the Sweet Track club is 650mm long and 65mm wide and made of hazel (Coles *et al*. 1978: 15, fig. 3.2). The Chelsea club is 640mm long, of alder, with a blade, handle and pommel. The blade has a flat striking face 165mm long, 115mm wide and 75mm thick, and is radiocarbon-dated to 3630–3350 cal BC (Beta-117088; 4660±50 BP; Webber with Ganiaris 2004: 126), around the same date as the Carn Goedog and Craig Rhos-y-felin quarries.

The bluestone quarries in context: prehistoric megalith quarries in Britain and Europe

The most ancient megalith quarries in the world date to the late tenth millennium BC at Göbekli Tepe in southeastern Anatolia where T-shaped limestone pillars of similar size to the bluestones were isolated from the limestone bedrock, presumably by pounding with stone tools (Schmidt 2010). They could then be raised from their horizontal position in their stone pit and dragged a short distance of *c*. 400m to be erected in the large oval buildings that form the centre of this PPNA complex. In one instance, a pillar remains *in situ*, still attached to the underlying bedrock but abandoned probably because of a crack across its centre.

Within Western Europe, Neolithic and Chalcolithic megalith quarries of the fifth–third millennia BC have been identified in both France (Mens 2009; 2013; Mens and Large 2010; Benéteau-Douillard 2013) and Iberia (Calado 2016; see case studies in Boaventura *et al*. 2020). Several of those in western France reveal the use of stone wedges, including Rocher-Mouton (Mens 2009) and La Butte de Moncoué (Poncet *et al*. 2021: 12–14). At the Rocher-Mouton granite quarry, a sandstone wedge had been hammered into a natural crack while granite hammerstones lay at the foot of the rock (Mens 2009). At La Butte de Moncoué, sandstone wedges of the same geology as the outcrops were driven into cracks between megalithic blocks (Poncet *et al*. 2021). At the megalithic complex of Bois de Fourgon in the Vendée, small fine-grained blocks of aplite were used as wedges within a granite outcrop (Benéteau-Douillard 2012).

Within Britain, megalith quarries are known at several Neolithic sites. Horizontal pillars were extracted and raised to form the Na Dromannan stone circle in the Isle of Lewis, Outer Hebrides, part of the 29th–27th-century BC Late Neolithic complex at Calanais (Richards 2013: 248–51). Numerous Early Neolithic dolmens (*c*. 3800–3600 BC) such as Garn Turne, Pentre Ifan and Carreg Samson in Pembrokeshire appear to have been constructed *in situ* by raising a capstone formerly embedded at that location: the quarry being directly beneath the dolmen (Cummings and Richards 2021: 97–116, 188–204).

The other megalith quarry in Britain extensively excavated is Vestra Fjold in Orkney (Richards 2013: 127–43). Situated on the island of Mainland, 10km northwest of the great stone circle of the Ring of Brodgar, the site of Vestra Fjold consists of two prone slabs of sandstone Caithness Flags, lying within a shallow depression. Both stones had been manoeuvred into position over the edge of the depression and one had been chocked up on a pile of small slabs which had subsequently collapsed. Associated stone tools included eight hammerstones, mostly broken. No wedges were found except for a single wedge stone, a small supporting prop inserted once wedges had opened a split in the laminated slabs (Richards 2013: 132, fig. 5.14). Experimental splitting of similar Orcadian sandstone Flags by Hugo Anderson-Whymark has revealed that this could be easily achieved with wooden wedges which may explain their absence except for the wedge stone. The Vestra Fjold quarry lies within 50m of a Neolithic horned cairn, and was presumably the source of its stones. It is thus likely to date to the same period of 2800–2500 cal BC as indicated by radiocarbon dates from the tomb's construction levels (Richards 2013: 160).

Conclusion

Overall, the wedges SF135, SF136 and SF137 are compositionally different from the rock on either side of their host cracks, the sides of the cracks being statistically different from each other but forming a compositional continuum across the crack associated with volcanic and depositional factors. The contained wedges do not sit within this compositional continuum, occupying different compositional spaces. They can thus be separated from their host crack compositions both on bivariate plots and statistically for many reliably determined elements. SF134 does not show a clear compositional separation from its host, showing a near continuous composition with the crack margins, leading us to conclude that this sample was not a stone wedge inserted manually into the crack. We also conclude that the stone flake found in the joint just northeast of SF137 is also a natural feature and is not influenced by human activity; its similarity to its margins supports the hypothesis that *in situ* materials will be of the same compositions as the material comprising their host crack.

The identification of flake scars around the tops of wedges SF 136 and SF 137 provides confirmatory evidence of their use as implements to open up cracks in the jointing at Craig Rhos-y-felin. Additionally, the absence of crushing on their tops is consistent with soft-hammer percussion deriving from use of a wooden mallet or club. With limited use of hammerstones, it is likely that percussive tools of both wood and stone were used to drive in the wedges. Similarly, wedges of both wood and stone may also have been employed: only those of stone have survived. Wedges SF 136 and SF 137 were positioned so as to extract a pillar directly behind the recess from which we reckon a monolith was removed and taken to Stonehenge. This was quite possibly the buried stump Stone 32d within the Bluestone Circle. Just why that second pillar was never removed from the Craig Rhos-y-felin outcrop is unknown. Was it surplus to requirements? Was it too securely bedded to be worth the effort of extraction? Or was it considered to be structurally unsound?

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References

Benéteau-Douillard, G. 2012. *Complexe mégalithique du Bois de Fourgon à Avrillé (Vendée), Etudes archéologiques et techniques d'un ensemble de menhirs et stèles anthropomorphes en Centre-Ouest Atlantique*. Coëx: Laboratoire d'Archéologie et d'Anthropologie Sociale.

Benéteau-Douillard, G. 2013. De la roche-mère aux géants de pierre, choix et opportunism des mégalitheurs en Vendée (France). In J.-N. Guyodo and E. Mens (eds) *Les Premières Architectures en Pierre en Europe Occidentale: du Ve au IIe Millénaire avant J.-C.: Actes du Colloque International de Nantes (Musée Thomas Dobrée, 2-4 octobre 2008)*. Rennes: Presses Universitaires de Rennes. 133-47.

Bevins, R.E., Ixer, R.A. and Pearce, N.J.G. 2014. Carn Goedog is the likely major source of Stonehenge doleritic bluestones: evidence based on compatible element geochemistry and principal components analysis. *Journal of Archaeological Science* 42, 179–93.

Bevins, R.E., Pearce, N.J.G. and Ixer, R.A. 2021. Revisiting the provenance of the Stonehenge bluestones: refining the provenance of the Group 2 non-spotted dolerites using rare earth element geochemistry. *Journal of Archaeological Science: Reports* 38, 103083.

Bevins, R.E., Pearce, N.J.G., Parker Pearson, M. and Ixer, R.A. 2022a. Identification of the source of dolerites used at the Waun Mawn stone circle in the Mynydd Preseli, west Wales and its implications for the proposed link with Stonehenge. *Journal of Archaeological Science: Reports* 45, 103556.

Bevins R.E., Pearce N.J.G., Ixer R.A., Hillier S., Pirrie D., Turner P. 2022b. Linking derived debitage to the Stonehenge Altar Stone using portable X-ray fluorescence analysis. *Mineralogical Magazine* 86, 1–13, DOI: https://doi.org/10.1180/mgm.2022.22

Bevins, R.E., Pirrie, D., Ixer, R.A., O'Brien, H., Power, M.R., Shail, R.K. and Parker Pearson, M. 2020. Constraining the provenance of the Stonehenge 'Altar Stone': evidence from automated mineralogy and U–Pb zircon age dating. *Journal of Archaeological Science* 120, 105188.

Boaventura, R., Mataloto, R. and Pereira, A. (eds). 2020. *Megaliths and Geology*. Oxford: Archaeopress.

Calado, M. 2016. No caminho das pedras : o povoado « megalítico » das Murteiras (Evora). In A.C. Sousa, A. Carvalho and C. Viegas (eds) *Terra e Agua. Escolher Sementes, Invocar a Deusa. Estudos em homenagem a Victor S. Gonçalves*. Lisbon: Centro de Arqueologia da Universidade de Lisboa. 113-23.

Coles, J.M., Heal, S.V.E. and Orme, B. 1978. The use and character of wood in prehistoric Britain and Ireland. *Proceedings of the Prehistoric Society* 44, 1–45.

Cummings, V. and Richards, C. 2021. *Monuments in the Making: raising the great dolmens in Early Neolithic northern Europe*. Oxford: Windgather.

Darbishire, R.D. 1874. Notes on discoveries in Ehenside Tarn, Cumberland. *Archaeologia* 44, 273–92.

Field, D., Anderson-Whymark, H., Linford, N., Barber, M., Bowden, M., Linford, P. and Topping, P. 2015. Analytical surveys of Stonehenge and its environs, 2009–2013. Part 2 – the stones. *Proceedings of the Prehistoric Society* 81, 125–48.

Frahm, E., 2014. Characterizing obsidian sources with portable XRF: accuracy, reproducibility, and field relationships in a case study from Armenia. *Journal of Archaeological Science* 49, 105–25.

Frahm, E., 2019. Introducing the Peabody-Yale Reference Obsidians (PYRO) sets: Open-source calibration and evaluation standards for quantitative X-ray fluorescence analysis. *Journal of Archaeological Science: Reports* 27, 101957.

Harding, P. and Ixer, R.A. 2018. Neolithic stone objects. In S. Thompson and A.B. Powell, *Along Prehistoric Lines: Neolithic, Iron Age and Romano-British activity at the former MOD Headquarters, Durrington, Wiltshire*. Old Sarum: Wessex Archaeology. 53–7.

Ixer, R.A. and Bevins, R.E. 2011. Craig Rhos-y-felin, Pont Saeson is the dominant source of the Stonehenge rhyolitic 'debitage'. *Archaeology in Wales* 50, 21–31.

Ixer, R.A. and Bevins, R.E. 2017. The bluestones of Stonehenge. *Geology Today* 33, 183–7.

Ixer, R.A. and Bevins, R.E. 2022. The petrography of bluestones and other lithics. In M. Parker Pearson, J. Pollard, C. Richards, J. Thomas, C. Tilley and K. Welham. *Stonehenge for the Ancestors. Part 2: Synthesis*. Leiden: Sidestone Press. 273-334.

Ixer, R.A., Turner, P., Molyneux, S. and Bevins, R. 2017. The petrography, geological age and distribution of the Lower Palaeozoic Sandstone debitage from the Stonehenge landscape. *Wiltshire Archaeological Magazine and Natural History Magazine* 110, 1–16.

Pearce, N.J.G., Bevins, R.E. and Ixer, R.A. 2022. Portable XRF investigation of Stonehenge Stone 62 and potential source dolerite outcrops in the Mynydd Preseli, west Wales. *Journal of Archaeological Science: Reports* 44, 103525.

Potts, P.J., Bernardini, F., Jones, M.C., Williams-Thorpe, O. and Webb, P.C., 2006. Effects of weathering on in situ portable X-ray fluorescence analyses of geological outcrops: dolerite and rhyolite outcrops from the Preseli Mountains, South Wales. *X-Ray Spectrometry: An International Journal* 35 (1), 8–18.

Mens, E. 2008. Refitting megaliths in western France. *Antiquity* 82, 25–36.

Mens, E. 2009. Technologie des mégalithes dans l'Ouest de la France: la carrière du Rocher Mouton à Besné (Loire-atlantique, France). XVe congrès de l'Union Internationale des Sciences Préhistoriques et Protoistoriques. In C. Scarre (ed.) *Megalithic*

Quarrying, Sourcing, extracting and manipulating the stones. Oxford: BAR International Series 1923. 59–69.

Mens, E. 2013. Technologie des premières architectures en pierre dans l'Ouest de la France, in Mens, E. Guyodo, J.N. (eds) *Actes du colloque international, Les premières architectures en pierre en Europe occidentale (5e au 2e millénaire av. J.-C.). Nantes, Musée Dobrée, 2,3 et 4 octobre 2008*. Rennes: Presses Universitaires de Rennes. 39–52.

Mens, E. and Large, J.M. 2010. Megalithic technology: a new approach to the earliest stone architecture of the west of France. Issues, methodology and results. In B. O'Connor, G. Cooney, J. Chapman (eds) *Materialitas: working stone and carving identity*. Oxford: Oxbow. 42–53.

Nash, D.J., Ciborowski, T.J.R., Ullyot, J.S., Parker Pearson, M., Darvill, T.C., Greaney, S., Maniatis, G. and Whitaker, K.A. 2020. Origins of the sarsen megaliths at Stonehenge. *Science Advances* 6 (31), eabc0133

Parker Pearson, M. 2019. Stonehenge's bluestones. In A. Teather, P. Topping and J. Baczkowski (eds) *Mining and Quarrying in Neolithic Europe: a social perspective*. Oxford: Oxbow. 83–100.

Parker Pearson, M., Bevins, R., Ixer, R., Pollard, J., Richards, C. and Welham, K. 2020a. Long-distance landscapes: from quarries to monument at Stonehenge. In R. Boaventura, R. Mataloto and A. Pereira (eds) *Megaliths and Geology*. Oxford: Archaeopress. 183–200.

Parker Pearson, M., Bevins, R., Ixer, R., Pollard, J., Richards, C., Welham, K., Chan, B., Edinborough, K., Hamilton, D., Macphail, R., Schlee, D., Simmons, E. and Smith, M. 2015. Craig Rhos-y-felin: a Welsh bluestone megalith quarry for Stonehenge. *Antiquity* 89, 1331–52.

Parker Pearson, M., Pollard, J., Richards, C., Thomas, J., Tilley, C. and Welham, K. 2020b. *Stonehenge for the Ancestors. Part 1: landscape and monuments*. Leiden: Sidestone.

Parker Pearson, M., Pollard, J., Richards, C., Welham, K., Casswell, C., French, C., Shaw, D., Simmons, E., Stanford, A., Bevins, R.E. and Ixer, R.A. 2019. Megalithic quarries for Stonehenge's bluestones. *Antiquity* 93, 45–62.

Pearce, N.J.G., Bevins, R.E., Ixer, R.A. 2022. Portable XRF investigation of Stonehenge Stone 62 and potential source dolerite outcrops in the Mynydd Preseli, west Wales. *Journal of Archaeological Science: Reports* 44, 103525.

Poncet, D., Mens, E., Laurent, A. and Ard, V. 2021. La Butte de Moncoué (Taizé-Maulais, Deux-Sèvres), un relief résiduel dans la Plaine Thouarsaise (sud-ouest du Bassin Parisien). Gisement de grès Éocènes et alignement de pierres dressées. *Bulletin d'Information des Géologues du Bassin de Paris* 58, 7–23.

Richards, C. (ed.) 2013. *Building the Great Stone Circles of the North*. Oxford: Windgather.

Schmidt, K. 2010. Göbekli Tepe – the Stone Age sanctuaries: new results of on-going excavations with a special focus on sculptures and high reliefs. *Documenta Praehistorica* 37, 239–56.

Steimer-Herbert, T. 2018. *Indonesian Megaliths: a forgotten cultural heritage*. Oxford: Archaeopress.

Webber, M. with Ganiaris, H. 2004. The Chelsea club: a Neolithic wooden artefact from the River Thames in London. In J. Cotton and D. Field (eds) *Towards a New Stone Age: Aspects of the Neolithic in south-east England*. York : CBA Research Report 137. 124–7.

Wunderlich, M. 2019. *Megalithic Monuments and Social Structures: comparative studies on recent and Funnel Beaker societies*. Leiden: Sidestone.

Figure captions

Figure 1. The location of the bluestone quarries at Carn Goedog and Craig Rhos-y-felin in north Pembrokeshire, Wales. The location of Waun Mawn unfinished and dismantled stone circle (blue) is shown in relation to bluestone sources (red) and Early Neolithic portal dolmens (black squares). The Neolithic causewayed enclosure of Banc Du and the palisaded enclosure of Dryslwyn (black rings) are also shown. Cerrig Lladron (the source of the dolerite standing stones remaining at Waun Mawn) is in blue

Figure 2. Top: Carn Goedog bluestone quarry viewed from the south; lower left: artificially widened crack above the stone platform ; lower right: artificially widened crack 30m to the west of the platform and main recess

Figure 3. Mudstone wedges from Carn Goedog, including an ovoid artefact (bottom left)

Figure 4. Top: Craig Rhos-y-felin bluestone quarry viewed from the north; lower left: the recess from which a pillar has been removed (left) and the pillar left *in situ*, with a 1-metre planning frame leaning against it; lower right: the stone wedge SF136 in the crack behind this pillar and the back of the recess

Figure 5. Top: Richard Bevins inspects the split slab beside the Neolithic occupation area at Craig Rhos-y-felin, viewed from the north (the recumbent Early Bronze Age monolith lies in the background); lower left: the stone wedge SF135 (top), hammerstone SF133 (middle) and broken wedge SF134 (bottom) within the split stone; lower right: stone wedge SF135

Figure 6. Two views of hammerstone SF 133 (135mm x 92mm x 43mm) from Craig Rhos-y-felin. It is formed from a water-worn rhyolite cobble, with batter damage along a 70mm-long section of the ridge on its wider end

Figure 7. Top: the back of the recess (top right) and the pillar left *in situ* (left) at Craig Rhos-y-felin, with west at the top of the picture, with stone wedge SF137 in the crack behind the pillar; bottom: close-up view, looking west, of stone wedge SF137 *in situ*. The scale is 15cm long

Figure 8. Top : three views of stone wedge SF136, showing flake scars around its top; bottom: stone wedge SF137

Figure 9. Positions of pXRF analyses relative to the positions of possible stone wedges at the north-eastern end of Craig Rhos-y-felin. Approximate analysis positions are marked with red dots, and where they were in position at the time the photographs were taken, the stone wedges are marked with white arrows. *L* and *R* mark Left and Right sides of a crack, relative to the direction from where analyses were performed ; *In* and *Out* mark the inside and outside margins of a crack, relative to the steep, north-west face of the crag (see analyses tables and Figure 10). **A**: General location image to show positions of wedges and analyses. For scale, the upper metal section of the tripod leg is 41 cm long. **B**: Stone Wedge SF135 in the crack which contained wedges SF134 and SF135. **C**: Stone wedge SF135 being analysed at Craig Rhos-y-felin some months after removal from the crack. **D**: Stone wedge SF137in its host crack. **E**: The thin

flake of rhyolite within its host crack (this flake was not removed) just northeast of SF137. **F**: The crack which contained stone wedge SF136.

Figure 10. Bivariate plots of K vs Rb, Rb vs Sr and Ba vs Sr for the thin flake near SF137, and the individual stone wedges SF134, SF135, SF136 and SF137 and the margins of their host cracks, set against all other analyses of the rhyolites at Craig Rhos-y-felin. Outlined fields encompass the composition of the wedge (solid line) and both margins (dashed line). All concentrations in ppm.

Figure 11. Plots of PC1, PC2 and PC3 from Principal Component Analysis of all analyses from Rb, Sr, Ba and K from a total of 253 analyses from Craig Rhos-y-felin and all analysed stone wedges (22 analyses contained missing values). PCA was conducted using Minitab® v14, using a covariance matrix and performed with no modification of the data (i.e. no scaling or normalisation). Each row presents the PCs for a particular stone wedge and its host crack taken from the full PCA data set.

Tables

Table 1. Operating conditions for the TestAllGeo procedure used to determine the composition of the samples. Those elements nominally detected with each filter as listed by Niton are given in *italics* (Niton XL3t 900 Analyzer with GOLDD Technology Users Guide, Version 6.5), with the elements shown in bold being those detected in the majority of analyses *and* reported in this study.

pXRF Filter Setting "TestAllGeo" mode	**Time (s)**	**Elements determined**
Main Range	30	*Mo, Zr, Sr, U, Rb, Th, Pb, Se, As, Hg, Zn, W, Cu, Ni, Co, Fe, Mn* **Zr, Sr, U, Rb, Th, Pb, Zn, Ni, Fe, Mn**
Low Range	30	*Cr, V, Ti, Sc, Ca, K, S* **Ti, Ca, K, S**
High Range	20	*Ba, Cs, Te, Sb, Sn, Cd, Ag, Pd, Nb, Bi, Re, Ta, Hf* **Ba, Nb**
Light Range (not used in all analyses)	20	*Al, P, Si, Ca, K, Cl, S, Mg* **Al, P, Si, Mg**

Table 2: Results from Student t-tests on the analyses of stone wedges and the margins of their host cracks, showing the probability (p) result. Where p <0.05 (**bold**), the concentrations of that element can be considered to be different between the samples at a 95% probability.

Element	**Average composition of wedge compared with average of both side of crack**					**Average composition of material either side of crack compared**			
	SF134 v. margins	SF135 v. margins	SF136 v. margins	SF137 v. margins	Thin flake v. margins	L v. R 134/5	L v. R 136	In v. Out 137	In v. Out Thin flake
Zr	**0.000**	0.898	**0.001**	**0.014**	0.283	**0.000**	0.341	0.769	0.807
Sr	0.347	**0.000**	**0.014**	**0.000**	0.304	**0.005**	**0.000**	**0.028**	0.120
U	0.225	0.301	0.282	0.643	0.183	0.903	0.864	0.091	**0.023**

Rb	**0.009**	**0.000**	**0.000**	**0.021**	0.088	0.453	**0.004**	0.506	0.575
Th	**0.008**	0.234	**0.001**	0.048	0.631	**0.013**	0.385	0.953	0.400
Pb	0.114	**0.044**	0.151	**0.041**	0.196	0.051	**0.005**	**0.043**	0.305
Fe	0.671	**0.006**	**0.000**	0.166	**0.021**	0.056	**0.048**	0.658	0.072
Mn	0.837	0.862	**0.000**	0.073	0.064	0.598	**0.038**	0.247	**0.004**
Nb	0.182	**0.023**	0.425	**0.043**	0.942	**0.009**	**0.003**	**0.001**	0.644
Ti	0.067	**0.031**	0.611	0.056	0.140	**0.000**	**0.000**	0.259	0.480
Ca	0.070		**0.015**	0.162	0.293	**0.001**	**0.000**	0.278	0.087
K	0.074	**0.000**	**0.000**	0.124	0.087	0.383	**0.003**	**0.004**	0.327
Ba	**0.000**	**0.000**	**0.000**	**0.006**	0.767	**0.016**	**0.000**	**0.002**	0.062

Table 3. Stone tools from Carn Goedog

	Dolerite	Other igneous	Mudstone	Quartz	Flint
Wedge	2	1	6		
Flake	44	2	2	6	1
Hammer	1				
Disc			3		
Ovoid			1		

Table 4. Stone tools from Craig Rhos-y-felin

	Rhyolite	Quartz	Chert	Flint
Wedge	5			
Flake	20	11	1	6
Hammer	5			
Disc	2			
Ovoid				
Worked cobble	2	1		
Scraper	1			
Core		2		