Lead isotope analysis of tooth enamel from a Viking Age mass grave in southern Britain and the constraints it places on the origin on the individuals.

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ABSTRACT

Pb analysis of tooth enamel from individuals recovered from a Viking Age burial pit in southern England provides further evidence for their childhood origins outside Britain. All except one of the men have very low Pb concentrations that exclude anthropogenic Pb exposure. Strontium and oxygen isotope compositions identify a core group of men who have Pb isotope compositions of $^{208}Pb/^{206}Pb = 2.065 \pm 0.021$ (n=20, 2SD) that, when compare with data from European soils, appear to exclude a childhood in the Scandinavian countries of Norway, Sweden and Finland whereas areas of northern continental Europe cannot be excluded.

INTRODUCTION

A burial pit containing an assemblage of at least 51 adult males was discovered on Ridgeway Hill during the construction of a road north of Weymouth, Dorset, in Southern England in 2009. No datable artefacts were associated with the pit, however, AMS radiocarbon dating of three individuals revealed them to be from the Viking Period AD 970–1025 (93% probability). All of the men had been decapitated, with the skulls and mandibles deposited in a pile at the southern edge of the pit, while the postcranial remains were scattered with little care, across the rest of the pit (Loe et al., 2014). A study of the postcranial remains concluded that 70% of the individuals were likely to have been under the age of 25 at the time of death. Thirty-four skulls show evidence of sharp-force trauma, with many exhibiting multiple injuries (Loe et al., 2014).

Both anthropological and isotope analysis have been used to determine the origin of these men and particularly to answer the question; where these men local (Anglo Saxon) or from outside the British Isles? Six of the 51 individuals exhibited dental modifications consistent with Southern Scandinavian practices. These individuals were not submitted for isotope analysis in order to preserve their entire dental assemblage for future examination. Fourteen other individuals were lacking suitable teeth for analysis due to severe dental pathologies (Loe et al., 2014). The remaining 31 men have been extensively studied, and the strontium (Sr) and oxygen (O) isotope composition of their tooth enamel is documented in two recent publications: Loe et al. (2014), includes a complete report on all isotope analysis up to 2014; and Chenery et al. (2014) provides a preliminary interpretation based on a pilot study of 10 men, carried out in 2012.

Isotope analysis provides a method of characterizing and excluding certain geographical options that constrain the childhood origin of these individuals. We use three independently controlled isotopic systems: O, which reflects drinking water compositions and its water sources; Sr, which reflects the composition of the land and is transmitted though food intake; and Pb, which again reflects the composition of the local geology and can be used to distinguish between anthropogenic and natural Pb sources.

Earlier studies on the groups O isotope values indicated that the majority of the men are unlikely to be of British origin, suggesting instead childhoods spent in a much colder climates (Fig. 1). The Sr isotope data, which is wide ranging (0.7078 – 0.72), suggests highly variable geological childhood origins, which does not include the area of Dorset in which they were found. When the Sr and O isotope data are plotted together we note that they reveal a core group of twenty individuals (Fig. 2) who have a $^{87}Sr/^{86}Sr$ value of 0.71134 ± 0.003(2SD) and a $\delta^{18}O_{(phos)SMOW}$ value of 15.9 ± 0.8 (2SD). The remaining data are widely scattered. A similar distribution of data has recently been reported from the Island of Öland, off SE

Sweden (Wilhelmson and Price, 2017). The suggestion has been made that the men in the Weymouth grave were the crew of a "viking" boat that was captured and killed in a manner similar to events recorded in the Anglo-Saxon Chronicle (Chenery et al., 2014; Swanton, 2000). However, the Vikings that arrived in Britain during the late 8th to the mid 11th centuries are most commonly cited as originating in Denmark and Western Norway (Downham, 2012; Lass, 1994; Swanton, 2000). Neither of these areas are supported as possible childhood homelands by the majority of O isotope data or, in the case of Denmark, the Sr isotope results (Frei and Frei, 2002).

THE APPLICATION OF Pb TO HUMAN TOOTH ENAMEL STUDIES.

Pb is ingested though hand to mouth contact and to a lesser extent though dust and vapour inhalation (Kamenov and Gulson, 2014). Human exposure to Pb can be divided into two components: First is exposure to natural levels of Pb in, and derived from, soil. The resultant concentration levels in teeth will vary, depending on the local geology, but are typically low c. 0.5-0.7ppm (Millard et al., 2014; Montgomery et al., 2010). The isotope composition of this type of exposure is variable and wide ranging as it reflects the isotope composition of local geological sources (Montgomery et al., 2010). The second component is anthropogenic Pb exposure. This comes in many forms and results from Pb released into the environment through human activity. For example; mining/smelting activities, the deliberate introduction of Pb to food stuffs, contamination from lead piping and other point sources, inhalation of airborne pollution from industry and/or, in the modern world, petrol fumes (Kamenov and Gulson, 2014). Anthropogenic exposure is typified by increased concentrations of Pb in the body, which are recorded and retained in tooth enamel (Fischer and Wiechuła, 2016; Kamberi et al., 2012). Such exposure is associated with a restricted Pb isotope composition, termed 'cultural focusing' (Montgomery et al., 2010) and reflects the averaging of the pollutant material composition.

The concentration and isotope composition of Pb in human teeth provides evidence for the nature and origin of Pb to which an individual was exposed in childhood/early adulthood (Gulson, 2008). Pb concentrations below 0.7ppm, are indicative of natural, bioavailable, Pb exposure (Millard et al., 2014; Montgomery et al., 2010). Pb concentrations above this threshold are symptomatic of exposure to Pb sources caused by human activity and may or may not be similar to the local isotope composition (Geraldes et al., 2006). This study uses Pb analysis to further assess the nature and origin of Pb exposure in this group of men as a constraint on identifying their childhood origins and interrelationship.

METHODS

Pb isotope ratios and concentration were determined using a Thermo Fisher Neptune Plus MC-ICP-MS and an Agilent 7500cx quadrupole ICP-MS respectively. Full details for the sample preparation and analytical methods are given in the supplementary data.

In this paper we apply, for the first time to human archaeological teeth, an alternative method of displaying Pb data, as proposed by Alberede et al. (2012). The traditional method of data display, utilized in many archaeological studies, is to plot the $^{207}Pb/^{206}Pb$ and $^{208}Pb/^{206}Pb$ ratios and describe compositional fields within this bivariate space. However, it has been noted that this method of representation tends to compress the data and make it a relatively poor discriminant. The inclusion of ^{204}Pb ratios have been recently advocated by Ellam (2010). Here we employ a graphical method of displaying the time-integrated $^{238}U/^{204}Pb$ (μ) as a function of the Pb model age (Albarede et al., 2012). This method is more complex than the classic $^{207}Pb/^{206}Pb$ versus $^{208}Pb/^{206}Pb$ plot as it requires derivation of the two axis variables from the measured ^{204}Pb isotope compositions, but the advantage being that it provides information about the geological origins of the data without recourse to reference datasets. $^{238}U/^{204}Pb$ (μ) reflects the geochemical nature of the source rocks from which the Pb was extracted, while the Pb model age gives an estimate of the tectonic age of the source terrain. See Albarede et al. (2012); Blichert-Toft et al. (2016); White et al. (2000) for further discussion and description of this method of data display and interpretation. The data are presented in a table in the supplementary section.

Pb CONCENTRATION AND ISOTOPE RESULTS FROM THE TOOTH ENAMEL OF THE 31 MEN WITHOUT DENTAL MODIFICATIONS.

Pb concentration data

All but one of the 31 samples have very low Pb concentrations, with an average of 0.11 ± 0.16ppm and a median of 0.09. The exception (SK 3729), which has been excluded from the calculation of average, has a Pb concentration of 5.88ppm. These low concentrations are well within the levels accepted as natural lead exposure (Millard et al., 2014; Montgomery et al., 2010). The average Pb concentration of the men contrasts with broadly contemporaneous 8^{th}-11^{th} century Britons, who record a median of 1.9 ppm (n=26) (Montgomery et al., 2010). These data show that the men (excluding SK 3729), have a common childhood environment typified by exposure to natural, rather than anthorpogenic lead, (Chiaradia et al., 2003; Montgomery et al., 2010).

Pb isotope data

The Pb isotope compositions and derived values for the 31 individuals display a wide range of composition with means and 2SD as follows: $^{206}Pb/^{204}Pb = 18.57 \pm 0.49$; $^{207}Pb/^{204}Pb = 15.64 \pm 0.04$, $^{208}Pb/^{204}Pb + 38.44 \pm 0.48$, model age ($T$) = 157 ± 257Ma, and $^{238}U/^{204}Pb$ (μ) = 9.74 ± 0.05. Pb isotope data from the Weymouth men's enamel are compared with Pb isotope values obtained on the enamel samples from two other British sites where there is good evidence that the individuals were of British origin. These sites are; the Anglian site (5^{th}-7^{th} century) at West Heslerton, North Yorkshire (Montgomery, 2002), and a Viking-Age (~780-1100AD) burial site at Cnip on the Outer Hebrides, Scotland (Montgomery and Evans, 2009). In addition, Pb isotope data from industrial Coventry and London, provide a field for tooth enamel reflecting English anthropogenic ore lead compositions from the 18^{th} century (Trickett, 2007). This British data, from West Heslerton, the Outer Hebrides and the Industrial Period data of London and Coventry, forms a steeply sloping field within $^{238}U/^{204}Pb$ (μ) –model age (Ma) space (Fig 3). The Pb mean model age (T) value of 200±78 Ma (n=67, 2SD) is consistent with exposure predominately to English ores such as those of the Pennines and Mendips, which formed at this time. In contrast, the data from the Weymouth men describe a more horizontal field, with the majority of the data plotting between model ages of 0 and 200Ma. Three outliers extend this range: SK3749 with a negative model age of -163Ma (common in samples from limestone terrains and caused by a disproportionate uptake of U compared to Pb in marine carbonates) (Jahn and Cuvellier, 1994), and SK37597 and SK3759 with model ages of 411 and 745 Ma respectively, suggesting exposure to a geological terrane that is older than the majority of the group. The orientation of the data field described by the Weymouth men is different to that of the British data and suggests that "en masse" their exposure to Pb is typically not British; however with ten of the individuals plotting in the overlap between fields. Of these, four are from the core group (3730, 3743, 3751 & 3761) and the remaining six from are from non-core data group.

In order to further constrain the origins of the Weymouth individuals, we have compared the data with two large, Europe wide, data sets. The data from this study are first compared with Pb isotope composition of the < 2 micron fraction of soil samples from across Europe (n=2100) (Reimann et al., 2014). Because the very low Pb concentrations within all but one of these individuals suggest that their exposure was natural, non-anthropogenic, in nature. This soil dataset does not, unfortunately, include ^{204}Pb ratio measurements. Because of this we are unable to convert the data into ^{238}U/^{204}Pb (μ)-model age (T) used previously and instead compare the more conventional ^{208}Pb/^{206}Pb data (Fig 4). This comparison shows that Norway, Sweden and Finland, and also the Baltic States of Estonia, Latvia and Lithuania, have ^{208}Pb/^{206}Pb population means and confidence intervals that do not overlap with mean and confidence interval of the Pb isotope composition of the enamel from the 31 men found in Weymouth. However, the soil data cannot reliably exclude much of the rest of continental Europe as a homeland.

Secondly, we compare our data to the trans-European ore deposit data (n = c. 6700) of Blichert-Toft et al. (2016), which is a comprehensive compilation of published Pb isotope data from various European ore bodies. This ore -field data generally support the conclusions drawn from the soil data in that the model ages show that a majority of ore Pb from Finland and Sweden record pre-Caledonian mineralisation events greater than 500 Ma while the British and Irish data record Caledonian ages around 391 Ma. These ages are significantly older than those calculated from the Pb in the teeth of the Weymouth men, who are characterised by much younger model ages of 0-200Ma, (n=28), and 3 outliers.

In summary, the Pb concentration data show that all but one (SK 3729) of the men had extremely low exposure to Pb during childhood, unlike the contemporaneous British populations, and hence their exposure route is likely to be of natural Pb uptake rather than being anthropogenically derived. In addition, the wide ranging Pb isotope compositions of the samples are typical of natural exposure (Montgomery et al., 2010). While it is not ideal to compare the teeth with soil and ore derived data this currently the only data available and such comparisons, while tentative, suggest that, for the majority of the men, Britain, Ireland, the Baltic States and much of the Baltic shield are unlikely areas of childhood origin.

DISCUSSION

The likely childhood origins of the thirty one men are discussed in two parts: firstly the data from the core group of twenty men as defined by Sr and O isotope composition (Fig 2), and secondly, the remaining eleven outlier samples.

Geographic constraints on the core group of twenty men.

The core group are defined by a mean $^{87}Sr/^{86}Sr$ value of 0.71134± 0.0025 (2SD), a mean $\delta^{18}O_{(phos)SMOW}$ value of 15.9 ± 0.7‰ (2SD), a mean Pb concentration of 0.11±0.17 (2SD), a mean $^{206}Pb/^{208}Pb$ of 0.484 ±0.005 (2SD), and a median Pb model age of 112 Ma.

The geographic restrictions that multi-isotope analysis places on the childhood origins of the core group are summarized in Figure 5. The limit to childhood origin, based on O isotopes, is shown by the dashed line, with the areas to the left of this unlikely to be a homeland (horizontal hashing indicating the excluded areas). It is based, in the north, on the drinking water contour of -9‰ (Lecolle, 1985) and is extrapolated into the continent using the data of Lightfoot and O'Connell (2016) Fig 6 making the area of modern Germany and Bulgaria the western limit of their likely origin on the continent. This would place the childhood origins of the Weymouth core group within the same oxygen zone as that of the "local group" from the Swedish Island of Oland which gives 16.2 ±1.0 (n=55, 2SD). The solid line is estimated to be their northern limit based on the Pb isotope composition of soil leaches. The areas that can be confidently excluded by Sr isotopes are shown with diagonal lines. These areas include Denmark and Iceland where the strontium biosphere values are too low (Evans and Bullman, 2009; Frei and Frei, 2002; Price and Gestsdottir, 2006) and southern western Sweden where biosphere value are too high (Sjogren et al., 2009; Wilhelmson and Ahlstrom, 2015,). The absence of data from some places, such as areas of western Russia, and limited data from Ukraine, means there are still large uncertainties in some areas. However, the shaded area of northern and coastal Europe, predominantly in modern Poland, (Gardeła, 2015) is the region which fulfils the isotope constraints of the enamel composition and is the area that cannot be excluded as a possible place of origin for the core group of men.

Constraints on childhood origin for men who are not part of the core group.

The men that are not part of the core group have to be discussed individually and as such, the statistical control on their possible origins is much poorer than that of the core group of 20. The diversity of the possible origins is summarized below in the light of the new Pb data; see also Loe et al. (2014).

Men for whom a Danish origin cannot be excluded: SK 3725, 3729, 3757

This group of three men have very similar O values ($\delta^{18}O_{(phos)SMOW}$ =17.8‰, 18,0‰ and 18.0‰) and $^{87}Sr/^{86}Sr$ isotope compositions (0.70945, 0.71043, & 0.70945) respectively. Their $^{206}Pb/^{204}Pb$ values are relatively low (18.418, 18.466, and 18.179) and SK 3729 has an elevated Pb concentration, which suggests exposure to anthropogenic Pb sources. The three men cannot be excluded as originating from areas such as Denmark, or in the case of SK 3729, from Britain/Ireland and other parts of North Western Europe where there is evidence of elevated Pb concentration in human teeth due to anthropogenic Pb exposure (Montgomery et al., 2010).

Men from the most extreme climate zones: SK 3694, SK 3711 and SK 3759

The extremely low O isotope values displayed by these samples ($\delta^{18}O_{(phos)SMOW}$ = 14.6, 14, and 14.5 respectively) require them to come from significantly further north or east or higher altitude than the core group of men. Areas of eastern Russia and arctic regions of Scandinavia cannot be excluded. Iceland can be considered as an option for SK 3694 as this is one of the few currently identified places in the viking domain where such low Sr isotope values (0.70798) have been measured (Price and Gestsdottir, 2006).

Men with Sr isotope values above 0.713:SK3711,SK3712, SK3726, SK3752 & SK3760.

The remaining five men have radiogenic Sr isotope compositions between $^{87}Sr/^{86}Sr$ = 0.713 and 0.72, O isotope compositions between $\delta^{18}O_{(phos)SMOW}$ = 15‰ and 17.4‰, and low Pb concentrations. These men's origins are hard to constrain but Denmark, and similar areas of young Neogene cover, can be ruled out on the basis of Sr isotope composition, which instead suggests a Palaeozoic/Proterozoic or granitic terrain. The Baltic Shield and Baltic states can also be excluded on the basis of Pb isotopes. Similarly, Western Europe is also an unlikely place of origin due to their low oxygen values. Finally there are the six men, on whom isotope analysis has not been undertaken because of their dental modifications. It is suggested, on the basis of comparative studies, that these modifications are in a style typical of southern Scandinavia (Arcini, 2005).

Who were these men?

The Pb data, in particularly the very low Pb concentrations (with the exception of SK 3729), suggest that all the men analysed in the mass grave had a common cultural origin insofar as they were not exposed to elevated/anthropogenic Pb during their childhood. This contrasts with their contemporaries in Anglo-Saxon Britain (Montgomery et al., 2010). However, the O and Sr data indicate bimodality within this cultural group, with a core group of men from a similar geographic origin and the remainder of the group of more widely scattered origin. If these men were transported to England together in a single boat (Chenery et al., 2014), were they all of equal status? The age profile of the men is similar to a number of modern social groups such as the armed forces, especially the Army (Statistics, 2014); modern day pirates (Report, 2010) and 18th -19th century slaves (Bergad et al., 1995). No evidence of previous battle injury was noted on any of the skeletons, but there was evidence of non-specific bone inflammation and one case of bone inflammation or osteomyelitis. They did not appear to be a battle hardened group but that does not exclude the possibility that some, or all, were peasants that were recruited to fight (Kjnellstrom, 2005; Loe et al., 2014). Were these young men predominantly oarsmen transporting high-status men to England, for instance, to collect the Danelaw payments? Perhaps such techniques as DNA can throw new light on these questions.

Answering the questions of childhood origin is limited by the current paucity of Pb isotope tooth enamel data available from Europe and Scandinavia. What this study has shown is that these men were not British and unlikely to originate from Norway or Denmark, which are the two countries most closely associated with Britain during the Viking Age. The Scandinavian diaspora is known to have been wide ranging, extending into areas of modern Russia and Ukraine and down to the Middle East. However, most models suggest that this occurred as a radiating pattern originating from the Scandinavian countries. Our study indicates that the mobility patterns were more complex than this and that the people were coming to Britain from further east than has been previously suggested.

SUMMARY

Lead analysis has provided further insight into geographic origins of Viking Age men found in a mass burial execution pit in Weymouth, southern England. Although the Sr and O isotope composition of tooth enamel from the men highlights the geographic diversity of the overall group, the Pb data provides a measure of commonality within this group (Abrams, 2016). The low Pb concentrations, coupled with the relatively diverse Pb isotope ratios, reflect a very different interaction with this element compared with the anthropogenic Pb seen in Anglo Saxon and subsequent populations in Britain. For the core group of 22 men the Pb isotope composition of the enamel, when combined with the Sr and O data isotope provide geographic constraints on their origin. The Baltic shield (Norway, Sweden and Finland), and the area of the Baltic states (Estonia, Latvia and Lithuania) are excluded as likely areas of childhood origin for the men. Furthermore, Denmark can be excluded on the basis of O and Sr composition. However, current data does not permit us to exclude the area that equates to Poland so this area has to be considered as a possible childhood origin for the core group. We can speculate that the bimodality in the entire dataset may reflect some kind of social structure, but further work will be needed to comment more constructively on this.

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Supplementary data

Pb isotope and concentration analyses were carried out on tooth enamel of 31 individuals who had previously been analysed for strontium, oxygen, carbon and nitrogen isotopes. Tooth enamel is a robust material and preserved the childhood life signature of Pb in a manner similar to that of Sr (Kamenov and Gulson, 2014). The enamel surface of the tooth was abraded to a depth of >100 microns using a tungsten carbide dental burr and the removed material discarded. Enamel samples were then cut from the tooth using a flexible diamond edged rotary dental saw. All surfaces were mechanically cleaned with a tungsten carbide burr to remove adhering dentine. The resulting samples were transferred to a clean (class 100, laminar flow) where they were: cleaned ultrasonically in high purity water, rinsed, dried, leached for 5 minutes in a mixture of HCl and HNO_3, rinsed clean with deionised water, dried and finally placed into pre-cleaned Teflon beakers. The samples were then dissolved in Teflon distilled 8M HNO_3, dried down, and taken up in 0.5MHBr. The Pb was separated using AG 1X8 anion exchange resin, and taken up in 2% HNO_3 ready for isotope analysis by MC-ICP-MS (multi-collector inductively coupled plasma mass spectrometer).

Pb isotope analysis of the samples was conducted using a Thermo Fisher Neptune Plus MC-ICP-MS. Prior to analysis, each sample was appropriately diluted (using Teflon distilled 2% HNO_3) and spiked with a thallium (Tl) solution, (added to allow for the correction of instrument induced mass bias). Samples were then introduced into the instrument via an ESI 50ul/min PFA micro-concentric nebuliser attached to a desolvating unit, (Cetac Aridus). Five ratios were simultaneously measured ($^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, $^{208}Pb/^{204}Pb$, $^{207}Pb/^{206}Pb$ and $^{208}Pb/^{206}Pb$). Each individual acquisition consisted of 25 sets of ratios, collected at 16-second integrations following a 60 second de-focused baseline measurement.

The precision and accuracy of the method was assessed through repeat analysis of a NBS 981 Pb reference solution, (also spiked with Tl). The average values obtained for each of the mass bias corrected NBS 981 ratios were then compared to the known values for this reference, (Thirlwall, 2002). All sample data were subsequently normalised, according to the relative deviation of the measured reference values from the true. The analytical errors reported for each of the sample ratios are propagated relative to the reproducibility of the NBS 981, to take into account the errors associated with the normalisation process. The normalised and error propagated sample data is presented in Table 1. Procedural blanks contributed <1% to analysis.

Pb concentrations were determined as follows: enamel samples were weighed into Ependorph centrifuge tubes and first cleaned by submersion for one minute in a mixed solution of 1%HNO_3 and 0.5%HCl followed by rinsing (x3) in MilliQ de-ionized water and dried. The samples were then dissolved in 0.2ml of a 2:1 mixture of 8MHNO_3 and 6MHCl. Once the enamel was dissolved the solution was made up to 10mls using de-ionised water. The enamel Pb concentrations were determined at the British Geological Survey, Keyworth, UK, using an Agilent 7500cx quadrupole ICP-MS. The instrument was calibrated using a series of synthetic chemical solutions diluted from multi-element stock solutions (SPEX Certprep), the calibration being validated using synthetic chemical standards from a separate source. Digest solutions were diluted such that the calcium concentration was between 100 and 200 ppm, optimal for long-term instrument stability, detection, and calibration ranges. The reproducibility of the Pb concentration data is ±10% (2SD).

Data from this study displayed on a conventional $^{208}Pb/^{206}Pb$ vs $^{207}Pb/^{206}Pb$ diagrams below.

Kamenov, G. D., and B. L. Gulson, 2014, The Pb isotopic record of historical to modern human lead exposure., *Science of the total environment*, **490**, 861-70.

FIGURE LEGEND

Figure legends

Fig 1 probability density curves for $\delta^{18}O_{(phos)VSMOW}$ values from the men from the Weymouth mass grave (n=31) and from Britain (n=615)(Evans et al., 2012).

Fig 2 $^{87}Sr/^{86}Sr$ vs $\delta^{18}O_{(phos)VSMOW}$ diagram for tooth enamel data from this study with the "core group" shown as an enclosed field.

Figure 3 Mu vs T_{DM} diagram after (Albarede et al., 2012) for Uranium and Pb isotope data from Weymouth samples (n=31) compared with data from the Anglian site (5th-7th century) at West Heslerton in Yorkshire (n=25)(Budd et al., 2004; Montgomery, 2002) and a Norse period (~780-1100AD) burial site at Cnip on the Outer Hebrides, Scotland (n=8) (Montgomery, 2002). Also shown is Industrial Period data from London and Coventry (n=34) providing a reference dataset for pre –modern British Anthropogenic isotope composition (Millard et al., 2014).

Figure 4 A comparisons of means for $^{206}Pb/^{208}Pb$ ratios from soils across Europe (Reimann et al., 2014) with the data from the tooth enamel values from the men from this study. The uncertainties are given as 95% Confidence Intervals on the mean. The Baltic States include data from Lithuania, Latvia and Estonia; Northern Europe includes France, Germany, Denmark, Poland, Belgium, Austria and Netherlands; Central Europe is Slovakia, Bulgaria, Romania, Czech Republic, Serbia, Montenegro and Bosnia; southern Europe is Greece, Cyprus, Italy, Spain and Portugal.

Figure 5 A line map of Europe showing areas that can be excluded as the childhood origin of the core set of the Weymouth men based on strontium (diagonal lines), oxygen and Pb isotope data. Northern limit of childhood origin based on Pb is given by black line and western limit of childhood origin, based on oxygen isotope composition is given by the dashed line. Shaded area cannot be excluded and hence has the potential to provide an area of childhood origin

Figure 6 $\delta^{18}O_{(phos)VSMOW}$ from archaeological human tooth enamel from across Europe and Scandinavia. The data are from the compilation by (Lightfoot and O'Connell, 2016) Lightfoot with additional data from Norway from (Hamre and Daux, 2016), and Bornholm Island, Denmark (Price et al., 2012). The uncertainties are given as 95% Confidence Intervals on the mean. Data sets from Greece and Ireland were too small to be statistically significant are excluded from the diagram.

References

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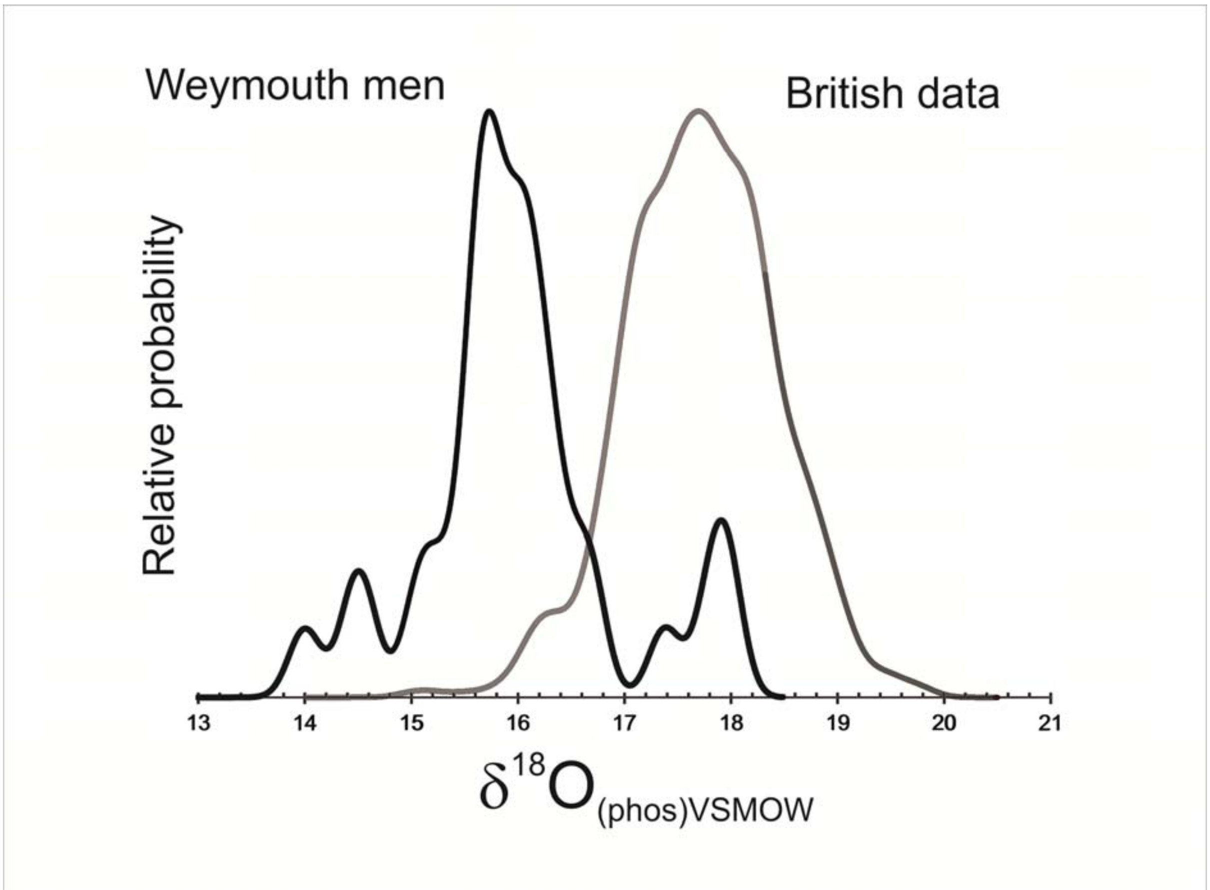
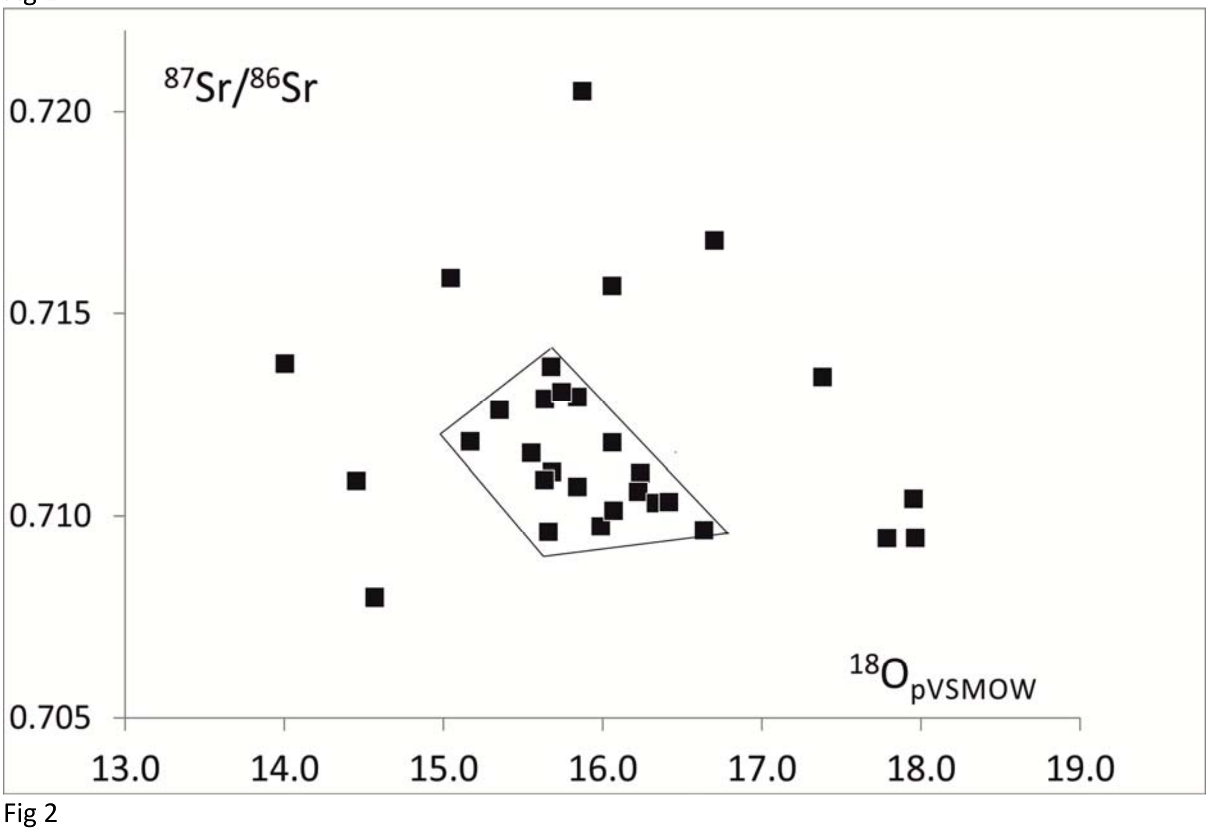
Evans JA, Chenery CA, Montgomery J. A summary of strontium and oxygen isotope variation in archaeological human tooth enamel excavated from Britain. Journal of Analytical Atomic Spectrometry 2012; 27: 754-764.

Hamre SS, Daux V. Stable oxygen isotope evidence for mobility in medieval and post-medieval Trondheim, Norway. Journal of Archaeological Science: Reports. 2016; 8: 416-425.



Weymouth men
British data
Relative probability
13
14
15
16
17
18
19
20
21
$\delta^{18}O_{(phos)VSMOW}$

Fig 1



$^{87}Sr/^{86}Sr$
0.720
0.715
0.710
0.705
$^{18}O_{pVSMOW}$
13.0
14.0
15.0
16.0
17.0
18.0
19.0

Fig 2

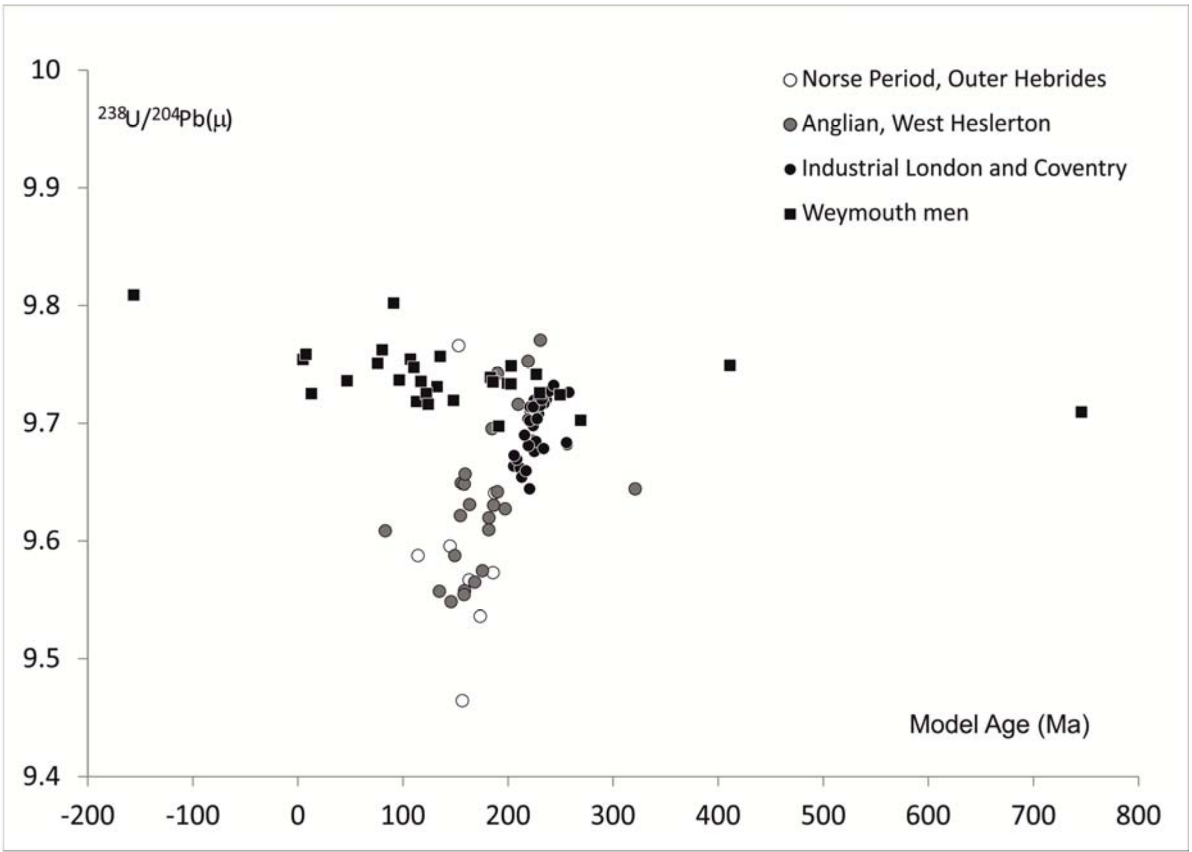

10
9.9
9.8
9.7
9.6
9.5
9.4
238U/204Pb(μ)
Norse Period, Outer Hebrides
Anglian, West Heslerton
Industrial London and Coventry
Weymouth men
Model Age (Ma)
-200
-100
0
100
200
300
400
500
600
700
800

Fig 3

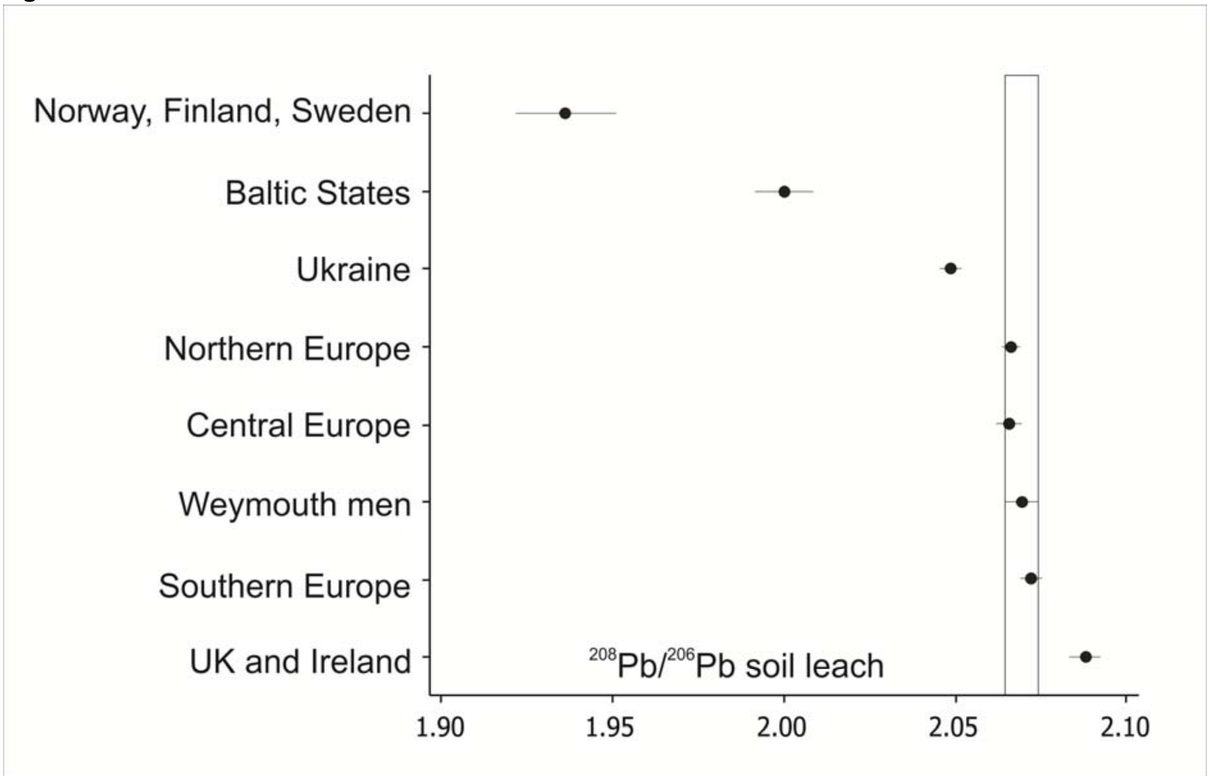

Norway, Finland, Sweden
Baltic States
Ukraine
Northern Europe
Central Europe
Weymouth men
Southern Europe
UK and Ireland
208Pb/206Pb soil leach
1.90
1.95
2.00
2.05
2.10

Fig 4

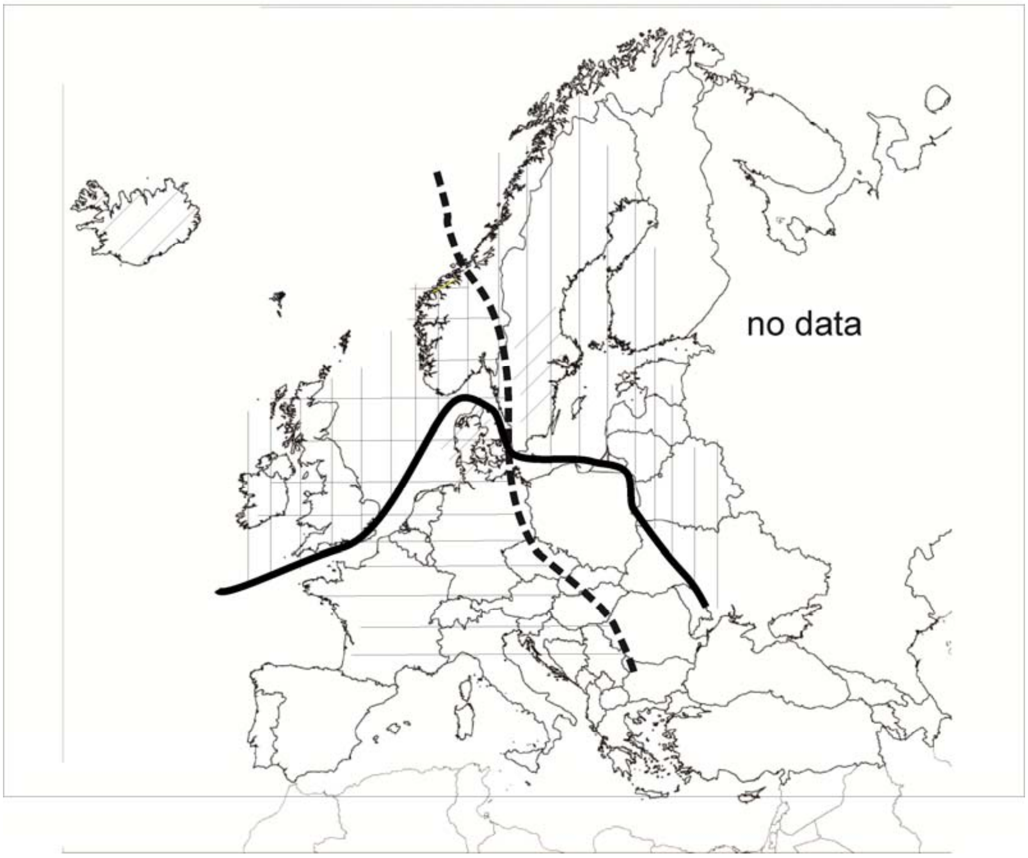


Fig 5 (not the final published version

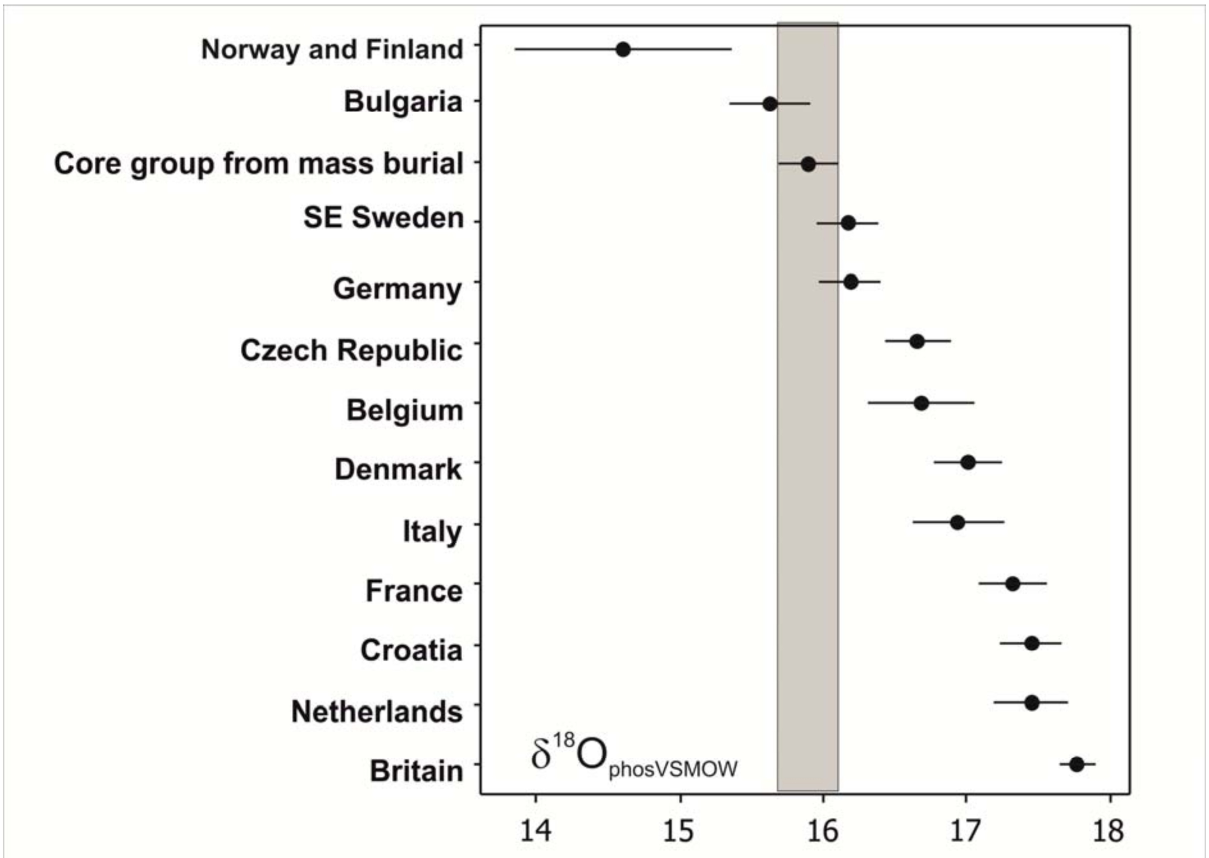


Fig 6

Sample	Sr ppm	$^{87}Sr/^{86}Sr$	$d^{18}O_{(phos)VSMOW}$	Pb ppm	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	$^{207}Pb/^{206}Pb$	$^{208}Pb/^{206}Pb$	T_{DM} (Ma)	$^{238}U/^{204}Pb$ (μ)	$^{206}Pb/^{208}Pb$
WEY08 SK3694	128	0.70798	14.6	0.25	18.5035	15.6368	38.4389	0.8451	2.0774	199	9.734	0.4814
WEY08 SK3711	95	0.71377	14.0	0.11	18.6048	15.6414	38.4444	0.8407	2.0664	133	9.731	0.4839
WEY08 SK3712	71	0.71588	15.0	0.08	18.5078	15.6416	38.1849	0.8451	2.0632	206	9.752	0.4847
WEY08 SK3724	58	0.72051	15.9	0.15	18.7826	15.6485	38.5909	0.8331	2.0546	13	9.725	0.4867
WEY08 SK3725	76	0.70945	17.8	0.03	18.4175	15.6294	38.3687	0.8486	2.0833	250	9.724	0.4800
WEY08 SK3726	62	0.71344	17.4	0.22	18.4979	15.6363	38.4385	0.8453	2.0780	203	9.733	0.4812
WEY08 SK3729	105	0.71043	18.0	5.88	18.4663	15.6366	38.4264	0.8468	2.0810	227	9.741	0.4805
WEY08 SK3752	70	0.71681	16.7	0.03	18.3704	15.6213	38.2301	0.8503	2.0808	269	9.702	0.4806
WEY08 SK3757	161	0.70945	18.0	0.09	18.1792	15.6213	38.0693	0.8593	2.0941	411	9.749	0.4775
WEY08 SK3759	93	0.71087	14.5	0.05	17.5988	15.5684	37.4141	0.8847	2.1261	746	9.709	0.4703
WEY08 SK3760	86	0.71567	16.1	0.03	18.5324	15.6395	38.4054	0.8439	2.0723	183	9.739	0.4826
Core group based on strontium and oxygen isotope composition.												
WEY08 SK3696	39	0.70974	16.0	0.2	18.6622	15.6504	38.5264	0.8386	2.0645	107	9.754	0.4844
WEY08 SK3704	70	0.71156	15.6	0.11	18.6646	15.6459	38.5414	0.8383	2.0650	97	9.737	0.4843
WEY08 SK3705	59	0.71182	16.1	0.02	18.6319	15.6439	38.5044	0.8396	2.0666	117	9.736	0.4839
WEY08 SK3706	85	0.71032	16.3	0.17	18.6062	15.6376	38.5048	0.8405	2.0695	124	9.716	0.4832
WEY08 SK3707	82	0.71306	15.7	0.13	18.7242	15.6657	38.6022	0.8367	2.0618	91	9.802	0.4850
WEY08 SK3710	74	0.7106	16.2	0.09	18.6161	15.6405	38.4681	0.8402	2.0664	122	9.725	0.4839
WEY08 SK3720	117	0.71294	15.8	0.09	18.7399	15.6493	38.5764	0.8351	2.0585	47	9.736	0.4858
WEY08 SK3722	70	0.71109	15.7	0.08	18.7072	15.6516	38.5298	0.8367	2.0597	76	9.751	0.4855
WEY08 SK3730	98	0.71013	16.1	0.26	18.4881	15.6266	38.4501	0.8452	2.0798	191	9.697	0.4808
WEY08 SK3733	93	0.71105	16.2	0.05	18.8172	15.6589	38.6805	0.8321	2.0557	8	9.758	0.4865
WEY08 SK3738	98	0.71035	16.4	0.03	18.6203	15.6488	38.4946	0.8404	2.0673	136	9.757	0.4837
WEY08 SK3739	61	0.71089	15.6	0.36	18.5716	15.6366	38.4751	0.8420	2.0717	148	9.719	0.4827
WEY08 SK3743	61	0.71225	16.1	0.14	18.4491	15.6317	38.3637	0.8473	2.0794	230	9.726	0.4809
WEY08 SK3744	85	0.71072	15.8	0.1	18.6249	15.6391	38.4832	0.8397	2.0663	113	9.718	0.4840
WEY08 SK3746	40	0.7096	15.7	0.04	18.6515	15.6480	38.5372	0.8389	2.0662	111	9.747	0.4840

WEY08 SK3747	85	0.71184	15.2	0.05	18.8180	15.6578	38.6595	0.8321	2.0544	5	9.754	0.4868
WEY08 SK3749	103	0.7129	15.6	0.05	19.1044	15.6846	38.8125	0.8210	2.0315	-156	9.809	0.4923
WEY08 SK3751	97	0.71263	15.4	0.16	18.5257	15.6383	38.4672	0.8441	2.0764	186	9.735	0.4816
WEY08 SK3758	113	0.70964	16.6	0.11	18.7095	15.6547	38.6437	0.8367	2.0653	80	9.762	0.4842
WEY08 SK3761	84	0.71369	15.7	0.02	18.5092	15.6408	38.4393	0.8450	2.0768	203	9.749	0.4815

Table 1