# Identification of the source of dolerites used at the Waun Mawn stone circle in the Mynydd Preseli, west Wales and implications for the proposed link with Stonehenge

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**Abstract**

A Neolithic stone circle at Waun Mawn, in the Mynydd Preseli, west Wales, has been proposed as the original location of some dolerite megaliths at Stonehenge, including one known as Stone 62. To investigate this hypothesis, *in-situ* analyses, using a portable XRF, have been obtained for four extant non-spotted doleritic monoliths at Waun Mawn, along with two weathered doleritic fragments from a stonehole (number 91). The data obtained have been compared to data from spotted and non-spotted dolerite outcrops across the Mynydd Preseli, an area known to be the source of some Stonehenge doleritic bluestones, as well as data from *in-situ* analysis of Stone 62 (non-spotted dolerite) and *ex-situ* analysis of a core taken from Stone 62 in the late 1980's.

Recently, Stone 62 has been identified as coming from Garn Ddu Fach, an outcrop some 6.79 km to the east-southeast of Waun Mawn. None of the four dolerite monoliths at Waun Mawn have compositions which match Stonehenge Stone 62, and neither do the weathered fragments from stonehole 91. Rather the data show that the Waun Mawn monoliths, and most probably the weathered stonehole fragments, can be sourced to Cerrig Lladron, 2.37 km southwest of Waun Mawn, suggesting that a very local stone source was used in construction of the Waun Mawn stone circle. It is noted that there is evidence that at least eight stones had been erected and subsequently removed from the Waun Mawn circle but probability analysis suggests strongly that the missing stones were also derived, at least largely, from Cerrig Lladron.

## 1. Introduction

Stonehenge, lying on Salisbury Plain in Wiltshire, England, is remarkable for the distance its stones have been transported, making it unique amongst European megalithic monuments (Parker Pearson et al., 2020). Its sarsen stones, fifty-two in number and weighing between 4-30 tons comprise the Outer Sarsen Circle, the Sarsen Trilithon Horseshoe and the outlying Station Stones, Slaughter Stone and Heel Stone. Nash et al. (2020) say that 50 of the 52 stones originate from a common source area and most probably came from West Woods, on the edge of the Marlborough Downs some 22.5 km to the north of Stonehenge. However, it is the smaller bluestones, forty-four in number (in 46 pieces) and weighing 1-4 tons, which are even more remarkable as almost all of them have been provenanced to the Mynydd Preseli area in north Pembrokeshire, some 225 km away as the crow flies. Whilst the sarsen stones are all silcretes the bluestones are a lithological assemblage comprising chiefly dolerites and andesitic, dacitic and rhyolitic tuffs, as well as sandstone. Locating exactly where the bluestones come from will provide a better understanding of this iconic and unique monument, possibly leading to a greater appreciation of the reasons behind its construction approximately 5000 years ago.

In 2021, following excavation at a partially preserved stone circle at Waun Mawn in the Mynydd Preseli, it was proposed that missing stones had been taken to contribute to the original construction of Stonehenge (Parker Pearson et al., 2021). The excavation appeared in a BBC TV documentary entitled ‘Stonehenge: The Lost Circle Revealed’ (first broadcast on December 12, 2021), in which Stonehenge was described as ‘a second-hand monument’ – a phrase quoted by the media around the world. In this paper we present the first geological analysis of the Welsh circle’s surviving stones and compare them to material at Stonehenge and to outcrops in north Pembrokeshire.

## 2. Previous studies

A possible north Pembrokeshire source for the bluestones was first mooted by A.C. Ramsay and colleagues in 1858 but it was H.H. Thomas, a geologist with the then Geological Survey of Great Britain, who provided the first detailed account of the bluestone lithologies in a seminal paper in 1923, assigning the dolerites to Carn Meini and Cerrigmarchogion, the

71 'rhyolites' to Carn Alw and the tuffs to the northern slopes of Foel Drygarn. He was
72 convinced that the majority of the bluestones came from this restricted area towards the
73 eastern extremity of the Mynydd Preseli. Key locations referred to in this paper are shown
74 on Figure 1.

75 Since 2009 we have been undertaking a systematic review of the bluestones, re-
76 examining their lithologies and investigating further their potential sources. The great
77 majority of the rhyolitic debitage recovered from the Stonehenge Landscape was
78 determined by Ixer and Bevins (2010, 2011) and Bevins et al. (2011, 2012) to be from Craig
79 Rhos-y-Felin, an outcrop on low ground to the north of the Mynydd Preseli. In addition,
80 investigations of the detailed mineralogy of the 'Altar Stone' (Stone 80), a grey-green,
81 carbonate-rich sandstone, have suggested that it does not come from the Cosheston Group
82 in the Milford Haven area (see Bevins et al., 2020; Ixer et al., 2020), an earlier proposal
83 which lay behind the notion that the bluestones were transported in part by sea up the
84 Bristol Channel (Atkinson, 1956).

85 It is re-examination of the sources of the dolerites that is pertinent to this paper. The
86 bluestone dolerites comprise spotted and non-spotted varieties, the spots being
87 saussuritized plagioclase phenocrysts/glomerocrysts (Bevins et al., 2021a). Bevins et al.
88 (2014), using standard laboratory-based XRF data generated in the late 1980's, identified
89 three compositional groups, namely Group 1 (spotted, low Ni and Cr), Group 2 (non-
90 spotted, high Ni, low Cr) and Group 3 (spotted, low Ni, high Cr). They suggested that the
91 majority of the spotted dolerites came from Carn Goedog, noting that none in fact matched
92 to Carn Meini, the source proposed by Thomas (1923). Regarding the Group 2 non-spotted
93 dolerites (which includes Stonehenge stones 44, 45 and 62 and debitage fragment OU6)
94 Bevins et al. (2014) suggested that they were derived from either Cerrigmarchogion or Craig
95 Talfynydd. However, using newly generated ICP-MS data, Bevins et al. (2021b) refined
96 slightly the sources of the non-spotted dolerites, concluding that, whilst Stone 45 did indeed
97 come from Cerrigmarchogion, none of the non-spotted bluestone dolerites were sourced
98 from Craig Talfynydd and whilst they were not able to conclusively identify the source of
99 Stone 62 or debitage fragment OU6 they noted a close similarity to non-spotted dolerite
100 from Carn Ddafad-las and Garn Ddu Fach. They were unable to suggest a source for Stone
101 44. In order to investigate further the source of Stone 62, Pearce et al. (2022) undertook *in-*

*situ* compositional analysis using portable XRF (pXRF) of that stone at Stonehenge and compared it with analyses by the same method from outcrops in the Mynydd Preseli. Their data showed that analyses from Stone 62 and from the Preseli outcrop Garn Ddu Fach occupied the same compositional space on various binary elemental plots, concluding that Garn Ddu Fach was the likely source of Stonehenge Stone 62.

As noted earlier, on the basis of archaeological excavations, Parker Pearson et al. (2021) have recently suggested that Stonehenge Stone 62 was removed from a partial stone circle at Waun Mawn in the Mynydd Preseli (see Figure 1). This has major implications for understanding the potential origins of the bluestones used in the construction of Stonehenge, suggesting that they might first have been used locally in the construction of stone circles which were subsequently dismantled, either completely or at least in part, with stones being transported to and used in the construction of Stonehenge. In order to test this, we have analysed by pXRF dolerite outcrops from across the Mynydd Preseli area, including those closest to Waun Mawn (Cerrig Lladron, Carn Fach and Carnau Ysfa) and compared the results with those from the four extant dolerite monoliths and from two non-spotted dolerite fragments from stonehole 91 at Waun Mawn. We also compare the pXRF data from Stone 62 at Stonehenge with the pXRF data for the four exposed non-spotted dolerite monoliths and the two stonehole fragments at Waun Mawn.

## 3. Archaeological context

Waun Mawn's four stones (three of them recumbent and one standing) have been considered to be the remains of a stone circle for the last hundred years (RCAHMW, 1925, 258–9). The site is located on the slope of a hill on the north side of the Mynydd Preseli ridge, about 3.9 and 4.6 km respectively from the bluestone sources of Craig Rhos-y-Felin and Carn Goedog with their evidence for quarrying of monoliths in the Middle Neolithic period in the centuries before and up to c. 3000 BC (Parker Pearson et al., 2015, 2019).

Excavations at Waun Mawn in 2017–2021 revealed empty stoneholes for another eight standing stones which had been erected to form an incomplete ring 110 m in diameter (Parker Pearson et al., 2021; Parker Pearson, 2022). The discovery of further pits, dug around the circumference but which never held standing stones, provides evidence that the circle was abandoned in mid-construction and left unfinished. Radiocarbon-dating of wood

charcoal and optically stimulated luminescence (OSL) dating of sediments within the stoneholes provide a likely construction date of c. 3400–3200 cal BC. Dating of the eight standing stones' removal is less precise, placing these events before 2120±520 BC, though this work is still on-going.

Close comparisons between Waun Mawn and Stonehenge include their sharing of entrance orientations towards midsummer solstice sunrise and Stonehenge's enclosing ditch having the same diameter as the Waun Mawn circle. A further possible link between Stonehenge Stone 62 and Waun Mawn was provided by the shape of one of the stoneholes (stonehole 91; Parker Pearson et al., 2021). Dolerite fragments recovered from this stonehole included one which has been thought to have become detached from the monolith which originally stood in this hole (Parker Pearson et al., 2021, Fig. 8).

## 4. Methods

### *4.1. Analysis*

Between 2017 and 2021 a series of outcrops of dolerite (both spotted and non-spotted) in the Mynydd Preseli in north Pembrokeshire were analysed by pXRF, whilst pXRF analyses were performed during 2021 on the four large stones at Waun Mawn stone circle and two dolerite fragments recovered from Waun Mawn stonehole 91. Analyses were performed using a Thermo Fisher Scientific™ Niton™ XL3t Goldd+ handheld XRF analyser. 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 manufacturer-installed "TestAllGeo" analysis method. This allows the instrument to determine a range of elements in geological materials from Mg to U by use of different filters which operate in sequence together to optimise sensitivity. The elements nominally determined in each mode are given in Table 1, during a total analysis time of 100 s. An 8 mm diameter analysis spot (analysed area ~50 $mm^2$) was used for all analyses, and the spectra were collected on a silicon drift detector, processed and calibrated by the instrument's manufacturer-installed calibration.

### *4.2. Accuracy of pXRF analyses*

To assess the accuracy of the Niton pXRF analyses, a series of reference materials (RMs) have been analysed, including the NIST SRM 610 "Trace elements in Glass", Geological Survey of Japan reference rocks JB-3 (Basalt) and JP-1 (Peridotite), and United States

Geological Survey CRM G-2 (Granite), taking reference values from published sources (Flanagan, 1976; Govindaraju, 1994; Pearce et al., 1997; GeoReM, 2014). The analysed concentrations from these RMs are presented in Supplementary Table 1. JB-3 and JP-1 were prepared as standard 32 mm diameter XRF pressed powder pellets using 10 g of sample pressed into a disk at 20 T with a few drops of Moviol® (PVA) binder. G-2, prepared in the same way, was made as a 10 mm diameter pellet. JB-3 and JP-1 were also prepared as a loose powder sample in a nylon holder, retained behind a Mylar® film as provided by Niton. The accuracy of the RM analyses by pXRF is variable; Rb, Sr, Zr, Ti, K are better than ± 10% while Ba, Zn, Fe, Nb and Zn are within ±25% of accepted values in JB-3 and G-2 (when detected) from standard XRF pressed powder pellets. Nickel is overestimated at low concentrations (JB-3) and underestimated at very high concentrations (JP-1), associated with a poor (slightly flat) calibration on the Niton instrument, probably related to relatively low sensitivity of the Ni Kα line and an interference from Fe Kβ radiation on the background. In G-2, Ni, which is well below the detection limits in basalts at 20-30 ppm, is recorded at about 55 ppm, over 10 times its reference concentration of <5 ppm. The "Niton" standards show slightly better analyses for some elements in JB-3, but worse in JP-1. The NIST glass, a 3 mm wafer about 15 mm in diameter containing about 450 ppm of most trace elements, gave accurate analyses for Ca, Ti, Rb, Sr, Sn, Pb and U (<±10%) while Zr, Nb and V were within ± 25%, but some elements were determined very poorly, including Ba and Cr, both analysed at less than 5% of the their true concentrations, presumably a reflection of the complexity introduced into the background X-ray spectrum from a material with non-geological concentrations of similar atomic number trace elements emitting X-rays of similar wavelengths to these elements. Overall, the trace elements Rb, Sr, Zr, Nb, Zn, Th, Ba, along with Ti, K, Fe, V, and Ca, have an accuracy within ±20% in basalts and granites, and whilst by no means perfect, this is acceptable for provenance studies using the same instrument. The abundant major elements Al and Si are determined poorly and show marked differences between the pressed powder XRF pellets and the Niton loose-powder samples, presumably related to differences in the mass absorption of X-rays leaving the different density samples. The pXRF also reports unrealistically high concentrations of Cd and Sc in all analyses, and the presence of high concentrations of many unexpected elements (e.g. Hg, Au, Pd) which will not be present at the reported concentrations. This attests to some calibration issues within the Niton instrument, the high Cd possibly a result of interference from the Compton

scattering of the Ag X-ray source radiation, and the Sc possibly an interference from a Ca Kβ line.

Supplementary Table 1 also shows repeat analyses of Preseli dolerite, from both a large hand specimen with weathered and fresh surfaces from Carn Goedog performed 5 years apart, and repeats of a field traverse from Carn Meini taken 2 years apart. There are only small differences in these repeat analyses for elements used in our attempts to correlate sources (within the expected heterogeneity of the sample, typically better than ±5 - 10%, see Pearce et al., 2022) and this indicates the long-term consistency of calibration of the pXRF instrument.

To ensure day-to-day consistency of pXRF analyses, in analysis sessions during 2021 a piece of obsidian from the Big Obsidian Flow (BOF) at Newberry Volcano, Oregon was analysed repeatedly to monitor the pXRF calibration. In Supplementary Table 2 we present BOF results from different analytical sessions during 2021 which did not change significantly during this study, meaning data from different sessions can be compared. For the analyses of the Newberry BOF, day-to-day precision is good for the elements Rb, Zr, Sr, Nb, K, Ca, Al and Fe (coefficient of variation, CV, from 5 analyses ~3-4%), less good for Ba and Mn (CV ~8%) and lower again for Th and U (CV ~8-13%), but all are within the range of all BOF analyses performed as part of our provenance investigations. Some published averages for analyses of the Newberry BOF are also presented in Supplementary Tables 1 and 2 (Laidley and McKay, 1971; Higgins, 1973) and show that the pXRF results (taken from a single sample of the flow) are in good agreement for some elements (Ba, Zr, Mn, Ca, K), again suggesting acceptable accuracy (within ±20%).

In pXRF analysis, limits of detection (LoD) vary from sample to sample, depending upon the X-ray intensity received at the detector, and this is affected by many factors, including sample composition (the effect of other elements in the same matrix) and analyser/sample geometry. The instrument software calculates the LoD as 3 times the standard deviation of the measurement, and no concentrations for those elements falling below the analysis LoD are reported. Many elements are <LoD in almost all samples analysed in this study (e.g. Se, Te, Au, As, Hg), but others may be close to the LoD in some samples but not in others (e.g. Ni with an LoD around 30 ppm in basaltic compositions). However, this non-reporting of

data provides some useful information on the general composition of a sample, suggesting the distribution of low concentrations in a population.

Many authors have commented on issues related to pXRF analysis, including amongst other issues spectral overlaps causing incorrect element identification, detection and calibration, sample homogeneity and analysed spot size issues, attenuation of signal from pore water or sample wetness, and surface weathering effects (Jones et al., 2005; Potts et al., 2006; Hunt and Speakman, 2015). We have discussed these issues in earlier publications related to provenance studies at Stonehenge using data obtained by pXRF (Bevins et al., 2022; Pearce et al., 2022) and have developed an approach for analysis of heterogeneous, coarse-grained dolerites which has been applied here, and which conforms to suggestions made in other studies of similar material (Jones et al., 2005; Potts et al., 2006). In such heterogeneous materials, where possible, we perform 20 analyses per orthostat, and these settle to an average composition varying by less than ±5% of the mean after about 15 analyses for most elements useful in discriminating sources (Pearce et al., 2022). For the outcrops in the Mynydd Preseli, methods of analysis are described below (Sections 4.3 and 4.4).

There has been much heated debate about the accuracy and reproducibility of pXRF, and whether in such provenance studies it should be viewed as an archaeological or geochemical tool (Frahm, 2013a; Frahm, 2013b; Speakman and Shackley, 2013).For analyses such as these, whilst the accuracy and precision of pXRF is by no means perfect, but where sampling for geochemical analysis by bulk methods of archaeological materials is unrealistic on conservation or other grounds, and where there are limits on sampling the source outcrops, pXRF provides an ideal analytical tool for provenance studies, provided its limitations are carefully considered during the data analysis and interpretation.

### *4.3. Analyses of Preseli dolerites*

Analyses of field outcrops considered in this study in the Preseli were conducted between July 2017 and November 2021, and included eight locations, namely Carn Goedog (2017), Cerrigmarchogion (2017), Carn Meini (2017 and 2019), Cerrig Lladron (2021), Carn Fach (2021), Garn Ddu Fach (2021), Carn Ddafad-las (2021) and Carnau Ysfa (2021). The distribution of these outcrops is shown on Figure 1. Analyses on the outcrops were

performed as a series of horizontal traverses of 10 or 15 analyses at a given height above ground level, with several traverses being performed through the vertical height of the outcrop. These were spaced 0.5 to 1 m apart, to give between 60-175 analyses per outcrop in total, the size of the outcrop and time available determining the specific analytical strategy. Our approach has been described elsewhere, and is not repeated here (Pearce et al., 2022), with analyses presented here all being conducted on dry days so that any effects of surface water attenuating light element fluorescent X-ray signals were minimal. The large number of analyses overcomes the heterogeneity of the dolerites caused by either their spotted or ophitic character (Jones et al., 2005; Pearce et al., 2022). Figure 2 shows field photographs of three outcrops in the western Mynydd Preseli in the vicinity of the Waun Mawn stone circle (viz. Cerrig Lladron, Carn Fach and Carnau Ysfa) which are all non-spotted dolerite. These outcrops display variously developed columnar jointing features, all have an ophitically-mottled surface (see Figure 2e) and all display late-stage veining (Figure 2f), the latter being avoided during the pXRF analyses.

### *4.4. Analysis of Waun Mawn stones and stonehole fragments*

We conducted *in-situ* pXRF analyses of the stones at Waun Mawn during dry weather in April 2021. Analysed surfaces were chosen to be free from lichen (which covers parts of some stones), they were all weathered, but not coated in Fe-oxides, and free from deposits of lanolin and dye from sheep scratching themselves on the stones. We performed between 10 – 34 analyses per stone, depending upon the size of the stone, with analyses following traverses between the small cards visible on the surfaces of the stones in Figure 3 (e.g. on Stone C we analysed between cards 9-10 and 10-11 in Figure 3d, but in the others analysed between adjacent numbers, i.e. 1-2 on Stone A in Figure 3b, 3-4, 5-6 and 7-8 on Stone B in Figure 3c, and 12-13, 14-15 and 16-17 on Stone D in Figure 3e).

Two dolerite fragments recovered from Waun Mawn stonehole 91 were analysed subsequently in the laboratory, but the same methodology was used for these samples as for the four Waun Mawn stones.

### *4.5. Statistical methods*

The use of statistics in correlating archaeological materials to geological sources can be helpful, such as Principal Component Analysis (PCA), including pXRF studies on obsidians

from an archaeological perspective (Campbell and Healey, 2016; Muşkara and Konak, 2022) or the use of other multivariate methods for obsidians (e.g. Schmuck et al., 2022), or for the Stonehenge sarsens (Nash et al., 2020). Similar statistical approaches in matching volcanic ash deposits to source volcanoes have been applied in tephra studies (Sarna-Wojcicki et al., 1979; Perkins et al., 1995; Perkins et al., 1998; Lowe et al., 2017) but it has been shown that these methods can also obscure the relationships in data where a mix of elements are used which are determined with varying precisions, depending on the statistical approach, e.g. electron probe microanalysis of tephra glasses for correlation/provenance studies (Pollard et al., 2006; Pearce et al., 2008). Many of these statistical approaches are often better for proving differences, rather than proving compositional equivalence (Pearce et al., 2008; Lowe et al., 2017) but again this can be unclear. Oftentimes variations in one or two elements, related to geological processes, can be crucial indicators of provenance, variations which may become hidden when multivariate approaches involving many elements are used, and a combination of approaches (compositional space on bivariate compositional diagrams, T-tests, statistical distance analyses, PCA) can often yield the most useful comparisons. It must be remembered that it is variation in the raw data which underpins all statistical tests, and an understanding of the range and variation in the raw data is of prime importance. We illustrate the different approaches below by first attempting PCA to try to correlate the Waun Mawn stones with possible sources, attempts which we refine using a geochemical approach to yield finally a robust correlation.

In addition, once we have defined the sources of the four remaining stones at Waun Mawn, in the light of the suggestion that the Waun Mawn circle was dismantled and removed to Stonehenge (Parker Pearson et al., 2021), we investigate the probability of leaving the four stones at Waun Mawn from an original 12, if the selection process to remove the stones was random, a process akin to pulling, at random, different coloured balls from a bag.

## 5. Results and discussion

### *5.1. Elements used for discrimination*

Our previous study using pXRF analyses to source Stone 62 from Stonehenge to Garn Ddu Fach in the Mynydd Preseli (Pearce et al., 2022) showed the utility of comparing the compositional space occupied by analyses from Stone 62 with analyses from individual

Preseli outcrops to discriminate potential sources. To this end, a selection of elements which are determined reliably by pXRF, i.e., having acceptable accuracy (better than about ±20%) and precision (around ±10% in homogeneous materials) and relatively unaffected by surface weathering (see Potts et al., 2006), provided useful discriminators. These elements are K, Ti, V, Fe, Mn, Ni, Zn, Rb, Sr, Zr, Nb and Ba. Nickel provides a discrimination between the spotted and non-spotted dolerites, the latter having higher Ni (Bevins et al., 2014; Bevins et al., 2021b) and whilst the spotted dolerites have Ni which is often close to the limits of detection in pXRF (around 30 ppm in these basaltic compositions), this lack of detection in the spotted Group 1 and 3 dolerites can be useful as a discriminant. Combining Ni and Ba data proved useful in discriminating many of the bluestone outcrops in the Mynydd Preseli (Pearce et al., 2022) and this is shown in Figure 4 for the Waun Mawn stones.

## 5.2. Waun Mawn stones

All four stones from Waun Mawn have a closely similar composition, occupying overlapping Ba vs Ni fields, with Ni contents ranging from about 40-150 ppm, and Ba between 200-400 ppm (Figure 4). Nickel in these samples is most probably related to the presence of pseudomorphs of chlorite after olivine, as seen in other non-spotted dolerites but not in the spotted dolerites, and Ba will most likely be associated with the feldspathic component.

Parker Pearson et al. (2021) suggested that the non-spotted dolerite bluestone Stone 62 at Stonehenge may potentially have occupied stonehole 91 at Waun Mawn, based on the coincidence of their sizes and shapes. Compositional data for Stone 62 from Stonehenge (from Pearce et al., 2022) is also shown in Figure 4, as well as analyses from the small drill core removed from Stone 62 (reported by Thorpe et al., 1991), alongside data from Waun Mawn. It is clear that Stone 62 is markedly different from any of the Waun Mawn stones, having notably higher Ba and a Ni distribution which peaks at higher concentrations (see histograms in Figure 4) than the analysed stones from this site. Stonehenge Stone 62 has recently been provenanced to Garn Ddu Fach, a small outcrop in the eastern Mynydd Preseli (Pearce et al., 2022), 6.79 km to the east-southeast of Waun Mawn (see Figure 1).

Figure 5 shows Ba vs Ni for the four Waun Mawn stones (WM-A to WM-D) plotted as fields compared with surface analytical data (determined by pXRF) for all analysed outcrops from Mynydd Preseli. About one-sixth of the analyses from Carn Fach and Carnau Ysfa Ni were below the detection limit for pXRF (around 30 ppm), thus the extent of the compositional fields on Figure 5 must continue to lower Ni. In contrast, for the Waun Mawn Stones and Cerrig Lladron only 3% of the Ni analyses fell below the LoD, thus these fields closely represent the complete compositional space occupied by the data (see Supplementary Table 3, Analyses falling below LoD). The general overlap of the composition of Cerrig Lladron with the Waun Mawn stones is clear, with Ba having the same range, and Ni rising to about 140 ppm in Cerrig Lladron, a little lower than the highest Ni shown by a Waun Mawn stone (170 ppm Ni from a single WM-C analysis, ~25 ppm higher than the three other WM stones). Comparing the WM stones against analyses from individual outcrops in the Mynydd Preseli, Carn Fach has Ba contents which extend to much higher concentrations (around 530 ppm) while Ni shows fewer high concentrations (>95 ppm). Carnau Ysfa has a composition which is restricted to lower Ni contents than many of the WM stone analyses (with only 1 analysis >95 ppm) but displays a similar range in Ba; hence it occupies a sub-set of the compositional space occupied by the WM stones. The outcrops of Carn Goedog, Cerrigmarchogion and Carn Meini in the eastern Mynydd Preseli have compositions which extend from similar to much higher Ba than occurs in any WM stone, but Carn Goedog and Carn Meini are relatively low in Ni. For Garn Ddu Fach and Carn Ddafad-las, the Ba compositions are almost all higher than the WM stones, whilst the range of Ni is similar. Cerrigmarchogion shows similar Ni to Garn Ddu Fach, Carn Ddafad-las and the WM stones, although has higher Ba than the WM stones which is lower than the Ba in Garn Ddu Fach and Carn Ddafad-las.

Table 2 shows the average composition of the four Waun Mawn stones compared to the three near-by western Mynydd Preseli outcrops for those elements determined in the majority of analyses. It is apparent that many of the average compositions of the outcrops overlap at ±1 standard deviation, although some elements show systematic differences in composition, for example Fe and Mn which are both about 50% higher in the Waun Mawn stones than the outcrops, potentially the result of weathering forming an Fe-oxide crust on the stones (see Potts et al., 2006).

To investigate if the similarity between the WM stones and Cerrig Lladron could be seen using a statistical approach, PCA (which had proved successful in previous studies using bulk sample analyses by XRF, Bevins et al. 2014), was conducted using Minitab® v14, using a covariance matrix for the elements Zr, Sr, Rb, Ni, Fe, Mn, V, Ti, Ba, K, and Nb, performed with no modification of the data (i.e. no scaling or normalisation) for all the analysed outcrops in the Mynydd Preseli and the four Waun Mawn stones. The summary PCA results are presented in Supplementary Table 4. This included 486 from 955 analyses where all elements were above the detection limits by pXRF. The principal components here are dominated by Fe (in PC1), Ti and K (in PC2) and K and Ti (in PC3). Figure 6 presents a series of plots for PC1, PC2 and PC3 from this analysis grouped similarly to Figure 5. The plots of PC1 vs PC2 largely separate the exposures of Cerrigmarchogion, Carn Goedog and Carn Meini from the Waun Mawn stones, and most of the other outcrops show variable degrees of overlap with the Waun Mawn stones. For PC3 vs PC2, there is a substantial overlap of all analyses from the Preseli outcrops with the Waun Mawn stones, and this selection of elements offers little discrimination other than separating two of the spotted dolerite outcrops (Carn Goedog and Carn Meini) from the non-spotted Waun Mawn stones, which simply confirms the petrographic observations. The variations in Fe which dominate the PCA are likely to be associated with weathering (see above and Potts et al. 2006).

The greatest degree of overlap in the PCA is shown by the Waun Mawn stones and the three outcrops closest to the stone circle, namely Cerrig Lladron, Carn Fach and Carnau Ysfa, and these similarities are noted also in the Ba vs Ni data. Based on these observations, Student T-tests were performed (using all compositional data) to assess any similarities between the Waun Mawn stones and these possible local sources, with results tabulated in Supplementary Table 3. Where the probability generated by the T-test exceeds 0.05 ($p>0.05$) the data cannot be separated at a 95% confidence level, and the samples cannot be said to be drawn from different populations. Here, many similarities are noted between the three outcrops in Cl, Mg (although in over 40% of cases Mg is not detected and this is therefore unreliable), Ca, V, and Pd (which is again unreliable, see above). The two most similar outcrops from the T-test results are Carnau Ysfa and Carn Fach, and this is reflected in similar Ni ranges and an overlap in Ba in the Ni-Ba diagram. This supports the field observations which suggest these outcrops are along-strike exposures of the same sill.

Comparison of the Waun Mawn stones with each outcrop show the same number (six each) of elements with $p>0.05$, although Cerrig Lladron has more "near misses" than the other outcrops ($p>0.01$). Only one element, Pb, has $p>0.05$ for all outcrops, and Pb has been suggested as an atmospheric contaminant in the Preseli dolerites by Potts et al. (2006). Other elements with $p>0.05$ include Mg, P, Al, Nb, Ba, K, Ca, Ti, Zr, Rb, and Ni. The T-tests do not unequivocally identify one outcrop as a potential source for the Waun Mawn stones. Principal component analysis, again on unscaled geochemical data, was repeated using this set of elements, excluding Pb and also Mg as it is not detected in a large number of analyses. The PCA here included 458 analyses where all elements were above detection limits, and the results are presented in Figure 7. Again, this offers no clear discrimination of the Waun Mawn stones from any of the analysed outcrops in the Mynydd Preseli, although a broad discrimination is evident in the compositional space occupied by these stones and outcrops in the bivariate plot of Ba vs Ni (Figure 5).

In this instance, applying PCA without consideration of the possible causes of geochemical variation amongst the analyses, has not been able to assist in the provenancing of the Waun Mawn stones.

### *5.3. Investigation of the compositional data*

We now return to consider the compositional data, our primary source of information for these materials. It is our contention that this should be the first data investigated in provenance studies (see Pearce et al., 2008) where statistical approaches, widely applied in many geoarchaeological studies, do not yield clear results, as shown above. Figure 8 shows the compositional data for the elements Sr, Rb, Zr, Ba, Ni and K for the four Waun Mawn stones A-D with each analytical traverse on each stone separated (see Figure 3), alongside plots for the variation of each element against height within the exposures of Carn Lladron, Carnau Ysfa and Carn Fach. This gives a clearer indication of the ranges of composition in each stone, and through the thickness of the exposed Preseli dolerite sills. Dotted lines on Figure 8 mark the compositional ranges from the four Waun Mawn stones combined. In some cases (e.g., Ni and Rb) the lower line most likely reflects the limit of detection for that element (~30 ppm for Ni, ~2 ppm for Rb) although the LoD varies for each analysis (see discussion in Pearce et al., 2022). For example, in Waun Mawn stone B there are many analyses where Rb is below detection limits, with only 2 analyses

detecting Rb in traverse T5-T6, and none in T3-T4, while Sr is detected in all analyses. These elements were selected as experience shows different outcrops occupy different compositional spaces (Pearce et al., 2022) which can be related to geochemical processes. Strontium is compatible in plagioclase and will be concentrated in the more felsic components of the magmas. Nickel is associated with the mafic component of the dolerites, particularly olivine and pseudomorphs thereafter, produced during the low-grade metamorphism of the dolerites (see Bevins et al., 1989), and provides a good discriminant between Group 2 and Groups 1 and 3 dolerites in the Mynydd Preseli (Bevins et al., 2014). Potassium and Rb are essentially incompatible in basaltic magmas and will build up during the evolution of the magma, so that crystallisation will cause these to increase. They are also soluble elements, and any hydrous metamorphism may mobilise/concentrate these. Zirconium is also highly incompatible but is immobile and should be little modified by metasomatism/metamorphism, although it will concentrate in any baddeleyite which is present (see Bevins et al., 2014). Barium, weakly incompatible in plagioclase, in basic magmas shows a behaviour similar to K and Rb, increasing in the more compositionally evolved magmas, and will generally associate with the felsic component of the melt. Strontium in many analyses is much higher in Carn Fach and Carnau Ysfa than the Waun Mawn stones, and is higher in a few analyses from Cerrig Lladron, whilst the lower range of Sr is similar for all three outcrops. The range of Rb in the Waun Mawn stones is encompassed by all three outcrops, and whilst its distribution appears similar to Carnau Ysfa, this outcrop lacks the highest Rb concentrations recorded in stones D and A. Zirconium (and also Nb, not shown) is similar between all outcrops and the Waun Mawn stones with the highest concentrations recorded from two Waun Mawn stones. Barium is very similar between the Waun Mawn stones and Cerrig Lladron, with Carnau Ysfa showing a notably lower range in Ba concentrations, and Carn Fach having many analyses which show higher concentrations. The Ni concentrations in Carn Fach and Carnau Ysfa are lower than in the Waun Mawn stones, which most closely resemble the range of Cerrig Lladron, and it must be remembered that about one sixth of the Ni analyses in Carn Fach and Carnau Ysfa are below the LoD of pXRF analyses. Potassium in the Waun Mawn stones similarly displays the same concentration range as Cerrig Lladron, and the stones show more analyses with higher concentrations than Carn Fach, which are also notably higher in K than Carnau Ysfa.

Taking the six elements (Ba, Sr, Zr, Rb, K, Ni) used in Figure 8, PCA (again using unscaled data) was undertaken for the outcrops analysed; the results are presented in Figure 9. The Waun Mawn stones show almost no overlap with non-spotted dolerites from Garn Ddu Fach and Carn Ddafad Las, only a slight overlap with material from Cerrigmarchogion (non-spotted), Carn Meini and Carn Goedog (both spotted), and the two proximal outcrops Carnau Ysfa and Carn Fach. There is however a complete overlap of the Principal Components for analyses from Waun Maun and from Cerrig Lladron. To investigate whether the use of scaled data in the PCA calculation would alter the interpretation, the data was scaled so that the average element composition = 0 and the standard deviation = 1, a widely used approach prior to PCA. The PCs shown in Figure 9 were replotted for the scaled compositions using both a covariance and a correlation matrix, and these PC plots presented in Supplementary Figures 1 and 2. No difference in the interpretation of the PCA was forthcoming using scaled data when compared with the raw data: the plots showed the same similarities and differences between the Waun Mawn stones and the various Preseli outcrops.

Thus, the similarity in Principal Component Analysis for raw and scaled data, the similarities in compositional space occupied by the analyses described above, alongside their petrography strongly suggests the Waun Mawn stones were derived from Cerrig Lladron.

To establish whether two flakes of non-spotted dolerite from stonehole 91 at Waun Mawn were possibly fragments from Stonehenge Stone 62 they were also analysed by pXRF and the data for these are included in Table 2 (samples Stonehole 91 WAU18 TR8 070/35 and 070/36) and presented in Figure 10. Both of these samples have an iron-rich weathering crust and sample 070/36 is particularly intensely weathered (see Figure 8 in Parker Pearson et al., 2021). It is apparent in Table 2 that these flakes show high Fe and Mn compared to all analyses of the western Mynydd Preseli outcrops and also the Waun Mawn stones, but also considerably higher Al, Si, V, Zr, Nb, and Ti, whilst Ca and Sr are lower, and K, Rb, Ba, Mg and Ni are similar. The formation of a Fe- and Mn-rich oxide crust during sub-surface weathering of dolerite is typical in soils of pH~6, as found in the Waun Mawn area (see UKSO, 2022). At this pH, high field strength elements (HFSE) such as Zr can be strongly sorbed onto hydrous ferric oxides (HFO) with Zr reaching concentrations of up 0.22 µmol per mmol Fe at ~pH 6

(equivalent to about 360 ppm in the HFO, Yu and Liu, 2005). The relationship between high Fe and Zr is shown in Figure 10a, with clear enrichment in the oxidised surfaces of these flakes compared to all analyses from dolerite outcrops in the Mynydd Preseli, and it is clear that both Fe and Zr have increased over normal dolerite compositions. The elevated Nb recorded here (see Table 2) maintains the Zr/Nb ratio of typical Preseli dolerites, and suggests Nb also behaves in this manner, and is not fractionated from Zr during weathering and HFO formation. Strontium, in contrast, has decreased (by perhaps 50% or more) with increasing weathering (increasing Fe, Figure 10b), associated with leaching of this soluble ion from plagioclase, and the same is true of Ca (not shown). However, Ni and Ba seem to be unaffected by this weathering, with these elements showing concentrations typical of the analyses of all outcrops in the Mynydd Preseli (Figures 10c and 10d). This attests to markedly different behaviours of Sr and Ba (both Group II elements) and Fe and Ni (transition metals) during the weathering process, and indicates the care needed in interpreting compositional data form weathered artefacts. Figures 10e and 10f show Ba vs Ni and Ba vs Sr from the two flakes of weathered dolerite from stonehole 91 at Waun Mawn compared to the compositions of outcrops from the western Mynydd Preseli outcrops close to Waun Mawn. The Ba and Ni concentrations are closely similar to Cerrig Lladron (though Ni is below detection in sample 070/36), and the Ba vs Sr data, when allowance is made for the likely reduction in Sr during weathering, are also very similar to Cerrig Lladron. The flakes also clearly have Ba, Ni and Sr which are all notably lower than analyses from Stone 62 at Stonehenge, and this shows that neither of these are pieces removed from Stone 62.

## 6. Summary of results

From the above, it is clear that the four non-spotted dolerite standing stones currently at Waun Mawn all have a composition which is closely similar (see Figures 4, 5,8,9), suggestive of a common or closely related source. They have a composition which is significantly different from Stone 62 at Stonehenge (Pearce et al., 2022), this being a stone which had been proposed as originally occupying stonehole 91 at Waun Mawn (Parker Pearson et al., 2021), and which has been sourced subsequently to Garn Ddu Fach, in the eastern Mynydd Preseli (Pearce et al., 2022).

The Waun Mawn stones differ markedly in composition from the dolerite outcrops in the eastern Mynydd Preseli and differ petrographically from Carn Meini and Carn Goedog in

that they are non-spotted and contain compositionally different secondary minerals. Cerrigmarchogion, Carn Ddafad-las and Garn Ddu Fach all extend to much higher Ba than any analyses from the Waun Mawn stones, and hence all of these outcrops can be ruled out as a possible source. However, the three outcrops which are local to Waun Mawn in the western Mynydd Preseli, viz. Cerrig Lladron, Carn Fach and Carnau Ysfa all show moderate to high Ni and low Ba (200-400 ppm) and display some compositional overlap with the Waun Mawn stones, with these three outcrops being possible sources. Comparing the compositional space occupied by these outcrops and the Waun Mawn stones, Cerrig Lladron is by far the most similar, having the same range of compositions of Ba, Zr, Rb, Ni and K, and similar Sr. Carnau Ysfa has a slightly lower range of Rb, Ni and Ba, notably lower K, higher Sr, and similar Zr, while Carn Fach displays higher Sr and Ba, marginally higher Rb, somewhat lower K and Ni, and similar Zr. Based on these compositional similarities and differences, we propose Cerrig Lladron as the most likely source of the four extant stones at Waun Mawn.

Adopting an approach where PCA is used to attempt to discriminate sources without any consideration of the geochemistry (simply treating the compositions of individual orthostats or outcrops as a variable without consideration of the differences or causes therefore exemplified by variations in the “compositional space” the data occupies), leads to an initial PCA result where all stones and sources appear similar. This is because the subtle differences between source compositions (range and distribution of the compositions) is masked for those elements which allow some discrimination (e.g. Ba, Ni, Sr, Rb, K, Zr related to geological processes and mineralogical differences) by elements which may be variable for other reasons (analytical considerations, weathering etc). When the selection of elements for PCA is based on variations which can be seen in the analytical data, even if these are subtle and which are related to geological/geochemical processes, then a successful discrimination between sources can be achieved and a correlation suggested with some confidence.

## 7. Can the composition of the stones removed from the Waun Mawn stone circle be inferred?

The majority of dolerite bluestones at Stonehenge are spotted dolerite. If some of these were once erected at Waun Mawn and removed (from the eight now unoccupied stone holes at Waun Mawn) to leave the four non-spotted dolerites at Waun Mawn, either

(i) any spotted dolerites originally present (up to a maximum of eight) were removed deliberately or (ii) a mix of eight stones, including spotted and non-spotted dolerites, were removed, by a random selection. If the latter option were the case (with random selection of the removed stones) consideration of the probability of leaving four non-spotted dolerites derived from Cerrig Lladron can suggest something about the possible composition of the original Waun Mawn circle. The probability of leaving behind, by random selection, four stones which all derived from Cerrig Lladron (this is termed "the outcome") from a starting collection of twelve stones which could have derived from more than one source has been calculated. The methodology is the same as calculating the probabilities of randomly removing coloured balls from a bag without replacement to leave a particular set of balls. In probability this is termed a "dependent event", where the first ball removed changes the probability for what is picked second, giving a "conditional probability" (i.e., what is the probability of an outcome dependant on prior actions?). This derives from Bayes' theorem, and the method of calculation is explained in Supplementary Methods 1. At Waun Mawn, eight stones must have been removed from the original twelve, to leave four which are all from Cerrig Lladron. The probability of this outcome can be calculated by removal of stones from a starting collection which can vary from, at one extreme, assuming all removed stones were from Cerrig Lladron, to, at the other extreme, none were from Cerrig Lladron. The calculated probabilities are given in Table 3. As would be expected, the probability of randomly leaving four stones behind from Cerrig Lladron is a likely outcome if the original mixture was dominated by Lladron material, but this becomes increasingly unlikely as more "foreign" stones are included in the original collection, so that there is only a 1 in 4 chance of the outcome if there were three foreign stones in the original twelve, a 1 in 7 chance with four foreign stones, and only a 1 in 33 chance starting with an equal mix of stones (i.e. six from Cerrig Lladron, six from elsewhere). If the stones were removed by a random selection, this strongly suggests that the original assemblage of the Waun Mawn circle was dominated by stones from Cerrig Lladron, if not entirely from that source. If the choice was however deliberate (to specifically remove all the spotted dolerite stones) then the probability analysis is not appropriate as this was not a random selection. Of course, the reasons why the eight stones were removed, how they were chosen, and by whom is unlikely ever to be known.

## 8. Conclusions

Of the twelve standing stones that can be considered as original to the Waun Mawn circle, the four which remain there are most likely sourced from Cerrig Lladron, just 2.37 km to the southwest. This raises the possibility that all of Waun Mawn's standing stones may have come from Cerrig Lladron which lies some 3.7km west of Cerrigmarchogion (the source of Stone 45 and 7km west of Garn Ddu Fach (the source of Stone 62. However, it should be noted that stone circles of this diameter are commonly built with standing stones from more than a single source (e.g. Stanton Drew, Somerset [Burl 1999, 55], Long Meg and her Daughters, Cumbria [Burl 1999, 38], and Ring of Brodgar, Orkney [Richards 2013, 105–7]). If the missing stones did all come from Cerrig Lladron then Waun Mawn's relevance for the initial construction of Stonehenge in 2995–2920 cal BC (Parker Pearson et al., 2020, 168) may only have been in terms of the failed completion of what was intended as a major Neolithic monument rather than in terms of its provision of Stonehenge's bluestones. Of course, it should be remembered that the remaining eight stones at Waun Mawn are of unknown lithology, removed at an as yet unconfirmed date in prehistory, and that only 44 of Stonehenge's estimated 81 bluestones have survived (Parker Pearson et al., 2020, 299).

Finally, putting to one side these unknowns, if it is assumed that Waun Mawn was not the source of any of Stonehenge's bluestones, then it is entirely possible that bluestones could have come direct to Stonehenge from their quarries. This would be consistent with radiocarbon dates of 3020–2920 cal BC and 3270–2910 cal BC for the end of the quarrying sequences at Carn Goedog and Craig Rhos-y-Felin respectively (Parker Pearson et al., 2019). Alternatively, the bluestones might have been erected at one or more additional stone circles that were entirely dismantled and have consequently remained undetected.

In summary, our findings lead to the following conclusions:

i). The four remaining dolerite monoliths at Waun Mawn were sourced locally, most probably from Cerrig Lladron, some 2.37 km to the southwest of the stone circle.

ii). The analysis of two flakes of stone from stonehole 91 are compositionally different to, and thus not pieces from, Stone 62 at Stonehenge.

iii). The weathered dolerite fragments from stonehole 91 are interpreted as also coming from Cerrig Lladron.

iv). If removal of the missing eight stones at Waun Mawn was random, probability analysis suggests that it is likely that the majority, if not all, of the missing stones were sourced from Cerrig Lladron.

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**References**

Atkinson, R.J.C., 1956. Stonehenge. London: Hamish Hamilton.

Bevins, R.E., Ixer, R.A., Pearce, N.J.G., 2014. Carn Goedog is the likely major source of Stonehenge doleritic bluestones: evidence based on compatible element geochemistry and Principal Component Analysis. Journal of Archaeological Science 42, 179-193.

Bevins, R.E., Ixer, R.A., Pirrie, D., Power, M.R., Cotterell, T., Tindle, A.G., 2021a. Alteration fabrics and mineralogy as provenance indicators; the Stonehenge bluestone dolerites and their enigmatic “spots”. Journal of Archaeological Science: Reports 36, 102826.

Bevins, R.E., Ixer, R. A., Webb, P.C., Watson, J.S., 2012. Provenancing the rhyolitic and dacitic components of the Stonehenge landscape bluestone lithology: new petrographical and geochemical evidence. Journal of Archaeological Science 39 1005-1019.

Bevins, R.E., Lees, G.J., Roach, R.A., 1989. Ordovician intrusions of the Strumble Head-Mynydd Preseli region: lateral extensions of the Fishguard Volcanic Complex. Journal of the Geological Society, London 146, 113-123.

Bevins, R.E., Pearce, N.J.G., Ixer, R.A., 2011. Stonehenge rhyolitic bluestone sources and the application of zircon chemistry as a new tool for provenancing rhyolitic lithics. Journal of Archaeological Science 38, 605-622.

Bevins, R.E., Pearce, N.J.G., Ixer, R.A., 2021b. 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., Ixer, R.A., Hillier, S., Pirrie, D., Turner, P., 2022. Linking derived debitage to the Stonehenge Altar Stone using portable X-ray fluorescence analysis. Mineralogical Magazine 86, 1-13. doi:10.1180/mgm.2022.22

Bevins, R.E., Pirrie, D., Ixer, R.A., O'Brien, H., Parker Pearson, M., Power, M.R., Shail, R.K., 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.

Burl, A., 1999. *Great Stone Circles*. Newhaven, CI: Yale University Press.

Campbell, S., Healey, E., 2016. Multiple sources: The pXRF analysis of obsidian from Kenan Tepe, SE Turkey. Journal of Archaeological Science: Reports 10, 377-389.

Flanagan, F.J., 1976. Descriptions and analysis of eight new USGS rock standards. US Geol. Surv. Professional Paper 840, 192.

Frahm, E., 2013a. Is obsidian sourcing about geochemistry or archaeology? A reply to Speakman and Shackley. Journal of Archaeological Science 40, 1444-1448.

Frahm, E., 2013b. Validity of "off-the-shelf" handheld portable XRF for sourcing Near Eastern obsidian chip debris. Journal of Archaeological Science 40, 1080-1092.

GeoReM, 2014. http://georem.mpch-mainz.gwdg.de/sample query.asp.

Govindaraju, K., 1994. 1994 compilation of working values and sample descriptions for 383 geostandards. Geostandards Newsletter 18: 1-331.

Higgins, M.W., 1973. Petrology of Newberry volcano, central Oregon. Geological Society of America Bulletin 84, 455-488.

Hunt, A.M., Speakman, R.J., 2015. Portable XRF analysis of archaeological sediments and ceramics. Journal of Archaeological Science 53, 626-638.

Ixer, R.A., Bevins, R.E., 2010. The petrography, affinity and provenance of lithics from the Cursus Field, Stonehenge. Wiltshire Archaeological & Natural History Magazine 103, 1-15.

Ixer, R.A., 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., Bevins, R.E., Pirrie, D., Turner, P., Power, M., 2020. 'No provenance is better than wrong provenance': Milford Haven and the Stonehenge sandstones. Wiltshire Archaeology and Natural History Magazine 113, 1-15.

Jones, M.C., Williams-Thorpe, O., Potts, P.J., Webb, P.C., 2005. Using field-portable XRF to assess geochemical variations within and between dolerite outcrops of Preseli, South Wales. Geostandards and Geoanalytical Research 29, 251-269.

Laidley, R.A., McKay, D.S., 1971. Geochemical examination of obsidians from Newberry Caldera, Oregon. Contributions to Mineralogy and Petrology 30, 336-342.

Lowe, D.J., Pearce, N.J.G., Jorgensen, M.A., Kuehn, S.C., Tryon, C.A., Hayward, C., 2017. Correlating tephras and cryptotephras using glass compositional analyses and numerical and statistical methods: review and evaluation Quaternary Science Reviews 175, 1-44.

Muşkara, Ü., Konak, A., 2022. Characterization of the Obsidian Used in the Chipped Stone Industry in Kendale Hecala. Quaternary 5, 3.

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

Parker Pearson, M., 2022. Archaeology and legend: investigating Stonehenge. Archaeology International 23, 144–64.

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., 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., Welham, K. Casswell, C., French, C., Shaw, D., Simmons, E., Stanford, A., Bevins, R.E., Ixer, R.A., 2019. Megalithic quarries for Stonehenge's bluestones. Antiquity 93, 45–62.

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

Parker Pearson, M., Pollard, J., Richards, C., Welham, K., Kinnaird, T., Shaw, D., Simmons, E., Stanford, A., Bevins, R.E., Ixer, R.A., Ruggles, C., Edinborough, K., 2021. The original

Stonehenge? A dismantled stone circle in the Preseli hills of west Wales. Antiquity 95, 85-103.

Pearce, N.J.G., Bendall, C.A., Westgate, J.A., 2008. Comment on "Some numerical considerations in the geochemical analysis of distal microtephra" by A.M. Pollard, S.P.E. Blockley and C.S. Lane. Applied Geochemistry 23, 1353-1364.

Pearce, N.J.G., Bevins, R.E., Ixer, R.A., 2022. Portable XRF investigation of Stonehenge bluestone 62 and potential source outcrops in the Mynydd Preseli, west Wales. Journal of Archaeological Science: Reports. https://doi.org/10.1016/j.jasrep.2022.103525

Pearce, N.J.G., Perkins, W.T., Westgate, J.A., Gorton, M.P., Jackson, S.E., Neal, C.R., Chenery, S.P., 1997. A compilation of new and published major and trace element data for NIST SRM 610 and NIST SRM 612 glass reference materials. Geostandards Newsletter 21, 115-144.

Perkins, M.E., Brown, F.H., Nash, W.P., McIntosh, W., Williams, S.K., 1998. Sequence, age, and source of silicic fallout tuffs in middle to late Miocene basins of the northern Basin and Range province. Bulletin of the Geological Society of America 110, 344-360.

Perkins, M.E., Nash, W.P., Brown, F.H., Fleck, R.J., 1995. Fallout tuffs of Trapper Creek, Idaho - a record of Miocene explosive volcanism in the Snake River Plain volcanic province. Bulletin of the Geological Society of America 107, 1484-1506.

Pollard, A.M., Blockley, S.P.E., Lane, C.S., 2006. Some numerical consideration in the geochemical analysis of distal microtephra. Applied Geochemistry 21, 1692-1714.

Potts, P., Bernardini, F., Jones, M., Williams-Thorpe, O., Webb, P., 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 8-18.

RCAHMW, 1925. *Inventory of the Ancient Monuments in Wales: VII County of Pembroke*. London: HMSO.

Ramsay, A.C., Aveline, W.T., Hull, E., 1858. Geology of Parts of Wiltshire and Gloucestershire (Sheet 34). London: HMSO.

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

Sarna-Wojcicki, A.M., Bowman, H.W., Russell, P.C., 1979. Chemical correlation of some late Cenozoic tuffs of northern and central California by neutron activation analysis of glass and comparison with X-ray fluorescence analysis. 2330-7102, for sale by the Supt. of Docs., US Govt. Print. Off. 1979.

Schmuck, N., Carlson, R.J., Reuther, J., Baichtal, J.F., Butler, D.H., Carlson, E., Rasic, J.T., 2022. Obsidian source classification and defining "local" in early Holocene Southeast Alaska. Geoarchaeology 37, 466-485.

Speakman, R.J., Shackley, M.S., 2013. Silo science and portable XRF in archaeology: a response to Frahm. Journal of Archaeological Science 40, 1435-1443.

Thomas, H.H., 1923. The source of the stones of Stonehenge. The Antiquaries Journal 3, 239-60.

Thorpe, R.S., Williams-Thorpe, O., Jenkins, D.G., Watson, J., Ixer, R., Thomas, R., 1991. The geological sources and transport of the bluestones of Stonehenge, Wiltshire, UK, Proceedings of the Prehistoric Society 57, 103-157.

UKSO, 2022. UK Soil Observatory data, https://www.bgs.ac.uk/map-viewers/uk-soil-observatory-ukso/

Yu, W., Liu, C., 2005. Sorption of $Zr^{4+}$ and $Hf^{4+}$ onto hydrous ferric oxide and their fractionation behaviours: An experimental study. Acta Geologica Sinica-English Edition 79, 343-348.

803 **Table captions**

804 **Table 1**. Operating conditions for the *TestAllGeo* procedure used to determine the composition of
805 the samples. An 8 mm diameter spot on the sample was analysed (approx. 50 $mm^2$). Those elements
806 detected with each filter as listed by Niton are given in *italics* (Niton XL3t 900 Analyzer with GOLDD
807 Technology Users Guide, Version 6.5), with the elements shown in **bold** being detected in the
808 majority of analyses conducted here and considered in this study.

**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 Configuration "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*<br>**Zr, Sr, Rb, Pb, As, Zn, Ni, Fe, Mn** |
| Low Range | 30 | *Cr, V, Ti, Sc, Ca, K, S*<br>**V, Ti, Ca, K, S** |
| High Range | 20 | *Ba, Cs, Te, Sb, Sn, Cd, Ag, Pd, Nb, Bi, Re, Ta, Hf*<br>**Ba, Nb** |
| Light Range | 20 | *Al, P, Si, Ca, K, Cl, S, Mg*<br>**Al, P, Si, Mg** |

809
810 **Table 2:** Average compositions determined by pXRF (all concentrations ppm) of the four Waun
811 Mawn stones (A-D) and the 3 outcrops in the western Mynydd Preseli. Also included is the average
812 of 4 analyses of late-stage veins cutting stone D at Waun Mawn, which have notably higher
813 incompatible element concentrations. The %>LoD row records the percentage of the 428 analyses
814 performed on these samples which were above the limit of detection, with only those elements
815 detected in >50% of analyses considered here. Cr has been excluded because of calibration issues
816 (see Pearce et al. 2022).

| Units %>LoD | n= | | Zr ppm 100% | Sr ppm 100% | Rb ppm 88% | Pb ppm 99% | As ppm 83% | Zn ppm 100% | Ni ppm 91% | Fe wt 100% | Mn wt % 100% | V ppm 100% | Ti wt % 100% | Ca wt % 100% |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| WM-A | 10 | Avg. | 57 | 178 | 7.0 | 26 | 13 | 68 | 111 | 7.16 | 0.12 | 157 | 0.37 | 4.11 |
| | | S.D. | 23 | 33 | 3.1 | 4 | 4 | 8 | 29 | 0.66 | 0.02 | 35 | 0.10 | 1.69 |
| WM-B | 30 | Avg. | 115 | 163 | 4.1 | 61 | 22 | 79 | 86 | 7.42 | 0.14 | 249 | 0.83 | 3.30 |
| | | S.D. | 28 | 25 | 0.8 | 24 | 10 | 11 | 20 | 1.16 | 0.03 | 58 | 0.24 | 0.63 |
| WM-C | 20 | Avg. | 56 | 185 | 3.6 | 21 | 12 | 66 | 103 | 7.58 | 0.11 | 172 | 0.29 | 3.58 |
| | | S.D. | 24 | 23 | 1.0 | 7 | 9 | 15 | 30 | 1.00 | 0.02 | 38 | 0.12 | 0.98 |
| WM-D | 30 | Avg. | 114 | 182 | 4.9 | 36 | 12 | 70 | 87 | 6.83 | 0.13 | 211 | 0.73 | 4.69 |
| | | S.D. | 34 | 16 | 1.2 | 14 | 4 | 14 | 22 | 1.08 | 0.02 | 37 | 0.24 | 0.74 |
| WM-v | 4 | Avg. | 441 | 237 | n.d. | 111 | 25 | 37 | 55 | 3.43 | 0.06 | 155 | 0.84 | 3.55 |
| | | S.D. | 21 | 30 | | 23 | 14 | 12 | 13 | 0.61 | 0.01 | 36 | 0.19 | 0.27 |
| Stonehole 91 | 15 | Avg. | 362 | 119 | 7.9 | 10 | 10 | 156 | 83 | 11.4 | 0.25 | 306 | 1.07 | 2.52 |
| | | S.D. | 91 | 20 | 6.1 | 3 | 0 | 18 | 15 | 1.66 | 0.07 | 100 | 0.30 | 0.57 |
| Stonehole 91 | 3 | Avg. | 313 | 59 | 10 | n.d. | n.d. | 165 | n.d. | 10.8 | 0.21 | 360 | 1.30 | 1.33 |
| | | S.D. | 24 | 7 | n=1 | | | 21 | | 0.61 | 0.02 | 33 | 0.11 | 0.23 |
| Cerrig Lladron | 115 | Avg. | 74 | 216 | 7.3 | 40 | 22 | 58 | 84 | 5.70 | 0.09 | 168 | 0.39 | 4.15 |
| | | S.D. | 38 | 33 | 3.8 | 14 | 16 | 15 | 21 | 1.03 | 0.01 | 42 | 0.21 | 1.40 |
| Carn Fach | 87 | Avg. | 103 | 281 | 5.7 | 47 | 26 | 48 | 65 | 5.15 | 0.08 | 175 | 0.59 | 4.20 |
| | | S.D. | 57 | 79 | 3.3 | 18 | 21 | 19 | 24 | 1.51 | 0.03 | 70 | 0.54 | 1.55 |
| Carnau Ysfa | 70 | Avg. | 85 | 216 | 5.5 | 47 | 32 | 37 | 62 | 4.52 | 0.07 | 168 | 0.54 | 4.46 |
| | | S.D. | 51 | 64 | 2.8 | 24 | 24 | 12 | 19 | 1.00 | 0.02 | 41 | 0.32 | 1.21 |

817
818 **Table 3.** Probabilities of removing 8 stones from 12 originally at Waun Mawn from different starting
819 mixtures to produce an outcome leaving 4 stones from Cerrig Lladron.

**Table 3.** Probabilities of removing 8 stones at random from 12 stones originally present at Waun Mawn, with different starting mixtures, to leave 4 stones which all derived from Cerrig Lladron. The method is explained in Supplemental Methods 1.

**Starting assemblage**

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Cerrig Lladron stones | 12 | 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 |
| Non-Lladron stones | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |

**Probability after removal of 8 stones at random to leave 4 stones, all from Cerrig Lladron**

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| p= | 1 | 0.6667 | 0.4242 | 0.2545 | 0.1414 | 0.0707 | 0.0303 | 0.0101 | 0.0020 |

820
821

822 **Figure captions**

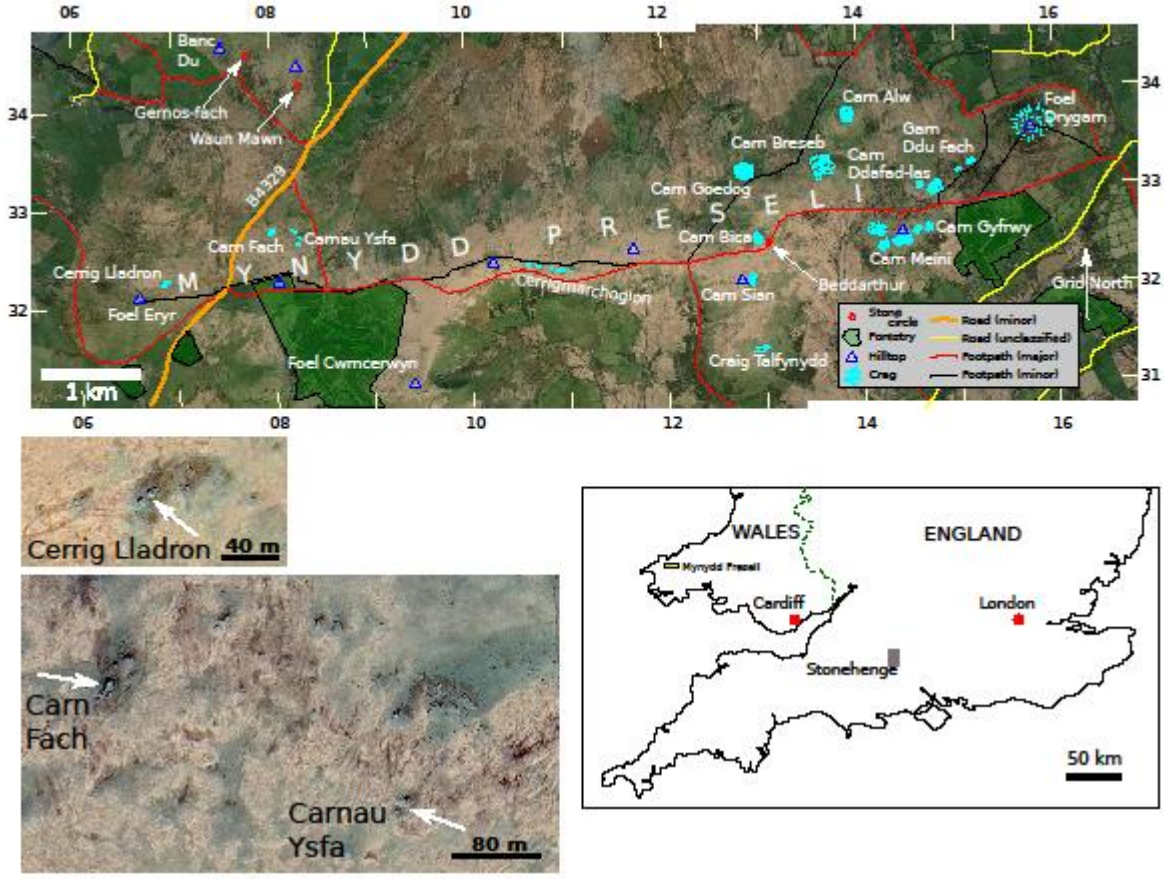
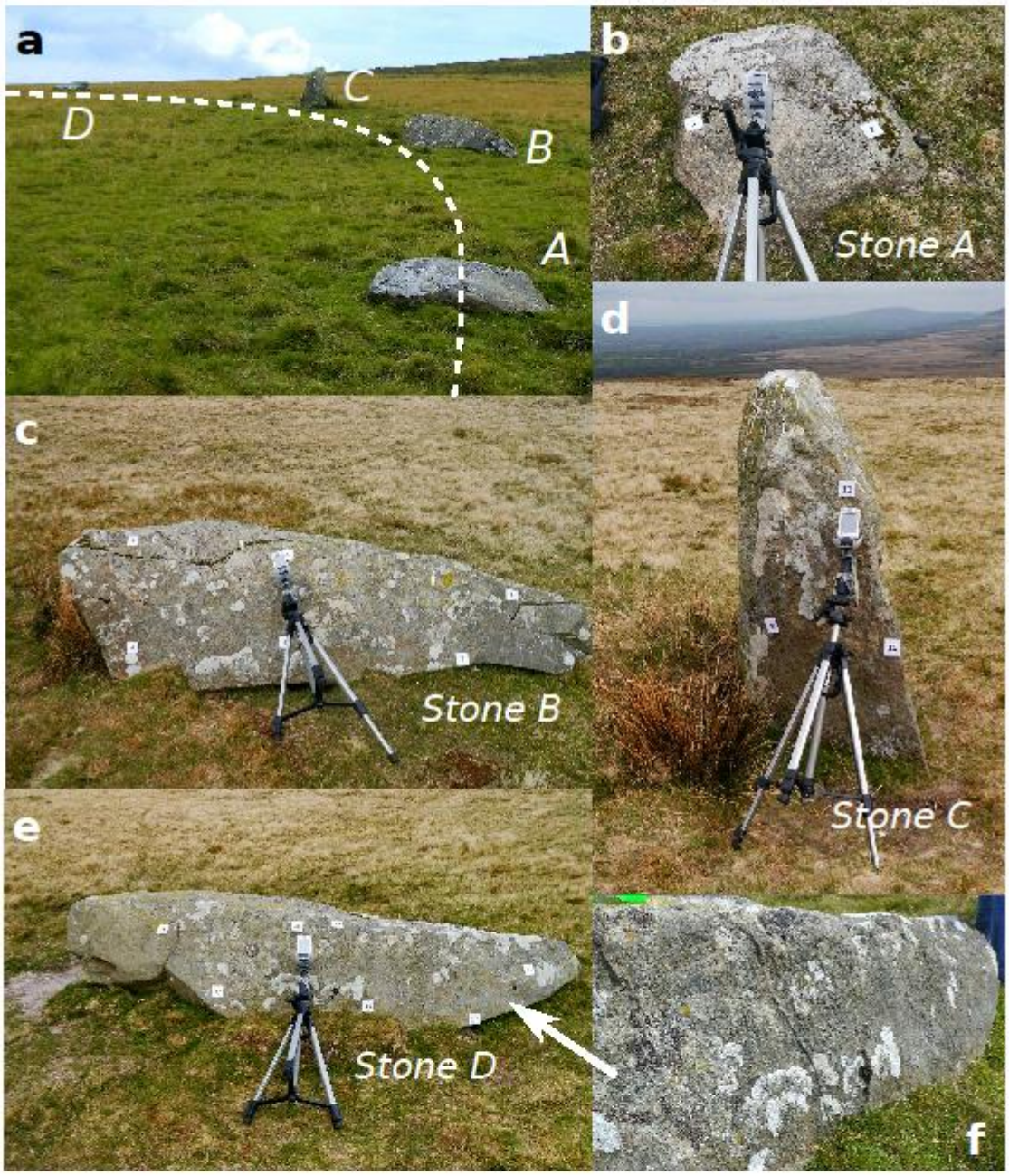



**Figure 1**: Map of the Mynydd Preseli region showing the locations of the Waun Mawn and Gernos-fach stone circles, and the various outcrops of dolerite exposed in the area. Lower figures show the exposure of dolerite in the areas of Cerrig Lladron and Carn Fach/Carnau Ysfa, with arrows locating the analysed sections. Base image and insets © Google Earth with imagery from CNES/Airbus. Road

and other detail from Edina Digimap Ordnance Survey Service, from 1:50,000 Sheet SN02. ©Crown copyright and database rights 2021 Ordnance Survey (100025252). Grid references refer to British National Grid.

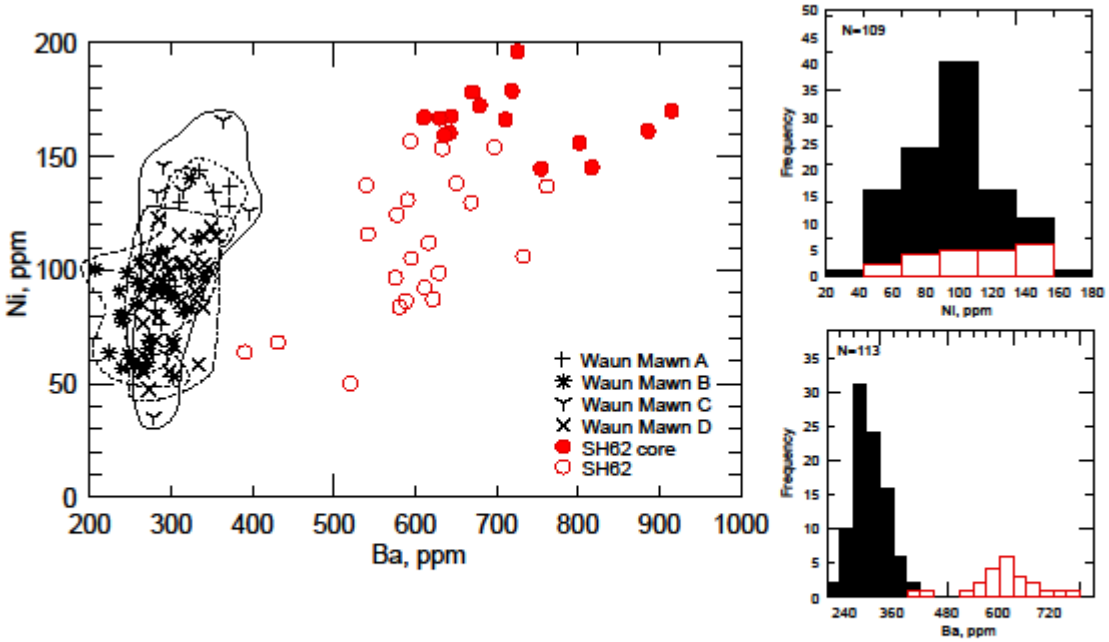

**Figure 2**. **a:** Carnau Ysfa. Waun Mawn is approximately 2 km to the N, on the hillside in the middle

distance, hidden behind the top of the outcrop above the pXRF. **b:** Carn Fach. Lies approximately 350 m WNW of Carnau Ysfa, view looking roughly NE. **c:** Cerrig Lladron. The arrow marks the position of the Waun Mawn stone circle, approximately 2.3 km to the NE. **d:** A toppled block of dolerite showing well developed columnar jointing at Cerrig Lladron. This block is behind the *in-situ* blocks in photo c. **e:** The mottled weathered surface of the dolerite at Cerrig Lladron picking out the ophitic texture of the dolerite – lens cap is 55 mm in diameter. **f:** Veins (varying from about 3 mm to 8 mm) cutting the dolerite at Cerrig Lladron. For scale, in most pictures, the uppermost metal portion of the tripod leg is 41 cm long.



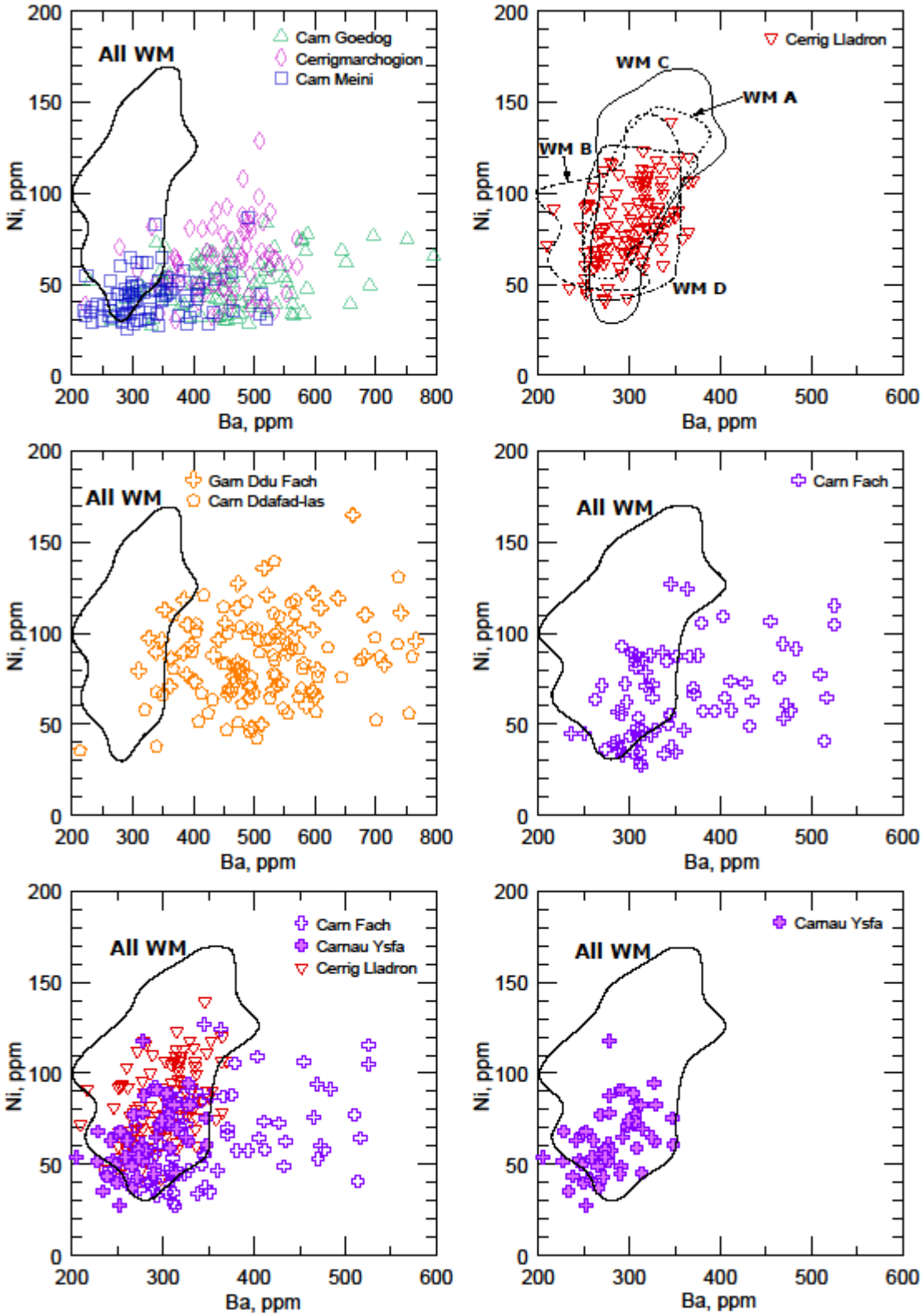

841
842 **Figure 3**: The arc of former standing stones at Waun Mawn. **a:** General view looking roughly NW,
843 with dotted line marking the approximate circumference of the circle; italic letters identify the
844 stones. **b:** Analysed stone A (this is stone 13 from Parker Pearson et al., 2021, Fig. 2). **c:** Analysed
845 stone B. **d:** Analysed stone C, the only remaining standing stone at Waun Mawn. **e:** Analysed stone

D. **f:** Oblique view showing detail of analysed stone D, picking out the mottled texture of the weathered surface of the stone (centre of image), and the network of veins cutting the dolerite (left of centre). The large lichens can be used to match the location in **e**. For scale, in most pictures, the uppermost metal portion of the tripod leg is 41 cm long. Photos **a** and **f** courtesy of Amy Pearce.

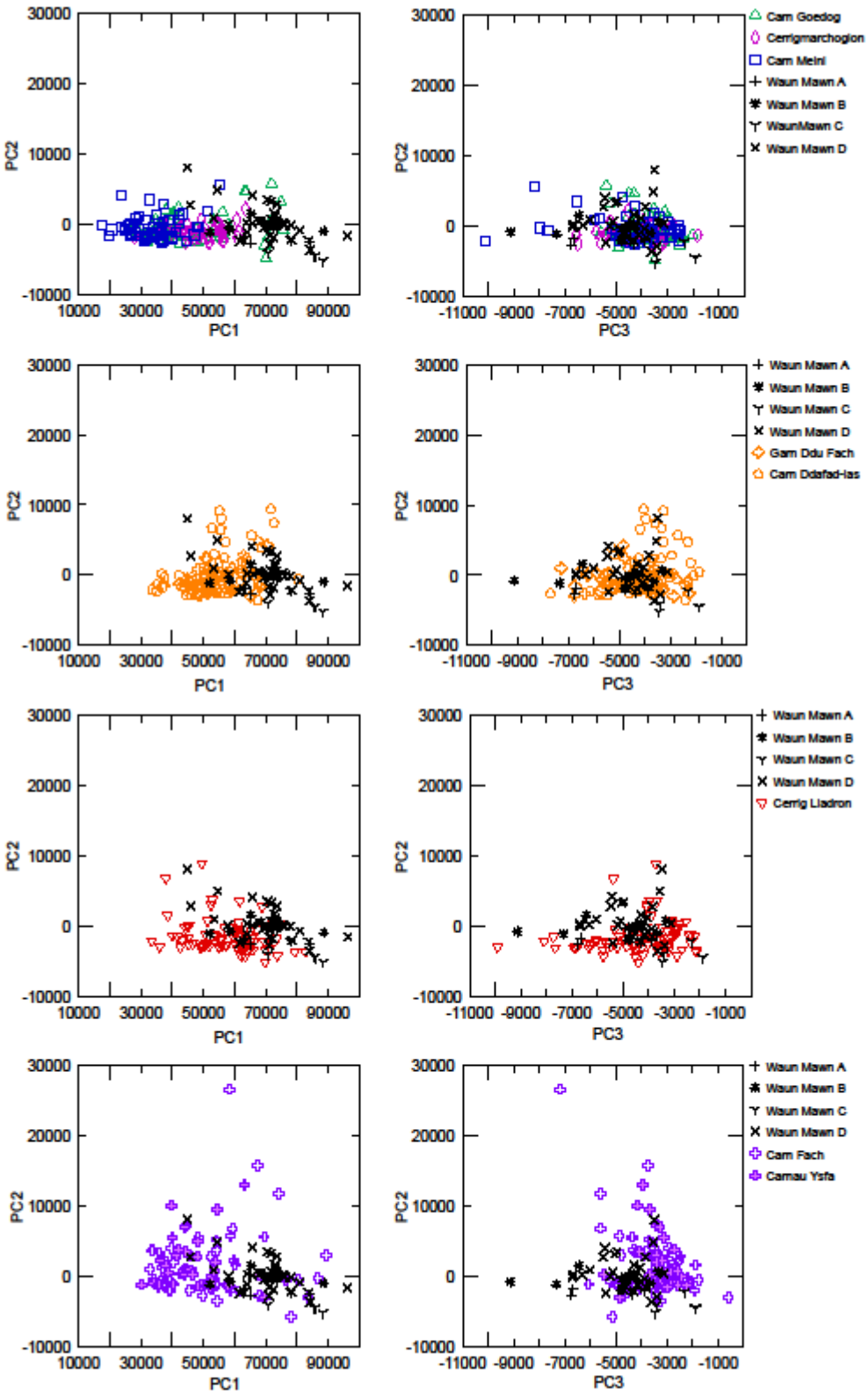



850
851 **Figure 4**: Ba vs Ni (ppm) compositions (determined by pXRF) of analysed stones at Waun Mawn
852 compared with the compositional data for Stone 62 (SH62) from Stonehenge, as both surface
853 analyses (open circles) and as analyses of the core of SH62 (filled circles) taken by Thorpe et al.
854 (1991). SH62 data from Pearce et al. (2022). Histograms show the differences in the distribution of

the Ba and Ni concentrations, for the surface analyses only (i.e. excluding the core from Stone 62), with the Waun Mawn stones grouped together (in black) and SH62 the red boxes – frequency is the total number of occurrences in both (combined) sets of data, and “N” is the number of analyses above the LoD.




859
860 **Figure 5**: Ba vs Ni (ppm) for the Waun Mawn stones (plotted as fields) compared with data for all
861 analysed outcrops from Mynydd Preseli, with the three outcrops closest to the Waun Mawn stone
862 circle, Cerrig Lladron, Carn Fach and Carnau Ysfa, plotted separately. Note the different scales for Ba.




863
864 **Figure 6**: Plots of PC1, PC2 and PC3 from Principal Component Analysis of all analyses of the Waun
865 Mawn stones and all analyses from outcrops in the Mynydd Preseli. These PCs represent 95%, 4.2%
866 and 0.8% of the total variance respectively. PCA was performed in Minitab® v14.0 using Zr, Sr, Rb, Ni,

Fe, Mn, V, Ti, Ba, K, and Nb using a covariance matrix. Each row presents the PCs for a selection of the outcrops taken from the full PCA data set.

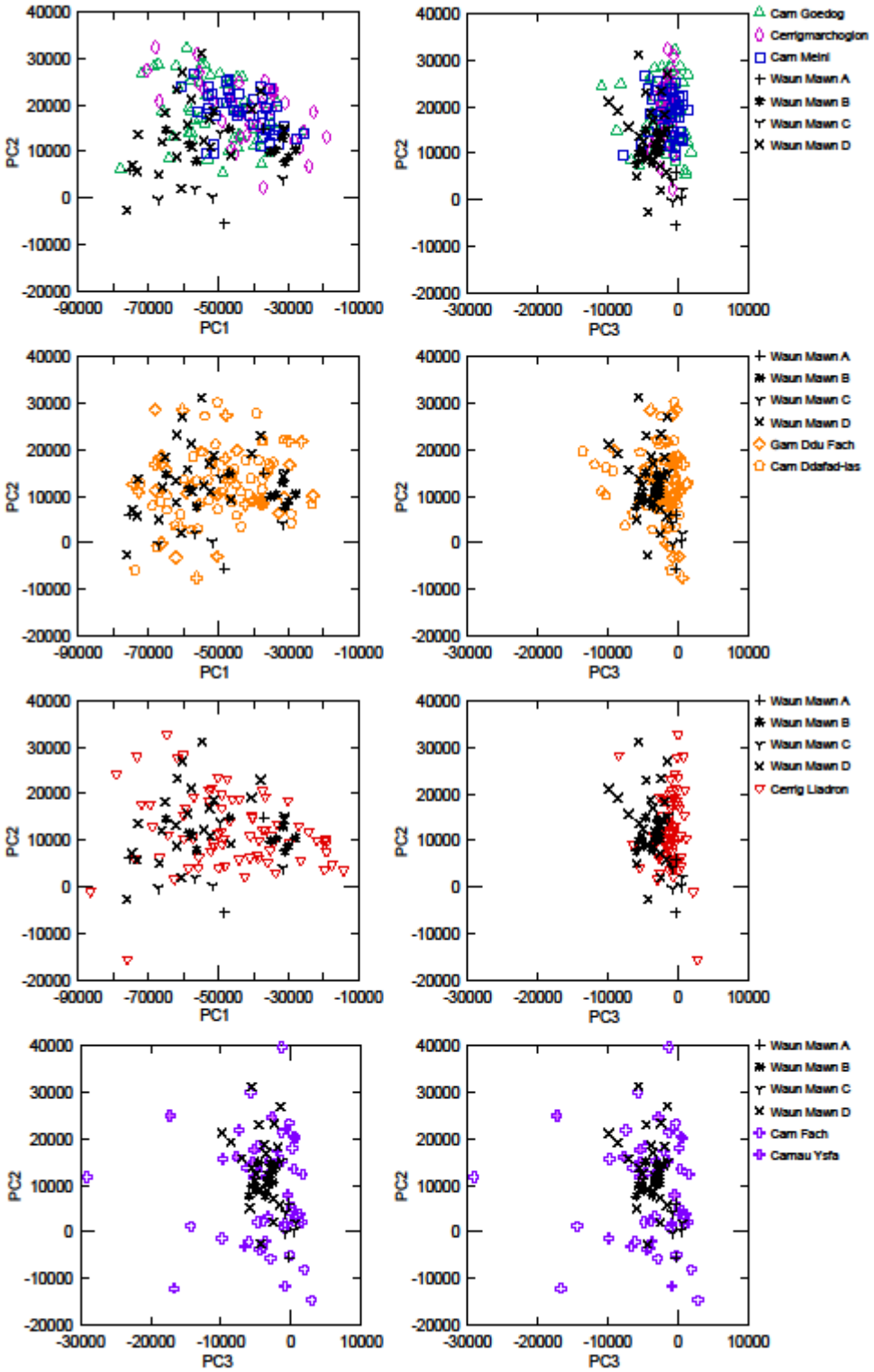
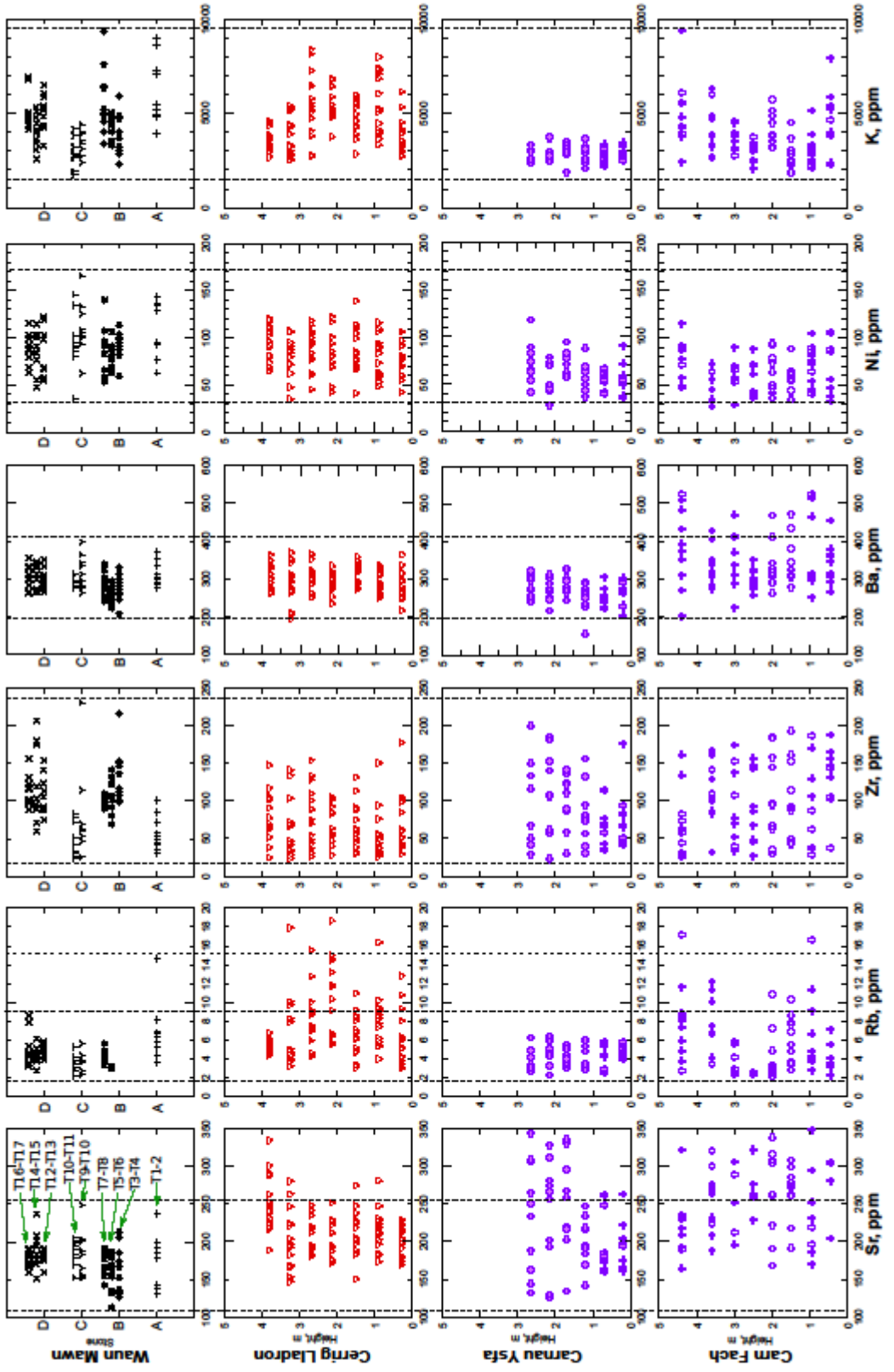



**Figure 7:** Plots of PC1, PC2 and PC3 from Principal Component Analysis of all analyses of the Waun Mawn stones and all analyses from outcrops in the Mynydd Preseli. These PCs represent 69.1%,

872 26.8% and 3.5% of the total variance respectively. PCA was performed in Minitab® v14.0 using Zr,
873 Rb, Ni, Ti, Ca, K, Ba, Nb, Al, and P using a covariance matrix. Each row presents the PCs for a selection
874 of the outcrops taken from the full PCA data set.




875
876 **Figure 8**: Compositional data for the four Waun Mawn stones A-D for the elements Sr, Rb, Zr, Ba, Ni

and K (in ppm) compared with the variation of each element against stratigraphic height within the outcrops of Cerrig Lladron, Carnau Ysfa and Carn Fach. Each Waun Mawn stone is plotted separately, with each analytical traverse indicated. Symbols for the Waun Mawn stones as in Figure 4.

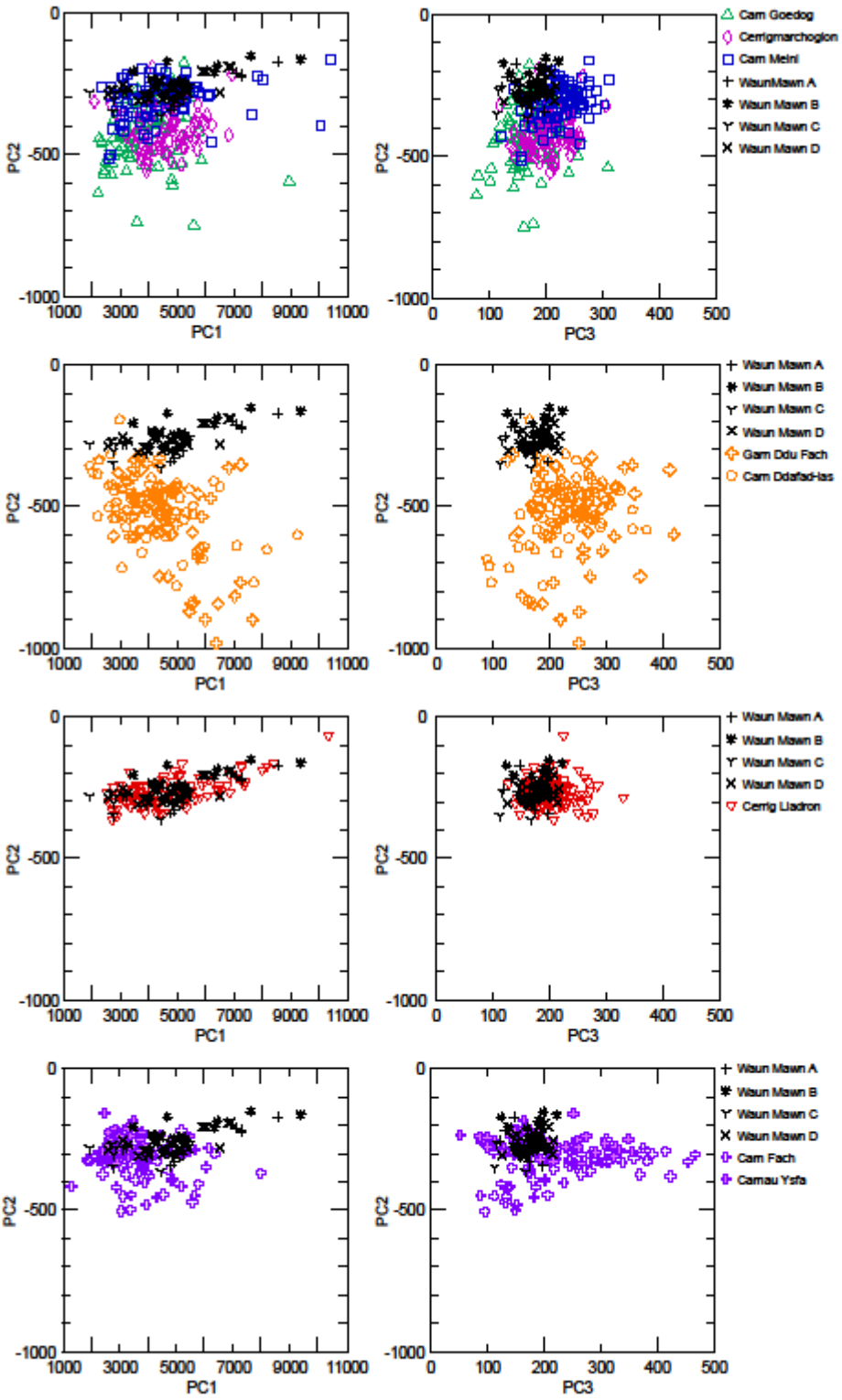



**Figure 9:** Plots of PC1, PC2 and PC3 from Principal Component Analysis of all analyses of the Waun

Mawn stones and all analyses from outcrops in the Mynydd Preseli. These PCs represent 98.7%, 1.0% and 0.2% of the total variance respectively. PCA was performed in Minitab® v14.0 using Ba, Zr, Sr, Rb, Ni, and K using a covariance matrix. Each row presents the PCs for a selection of the outcrops taken from the full PCA data set.

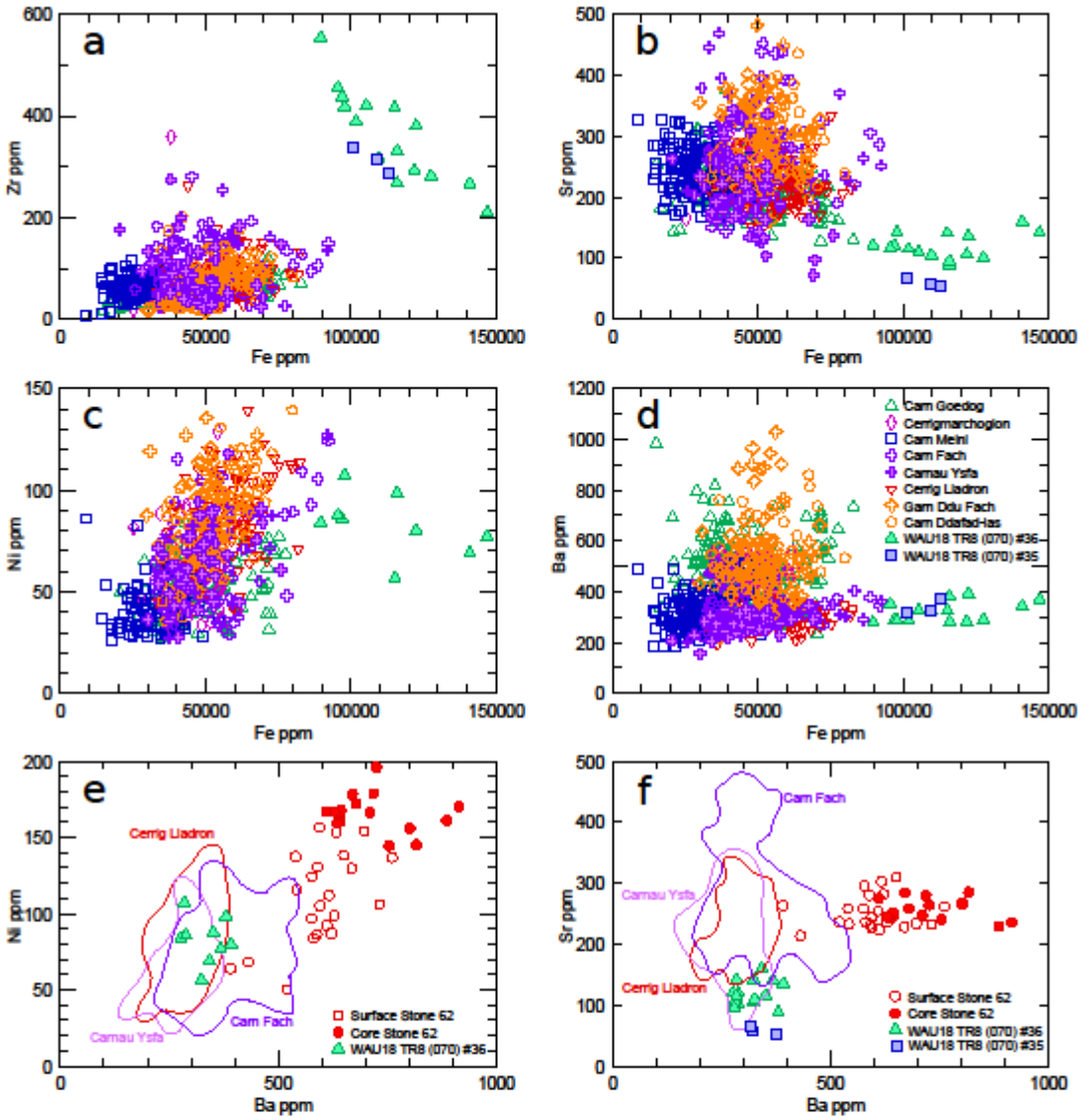



**Figure 10: a-d**. Compositional variation in all analysed dolerites from the Mynydd Preseli compared to analyses of two weathered flakes of dolerite from stonehole 91 at Waun Mawn described by Parker-Pearson et al. (2021), plotted as Fe vs Zr, Sr, Ni and Ba respectively. Note Ni (LoD ~30 ppm by pXRF) was not detected in WAU18 TR8 (070) #35. All concentrations in ppm. **e-f.** Ba vs Ni and Ba vs

Sr (ppm) compositions of Stone 62 at Stonehenge (data from Pearce et al., 2022), the small core taken from Stone 62 by Thorpe et al. (1991), and two weathered flakes of dolerite from stonehole 91 at Waun Mawn, with fields of data from the three western Mynydd Preseli outcrops. In Fig. e WAU18 TR8 (070) #35 Ni is below the limits of detection by pXRF.