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1 **Large-scale, linked drainage systems in the NW European Triassic: insights from the Pb**
2 **isotopic composition of detrital K-feldspar.**

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21
22 Running head: Palaeodrainage in the NW European Triassic

23
24 Abstract: Pb isotopic data from K-feldspars in Middle Triassic (Anisian) sandstones in the Wessex
25 Basin, onshore southwest UK, and the East Irish Sea Basin, some 350 km to the north, show that
26 the same grain populations are present. This indicates that the drainage system (the
27 "Budleighensis" River) feeding these basins originated from the same source/s, most probably the
28 remnant Variscan Uplands to the south. Fluvial and aeolian sandstones have the same
29 provenance, suggesting that if water- and wind-driven sands were originally derived from different
30 sources, this has been obscured through reworking prior to final deposition. Significant recycling
31 of feldspar from arkosic sandstones in earlier sedimentary basins can be ruled out. The
32 provenance data agree with previous depositional models, indicating transport distances in
33 excess of 400 km, with a drainage pattern that linked separate basins. This supports the idea that
34 the regional fluvial system was driven by topography and episodic flooding events of sufficient
35 magnitude to overcome evaporation and infiltration over hundred's of kilometres. Importantly, this
36 drainage system appears to have been isolated and independent from those operating

37 contemporaneously to the northwest of the Irish and Scottish massifs, where the remnant
38 Variscan Uplands apparently exerted no influence on drainage or sand supply.

39

40

41 The Southern UK and offshore Ireland Triassic succession, comprising the Early – Middle
42 Triassic (Olenekian – Anisian) Sherwood Sandstone Group (SSG) and the Middle – Late Triassic
43 (Ladinian – Norian) Mercia Mudstone Group, represents the deposits of large-scale endorheic
44 drainage systems that accumulated in the arid to semi-arid interior of the Pangaeian
45 Supercontinent. Infilling a series of wide, extensional rift basins, the distribution and depositional
46 style of these successions is well constrained, both onshore and offshore UK and include
47 ephemeral fluvial, alluvial and playa lacustrine with sub-ordinate aeolian facies. The Variscan
48 Uplands of west and central Europe are thought to have exerted a strong control on drainage
49 evolution, resulting in large-scale (> 300 km), south-to-north flowing rivers (i.e. the 'Budleighensis'
50 river system; Wills 1970; Audley-Charles 1970; Warrington & Ivimey-Cooke 1992) which fed a
51 series of sedimentary basins and terminated in playa lake environments. It has also been
52 established that the distribution of sedimentary facies in the Triassic basins was controlled by a
53 complex interplay of climate and tectonics (Ruffell & Shelton 1999). Dispersal of clastic material
54 from the uplands into the basins was likely driven by both topography and by climate, and was
55 particularly influenced by periodic (perhaps seasonal) variations in precipitation (McKie and
56 Williams, 2009). Palaeomagnetic data suggest that this area of NW Europe lay between 15 and
57 25° N and was influenced by SW-directed subtropical trade winds giving rise to general semi-arid
58 conditions (McKie and Williams, 2009) but with an annual summer monsoon (Kutzbach &
59 Gallimore 1989; Szulc 1999; Preto *et al.* 2010). Cyclic variability in sedimentation in the European
60 Triassic (Meadows & Beach 1993; Bourquin *et al.* 2009) suggests that large scale fluvial systems
61 were more active during phases of increased precipitation (McKie & Williams 2009). The majority
62 of this precipitation likely fell on the high ground and especially on the remnant Variscan Uplands,
63 as this would have been the first significant high ground encountered by the monsoonal weather
64 systems originating from the south. Flooding was, therefore, likely an annual occurrence, driving
65 transport of clastic material from the uplands into the hinterland basins and beyond.

66

67 The term 'Budleighensis' river was first proposed to account for the deposition of thick, regionally-
68 significant, fine to medium-grained, red-bed sandstone-dominated facies of Triassic (Olenekian –
69 Anisian) age across south, central and north-east England (Wills 1970; Audley-Charles 1970).
70 Interpreted to flow from south to north, and with deposits apparently related to this system
71 encountered in the Wessex, Knowle, Worcester, Stafford, Cheshire and East Irish Sea basins
72 (and perhaps further north into the Solway and Ulster basins) (Figure 1, 2), it is among the better
73 documented large-scale, climate-controlled fluvial systems of the Triassic. The topographically

74 significant Variscan Uplands to the south are suggested to be the source for these sandstones
75 (Wills 1950; Fitch *et al.* 1966). However, the source areas of these sedimentary rocks have not
76 been explicitly demonstrated.

77

78 Various approaches have been applied to determine the provenance of Early – Middle Triassic
79 successions in central Europe (e.g. Koppen and Carter 2000), in the North Sea (Mearns *et al.*
80 1989; Knudsen 2001; Preston *et al.* 2002), in basins west of Ireland (Tyrrell *et al.* 2007) and west
81 of Shetland (Morton *et al.* 2007; Tyrrell *et al.* 2009) but provenance research specifically on the
82 'Budleighensis' system has been limited. Previous provenance work in the Wessex Basin mainly
83 focussed on the lithological comparison of clast assemblages in conglomeratic horizons
84 (especially in the Budleigh Salterton Pebble Beds, Smith 1990; Smith & Edwards 1991), which do
85 not necessarily share the same provenance as the finer grained sandstones that dominate higher
86 in the succession and that are the focus of this study. Nonetheless, these petrographic studies
87 identified detritus of Variscan granites and gneisses of likely Cadomian affinity, both sourced from
88 northern France. Fitch *et al.* (1966) utilised detrital muscovite ages to demonstrate the
89 predominance of Variscan-aged detritus in the Cheshire Basin. Detailed analysis of heavy
90 mineral assemblages in feldspar-rich sandstones from the East Irish Sea Basin (Mange *et al.*
91 1999) was used to correlate barren strata. Mange *et al.* (1999) argue that local input, particularly
92 from the Welsh Massif, was significant, mostly from reworked metasedimentary and sedimentary
93 rocks. There are also components (especially tourmaline) which indicate a southern, Variscan
94 Upland, source, whereas zircon could not be linked to a specific provenance. Notably, the source
95 areas suggested by Mange *et al.* (1999) cannot account for the abundance of K-feldspar in these
96 sandstones.

97

98 The sandstones targeted in this study form a regionally important aquifer and a proven reservoir
99 for hydrocarbons in a number of sedimentary basins in the area, including the Wessex and East
100 Irish Sea basins (McKie *et al.* 2007; Meadows and Beach 1993). Provenance analysis of the
101 drainage system supplying these sands is important because its scale is relatively poorly
102 constrained (<200 km or >500 km?) and it is uncertain as to how far it extends northward,
103 possibly beyond the East Irish Sea Basin and into the Solway (Brookfield 2004) and/or Ulster
104 basins. Furthermore, it is unclear to what extent these separate basins drained internally or
105 whether the envisaged large-scale fluvial system was through-going within the array of
106 sedimentary basins from the Wessex Basin northward to the East Irish Sea Basin. There are also
107 uncertainties as to the relative contributions of axial (i.e. the Variscan Uplands) and more local
108 transverse sources (e.g. the Welsh Massif, the London-Brabant High) and the potential contrasts
109 in sources of fluvial and aeolian sediment. Moreover, it is not certain how or if these systems are
110 related to contemporaneous drainage systems operating further to the north and west in the

111 Atlantic Margin basins. Although it was originally envisaged that Triassic drainage systems in the
112 Atlantic Margin basins were derived from and controlled by the Variscan Uplands to the south
113 (e.g. in the Slyne Basin, Dancer 2005), recent work has shown this not to be the case (Tyrrell *et al.*
114 *et al.* 2007; McKie & Williams 2009; Redfern *et al.* 2010). In terms of the broad regional Triassic
115 system, therefore, it is important to recognise how, and to speculate why, these systems may
116 differ. In broader terms, these types of provenance studies help constrain the pattern of rifting
117 within this part of the Pangaeian Supercontinent, as the uplift and availability of specific source
118 domains is recorded in the detrital archive.

119

120 In petrographic terms, the nature of these sandstones poses some additional questions. It is
121 unclear how the interaction of topography, tectonics and climatic factors can produce extensive
122 regional spreads of sandstones such as those seen in the Triassic in NW Europe. The origin and
123 genesis of these widely-dispersed, texturally mature, yet mineralogically sub-mature (arkosic),
124 sandstones is believed to result from the complex interplay of climate and tectonics (Ruffell &
125 Shelton 1999; Brookfield 2004). Establishing the provenance of these sandstones, especially with
126 a method that utilises a key framework component (i.e. K-feldspar), allows for a better
127 understanding of these processes.

128

129 The Pb-in-K-feldspar provenance tool is particularly applicable to addressing some of the above
130 issues, especially given the feldspathic nature of the Triassic sandstones in these basins. Recent
131 studies have demonstrated the value of the Pb isotopic composition of detrital K-feldspar as a
132 regional scale sand provenance tool (Tyrrell *et al.* 2007, 2009, 2010; Clift *et al.* 2008). It has been
133 shown that K-feldspar retains the signature of its source despite erosion, transport and
134 diagenesis (Tyrrell *et al.* 2006). The continental crust exhibits sub-orogenic scale (~100 km)
135 variations in Pb isotopic composition and potential sourcelands can thus be characterised on a
136 scale appropriate to that of major drainage systems. Furthermore, the Pb isotopic signature of a
137 granitic or gneiss does not vary with depth, hence K-feldspar with the same distinct Pb signature
138 will always be supplied for a discrete source area regardless of the erosion level. The method
139 involves *in situ* Pb isotopic analysis of individual detrital K-feldspar sand grains using laser
140 ablation multi-collector inductively-coupled plasma mass spectrometry (LA-MC-ICPMS) preceded
141 by detailed imaging (Backscatter electron (BSE) and cathodoluminescence (CL) imaging) so that
142 heterogeneities (e.g. inclusions, alteration) can be avoided. The use of ion counters to measure
143 Pb ion beams means that data can be retrieved at a spatial resolution (~30 µm laser spot sizes)
144 similar to that achieved using the ion microprobe technique, but with better analytical precision
145 (Tyrrell *et al.* 2010). Using LA-MC-ICPMS to analyse the Pb isotopic signal means the data can
146 be acquired rapidly and relatively inexpensively and the technique requires only a previously-

147 imaged, thick polished section, thereby retaining the grain context within the sedimentary rock
148 sample.

149

150 One of the major advantages of the Pb K-feldspar provenance tool is that, in contrast to
151 provenance approaches that utilise signals in robust grains (e.g. U-Pb zircon), it provides a
152 means of assessing first-cycle sand-grain provenance. Furthermore, where it occurs as a
153 significant framework component (~20% modal abundance), K-feldspar must presumably be
154 more representative of the source area than relatively minor components such as zircon which
155 typically make up << 1% of the mode. In these circumstances, K-feldspar can be a proxy for the
156 source of a large portion of the detrital quartz as there is a reasonable probability both minerals
157 are derived from the same source/s. As fresh detrital K-feldspar is unlikely to survive more than
158 one sedimentary cycle, these grains can be tracked back directly to their basement source,
159 allowing the scale and geometry of the drainage system to be constrained. These types of
160 insights can improve prediction of reservoir sandstone distribution and quality in the subsurface.
161 Importantly, there is much published Pb data from potential basement source areas in the North
162 Atlantic Region with which detrital data can be compared. In this study, additional basement data
163 were collected to provide further constraints on possible sources.

164

165 This study is specifically focussed on Middle Triassic sandstones. Although there are
166 uncertainties with the definitive ages within the Triassic system due to the scarcity of
167 biostratigraphic markers, Rhynosaurs provide constraints on the Otter Sandstone Formation
168 (Hounslow and MacIntosh 2003) in the Wessex Basin and palaeomagnetic data helps constrain
169 the age of the Ormskirk Sandstone Formation in the EISB (Meadows 2006). These sandstones
170 units are considered to correspond to the upper part of SSG, are very likely of Anisian age and
171 are both near contemporaneous (Figure 1, 2). Both units lie directly above a distinct and widely
172 recognised discontinuity, namely the Hardsgan Unconformity (McKie & Williams 2009; McKie &
173 Shannon 2011). Correlated well log data illustrate that Otter Formation sandstones comprise a
174 relatively thin succession within the Wessex Basin, but their equivalents are thicker in the basins
175 to the north (Figure 2; McKie & Williams 2009). This thickening is not as significant as that seen in
176 the Early-Middle Triassic sandstones (Lower SSG) where the increased accommodation space to
177 the north is likely due to a combination of differential subsidence and tectonism. In the EISB, the
178 Ormskirk Formation sandstones are interbedded with thin mudstones and mud-prone
179 sandstones, likely of playa lake and damp aeolian sandsheet origin, and may reflect the onset of
180 termination of the drainage system (McKie & Williams 2009).

181

182

183 **Methods:**

184 ***Sampling and petrography:***

185 Cores from four East Irish Sea Basin wells (Figure 1) were sampled at the Department of Energy
186 and Climate Change (DECC) core store, Edinburgh, UK. The choice of EISB sandstone samples
187 was guided by extensive sedimentary logging carried out by Meadows (2004). The sampling
188 strategy was designed to target the same range of stratigraphy and facies from four wells
189 penetrating the Ormskirk Sandstone Formation. Coastal outcrops of Budleigh Salterton Pebble
190 Beds and the overlying Otter Sandstone Formation were also sampled at Budleigh Salterton in
191 the Wessex Basin. New basement samples were collected in the field, or, in the case of granites
192 from southwest UK and northern France, selected from petrographic collections based at the
193 UCD School of Geological Sciences (see table 2 for locations). Thin sections of all samples were
194 examined using standard optical petrography.

195

196 ***Backscatter electron and cathodoluminescence imaging:***

197 After initial petrographic assessment, sections of ~300µm thickness were prepared from which K-
198 feldspar grains were selected and imaged using backscatter electron (BSE) and
199 cathodoluminescence (CL) at the Electron Microprobe Laboratory, Geowissenschaftliches
200 Zentrum, Göttingen, Germany. Further BSE images K-feldspars were collected using a Hitachi
201 TM-1000 desktop scanning electron microscope at the School of Geological Sciences, University
202 College Dublin, Ireland.

203

204

205 ***Pb analysis:***

206 Pb, U and Th concentrations were determined at the Microanalysis Facility, InCo Innovation
207 Centre, Memorial University, Newfoundland (MUN), using an ELEMENT ICPMS connected to a
208 Geolas 193nm Excimer laser. Pb isotopic analyses were carried out both at MUN and at the
209 National Centre for Isotope Geochemistry (NCIG) at UCD, Dublin, using NEPTUNE MC-ICPMS
210 instruments. A New Wave 193nm excimer laser was employed to ablate the target grains at
211 NCIG.

212

213 Two different collector configurations were used during analysis. An ion counter collector
214 configuration was implemented at MUN, allowing Pb analysis from ~30 µm laser ablation pits,
215 which is only slightly larger than spot sizes used to collect Pb isotopic data using secondary ion
216 mass spectrometry (SIMS) (e.g. Clift *et al.* 2008), but with much lower errors and better
217 reproducibility. A Faraday collector array was utilised at the NCIG, where tracks of <150 µm with
218 a spot size of 75 µm were ablated in preference to single spots. The larger volume of material
219 was ablated when using the Faraday collectors, as these are not as sensitive as the ion counters.
220 Repeat analyses of the same grains replicated the initial data within error (Table 1).

221

222 The analytical technique is described in more detail in Tyrrell *et al.* (2009, 2010). ^{204}Pb , ^{206}Pb ,
223 ^{207}Pb and ^{208}Pb were measured. ^{202}Hg was also measured during analysis in order to correct for
224 isobaric interference of ^{204}Hg on ^{204}Pb . In the case of the Faraday collectors, ^{203}Tl and ^{205}Tl were
225 measured and utilised in the standard-sample bracketing fractionation corrections. For both
226 collector configurations, these instrumental mass bias corrections were based on isotopic ratios
227 measured in either standard glasses BCR2g or NIST 612. Analytical uncertainties (2σ on
228 $^{206}\text{Pb}/^{204}\text{Pb}$) are $<0.1\%$. Within each analytical run, standard glasses, including NIST 612 and
229 BCR2g and samples of Shap Granite feldspar (which has a well-characterised and narrow range
230 of Pb isotopic composition) were run as unknowns in order to verify the data reduction. The
231 values obtained for these “unknown knowns” standards and the Shap Granite K-feldspar are
232 within error of published values, which have been obtained through isotope dilution thermal
233 ionisation mass spectrometry.

234

235 **Results**

236 The sampled arkosic sandstones are generally medium-grained and well-sorted with feldspar
237 contents (dominantly K-feldspar) varying between 12.5% and 22.5%. The sandstones contain
238 patchy dolomite cements, authigenic quartz and K-feldspar overgrowths. SEM imaging of K-
239 feldspars show a variety of inclusions, dominantly albitic lamellae, albitic veins and quartz, and
240 often display areally restricted alteration. This alteration usually comprises discrete zones of the
241 grains which have undergone albitisation, but less frequently the K-feldspar has been further
242 altered such that only a skeletal framework remains. In any case, altered zones were avoided
243 during laser ablation. Rounded K-feldspar grains are common, both in fluvial and aeolian
244 sandstones, and there is no obvious association between grain morphology and sedimentary
245 facies. Authigenic K-feldspar overgrowths are common in all the sampled sandstones, often
246 modifying the primary detrital K-feldspar grain shape (Figure 3). CL imaging proved particularly
247 useful in indicating the overgrowths, with the authigenic component often picked out by a darker
248 CL response in contrast to the bright luminescence of the original detrital grains (Figure 3B).
249 Although the overgrowths were not wide enough to analyse, they were avoided during analysis in
250 case their Pb signal differed from that in the detrital grains.

251

252 The Pb concentration (where analysed) and isotopic composition of 187 individual K-feldspar
253 grains from 20 samples are shown in Table 1. This dataset comprises analyses of 73 K-feldspars
254 from the Ormskirk Sandstone Formation in four wells (110/14-3; 110/13-5; 110/8a-5; 110/2-6) in
255 the East Irish Sea Basin (locations shown in Figure 1) and 114 K-feldspars from the Otter
256 Sandstone Formation and 2 K-feldspar crystals from a clast of feldspar porphyry from the
257 Budleigh Salterton Pebble Beds (BSPB), both from coastal outcrops in the Wessex Basin. Ninety

258 one of the 114 K-feldspars analysed from the Otter Sandstone Formation were obtained using the
259 Faraday collector configuration (see above). This included the re-analysis of several grains, the
260 results of which replicated the initial data (see data marked “repeat” in table 1).

261

262 Where measured, Pb concentrations of K-feldspar grains varied between 5 and 200 ppm (mean =
263 75 ppm). U and Th concentrations for measured grains and are typically < 0.01 ppm. A small
264 number of grains had U and Th concentrations in excess of 0.5 ppm, but the vast majority had
265 sufficient U or Th to require corrections to the common Pb signature for radioactive decay. There
266 is no discernable link between the Pb, U and Th concentration and the isotopic composition of the
267 grains. Pb isotopes from the K-feldspars are generally radiogenic with $^{206}\text{Pb}/^{204}\text{Pb}$ in the range
268 17.124 to 18.561 (mean = 18.136) and $^{207}\text{Pb}/^{204}\text{Pb}$ in the range 15.289 to 15.849 (mean =
269 15.591). The more radiogenic grains are more abundant, with the most dense grouping in the
270 $^{206}\text{Pb}/^{204}\text{Pb}$ range of 18.1 to 18.5 (Figure 4).

271

272 Detrital K-feldspar data can be compared directly with Pb data from basement rocks in NW
273 Europe, comprising both K-feldspar and whole rock analyses. These comparative datasets are
274 compiled from published work and are supplemented with new basement data (Table 2).
275 Published data come from numerous sources, summarised in Tyrrell *et al.* (2006, 2007, 2009,
276 2010). New data comprise analysis of K-feldspars in granitic rocks from northern France, south
277 east Ireland and the south east UK and Carboniferous sandstones from NW Ireland. Rocks from
278 northern France were analysed in order to verify the Pb isotopic signature of K-feldspar from
279 Variscan Granites in this area and to constrain that of older granites and granitic rocks in the
280 region. Data from Variscan Granites in Normandy and Brittany largely agree with published
281 values from Vitrac *et al.* 1981, although they form a broader range (Figure 5A, 5B). However it
282 should be noted that although the range of new data includes a 2σ error, the errors are not shown
283 for the previously published data. Pb K-feldspar analyses of Cadomian-aged granites from the
284 same region yield less radiogenic Pb than the Variscan granites (Figure 5A, see discussion
285 below). Analysis of Variscan Granite from Cornwall (the Lands End Granite) yields a slightly more
286 radiogenic signature than the pene-contemporaneous granites from northern France (Figure 5A).
287 Further new analyses from granitic rocks from south east Ireland constrain the Pb isotopic
288 signature of the Carnsore and Leinster Granites and a granitic vein cutting the Rosslare Complex
289 (Figure 5C). Although these could potentially be a source of K-feldspar themselves, especially for
290 the EISB K-feldspars, they also may be a reasonable proxy for the Pb isotopic signature of the
291 Welsh Massif (see discussion below). It is worth noting that although the Caledonian-aged
292 Leinster Granite has a Pb isotopic signature which is almost identical to other Caledonian
293 granites along structural strike, south of the Southern Uplands (i.e. the Shap Granite, Figure 5C,
294 D), the Carnsore Granite (also Caledonian in age) has a less radiogenic signature and has more

295 in common with the Cadomian granite of northern France (Figures 5C, A). The Pb isotopic
296 composition of detrital K-feldspar from arkosic Lower Carboniferous sandstones (Mullaghmore
297 Sandstone Formation) in NW Ireland was analysed (Figure 6) in order to constrain potential
298 second-cycle K-feldspar sources on the Irish Massif.

299

300

301

302 **Discussion:**

303 ***The 'Budleighensis' river system:***

304 The Pb isotopic composition of detrital K-feldspar grains in contemporaneous Middle Triassic
305 sandstones from 1) the Ormskirk Sandstone Formation from exploration well cores in the EISB
306 (offshore East UK); and 2) outcrops of Otter Sandstone Formation in the Wessex Basin (onshore
307 southwest UK) broadly show the same ranges of Pb isotopic composition (Figure 4C). There is a
308 subtle difference in that, although the range of $^{206}\text{Pb}/^{204}\text{Pb}$ is almost identical between the two
309 sandstone units, the $^{207}\text{Pb}/^{204}\text{Pb}$ range and average is slightly lower in the Wessex Basin
310 sandstones (Figure 4A, B). This variation is small and, although it might reflect differences in the
311 relative proportions of grains derived from each contributing source areas, it does not suggest a
312 significantly different provenance (Figure 5). The suggestion of common source areas for both
313 these sandstone units indicates that the drainage system supplying the two basins was linked,
314 suggesting they lay along the same regional sand dispersal path which threaded northward
315 through the intervening basins and sub-basins.

316

317 The most likely source (i.e. the best fit given the range of data) for the bulk of the K-feldspar
318 grains are granites and granitic rocks of Variscan and older age comprising the remnant Variscan
319 Uplands to the south, especially those from northern France (Brittany and Normandy; Figure 5A)
320 and, to a lesser extent, the French Massif Central and the Pyrennes (Figure 5B). There is also
321 input from more local sources on the Cornubia Massif, though the data indicate this is a relatively
322 minor component compared to the contribution from northern France sources (Figure 5A).
323 However, data are from one granite (the Land's End granite) and there may have been a larger
324 contribution from other granites such as the volumetrically significant Dartmoor Granite for which
325 Pb isotopic data are not yet available.

326

327 New Pb basement data suggests that the less radiogenic Pb K-feldspar (i.e. $^{206}\text{Pb}/^{204}\text{Pb} < 18$) is
328 likely derived from Precambrian granites and gneisses within the Variscides (Figure 5A). These
329 rocks, either associated with the Cadomian orogeny or of older ambiguous origin, comprise part
330 of modern Brittany, Normandy and the Channel Islands. Although there are data from only one
331 rock unit of this affinity (the Carolles Granite) it is postulated that basement of Cadomian and pre-

332 Cadomian affinity was partly/wholly reworked on a regional scale to produce Variscan granites,
333 so the Pb component in the later granites was inherited from early basement (Vitrac *et al.* 1981).
334 The reworking of Cadomian basement Pb into Variscan granites is also recorded in central
335 Europe (Klötzli *et al.* 2001). This agrees with the new data, where Pb in Cadomian K-feldspar is
336 less radiogenic than its Variscan successor, and hence these rocks are an appropriate source for
337 the less radiogenic populations in the Triassic detrital record.

338

339 The Pb isotopic signature of the authigenic K-feldspar overgrowths is not known and it remains
340 unclear how these might relate to that of the detrital grains. An understanding of these could
341 provide constraints on the nature and source of early pore fluids. With smaller spot sizes and
342 optimised ICPMS conditions it should be feasible in future to measure the Pb isotopic
343 composition of these thin grain coating rims.

344

345 These data suggest minimum drainage length-scales in excess of 400 km for the 'Budleighensis'
346 river system. This is in agreement with published palaeoflow data and with palaeogeographic
347 reconstructions for the period (Audley-Charles, 1970). However, sources from farther south
348 cannot be ruled out and it is consistent with the Pb data that some grains have been transported
349 from the Pyrenees or the Massif Central. This would imply drainage scales in excess of 800 km.

350

351 There are some ambiguities within the data which prevent the ruling out of certain sources. For
352 example, basement data from Southern Uplands granites partially overlap with Variscan Pb
353 domains. Hence, feldspar data from the WB corresponds well with that from Southern Uplands
354 Granites (Figure 5D), but it is extremely difficult to envisage a process where this could be a
355 major source for sandstones in the Wessex Basin. This 'sourcing' would also conflict with the
356 wealth of published palaeocurrent data indicating northward transport. However, the Southern
357 Uplands could reasonable contribute a minor source for sand in the more proximal EISB. In
358 addition, feldspar data from the EISB partially overlaps with the range of Shap Granite K-feldspar
359 (Figure 5D). This, therefore, is a possible source for some of the sand in the EISB, but the lack of
360 significant grains from a broader area of Northern England or the Scottish Massif suggests this
361 area was, at most, a minor contributor of K-feldspar.

362

363 There are no comparative basement Pb data available from the Welsh or the London-Brabant
364 Massifs, therefore it remains uncertain to what extent these areas could be a source for clastic
365 detritus during the Triassic. There is little evidence to suggest that the London-Brabant Massif
366 comprised significant sources of K-feldspar. New Pb K-feldspar basement data from Caledonian
367 granites (Carnsore and Leinster Granites), and a mylonitised granitic vein (cutting the Rosslare
368 Complex, a terrane of Avalonian affinity, correlated with the Monian of NW Wales (Gibbons and

369 Horak 1996)) and published galena data from the Irish Massif (Figure 5C) are likely a reasonable
370 proxy for the Pb isotopic basement composition of the Welsh Massif as these southern Irish
371 domains extend along strike north-eastward. Although there is some overlap between these
372 basement data and the detrital data, the same range of data is not seen in the detrital dataset
373 (Figure 5C), indicating that the Welsh Massif was likely only a minor source for the K-feldspar
374 grains in the EISB and WB. There are also grains with Pb isotopic compositions that outlie the
375 range of characterised Variscan or Cadomian K-feldspar (Figure 5E) and do not appear to
376 correspond to any other specific source. These grains may represent uncharacterised Variscan,
377 Cadomian or a more minor contributory basement source and their presence supports the
378 preferred models of palaeodrainage which envisage detrital contributions from a wide catchment
379 via an extensive tributary system.

380

381 The work of Mange *et al.* (1999) concluded that a significant fraction of the heavy mineral detritus
382 in the Ormskirk Sandstone Formation was recycled, speculatively from the Welsh Massif. It is
383 sensible to assume that a portion of the detrital zircon present was also recycled from older
384 sedimentary successions. Geochronological data from zircons in these sandstones are likely,
385 therefore, to have yielded a “mixed” and non-unique range of ages, due to the incorporation of
386 recycled and/or inherited zircon from the numerous igneous, sedimentary and meta-sedimentary
387 sources which may have been available. It is possible to imagine such diverse sources for
388 recycled zircon as Lower Palaeozoic meta-sedimentary successions on the Welsh Massif, Old
389 Red Sandstone and Culm-facies equivalents from Cornubia, or from Upper Carboniferous
390 sandstones from the Pennine Basin. It would be extremely challenging to unravel this potential
391 mix of contributors, especially as it would likely be impossible to distinguish first cycle from
392 polycyclic material. However, it is worth noting that the modal abundance of K-feldspar in these
393 Triassic sandstones (between 12.5 and 22.5%) implies that lithologies with high K-feldspar
394 contents (granites and gneisses) must have supplied a significant portion of the sand. Rocks with
395 little or no K-feldspar must also have contributed – at the very least contributions from the country
396 rocks surrounding the granitic sources would be anticipated and these, being dominantly
397 sedimentary and metasedimentary in nature, are the likely sources for the recycled components
398 recognised by Mange *et al.* (1999). A more rigorous methodology, incorporating a multiproxy
399 approach, may enable recycled components to be distinguished and quantified, especially if
400 tailored such that signals in both stable and more labile components are interrogated. Preliminary
401 work (Tyrrell *et al.* 2009) has shown that an integration of the Pb-K-feldspar and zircon
402 geochronological techniques can aid in the recognition of recycled components, and
403 consequently can lead to an improved understanding of palaeodrainage.

404

405 K-feldspar grains from aeolian and fluvial facies in the EISB cannot be distinguished on the basis
406 of their Pb isotopic compositions (Figure 4D). Therefore, if there were different input points
407 associated with different transport mechanisms into the basin/s (or into sediment storage areas
408 adjacent to the basin), this information has been lost through reworking and mixing of this signal
409 by the last transport prior to deposition. Furthermore, as noted above, rounded feldspar grains of
410 likely aeolian origin are common within the fluvial sandstones of the Otter Sandstone Formation.
411 These phenomena are perhaps expected given that aeolian sediments will be reworked by fluvial
412 mechanisms during wet periods and *vice-versa* during dry periods and have been described in
413 the Triassic Helsby Sandstone Formation in the Cheshire Basin (Mounteney and Thompson
414 2002). This is therefore in agreement with models of Triassic climate which evoke an annual
415 monsoon and associated flooding (see above; (Kutzbach & Gallimore 1989; Szulc 1999; Preto *et*
416 *al.* 2010). It would be anticipated that monsoon weather systems, pulled from the south during
417 summer continental heating and carrying moist air from Tethys, would shed much of their
418 precipitation upon reaching the remnant uplands resulting in large-scale north-directed flooding
419 (McKie & Williams 2009). Such reworking, associated with flooding and wet-dry fluctuations, is
420 observed in the evolution of modern monsoon-influenced drainage systems such as the Indus
421 (Alizai *et al.* 2011).

422

423 It has been previously suggested that K-feldspar in the EISB Triassic could have been recycled
424 and supplied from Upper Carboniferous sandstones (the Millstone Grit Group of the Pennine
425 Basin) cropping out to the east of the basin (Meadows 2004, 2006). However, published Pb
426 analyses of K-feldspars from these sandstones (Tyrrell *et al.* 2006) show that they contain a
427 distinct bimodal distribution of grains, including an unradiogenic population (ultimately linked to a
428 Lewisian or Greenland source) which is not found in the EISB Triassic (Figure 6). This suggests
429 that the Millstone Grit Group in the Pennine Basin 1) was not available as a source for sediment
430 in the EISB during the Triassic; 2) was eroding at this time but sediment was “trapped” in the
431 hangingwalls adjacent to the eastern basin-bounding faults; or 3) contributed detritus but the K-
432 feldspar component did not survive a second sedimentary cycle.

433

434

435 ***Implications for regional palaeodrainage and sandstone distribution:***

436 The provenance interpretation presented in this paper indicate that the sand carried by the
437 'Budleighensis' river system was dominantly sourced from the Variscan Uplands (Figure 7). This
438 interpretation supports the original drainage models based on sedimentology and palaeocurrent
439 data (Wills 1950; Wills 1970; Audley-Charles 1970; McKie & Williams 2009). Other regional
440 basement highs, such as the Welsh and Cornubia massifs appear to make more minor
441 contributions.

442

443 The drainage directions within the Budleighensis system contrast with those interpreted from
444 feldspar provenance data in Triassic sandstones from basins west and north of the Irish and
445 Scottish Massifs. It has been demonstrated (Figure 6) that K-feldspar grains from apparent SSG
446 equivalents in the Atlantic Margin basins (including data from the Corrib Gasfield in the Slyne
447 Basin, from the Foula Formation, Strathmore Field in the Faeroe-Shetlands Basin and from the
448 Dooish Gas Condensate accumulation on the eastern margins of the Rockall Basin, which, it
449 should be noted, is of uncertain age) comprise unradiogenic Pb and there are no grains which
450 could have been derived from the Variscan Uplands or from any southern source. This suggests
451 no discernable Variscan influence in these areas, and grain populations are dominantly derived
452 from Archaean and Proterozoic rocks in Greenland, NW Scotland, various now semi-observed or
453 poorly characterised basement highs in on the present continental shelf and possibly from
454 Grenville-affinity rocks from eastern Canada (Tyrrell *et al.* 2007, 2009, 2010; Redfern *et al.* 2010).
455 McKie & Williams (2009) envisage southern derivation directions for SSG equivalents hosting the
456 Corrib Gasfield in the Slyne Basin. This interpretation is in agreement with palaeoflow directions
457 suggested by orientated core (Dancer *et al.* 2005). These interpretations do not consider the
458 significance of K-feldspar grains of Archaean affinity in these sandstones which is strongly
459 indicative of ultimate sand dispersal and input from a northern or northwestern source. However,
460 it is possible to reconcile both datasets, with the provenance data indicating the orientation of the
461 transport system into the Slyne Basin, and the palaeocurrent data recording the orientation of
462 drainage system within the confines of the basin (Figures 7, 8).

463

464 This change in dominant drainage direction suggests that the Irish and Scottish Massifs (south of
465 the Great Glen Fault; Figure 7) divide areas draining different catchments during the Early to
466 Middle Triassic. There is currently no K-feldspar provenance data from Ormskirk Sandstone
467 Formation equivalent rocks in the Solway or Ulster basins; hence it is not possible to assess or
468 limit the potential dispersal of Variscan detritus northward beyond the EISB. Interestingly the
469 Ulster Basin appears to thread through and link between the two areas with contrasting drainage
470 regimes (Figure 7, 8). Intriguingly, although the Irish and Scottish massifs appear to act as
471 drainage divides separating systems influenced by and independent from the Variscan Uplands,
472 Pb data from crystalline basement comprising these massifs are insignificant contributors of K-
473 feldspar detritus to either the Atlantic Margin basins (Tyrrell *et al.* 2007, 2010) or to the
474 Budleighensis system (Figure 7, 8). Furthermore, new Pb-in-K-feldspar data from arkosic
475 sandstones of Visean age within the Irish NW Carboniferous Basin (Mullaghmore Sandstone
476 Formation), onshore northwest Ireland, show similar grain populations to those seen in the
477 Serpukhovian-Bashkirian of the Pennine Basin (i.e. they have a bimodal distribution of grains
478 sourced from Archaean – Palaeoproterozoic rocks and more proximal Caledonian Granites; Figure

479 6). These data rule out recycling of K-feldspars into the Atlantic Margin basins from older
480 Carboniferous sandstones on the Irish Massif. In overall terms, therefore, these data suggest
481 that, although the Irish and Scottish Massifs were of sufficient relief to form a barrier to evolving
482 drainage, they remained topographically subdued such that precipitation on, and ensuing
483 associated clastic transport from, these areas was minimal. It could have been the case that the
484 interior was too arid for these areas to be significant sources, with sediment dispersal relying on
485 runoff from the wetter catchments outside the arid interior. This would agree with
486 palaeogeographic and climate models for these areas during the Middle Triassic (Naylor &
487 Shannon, 2011). Alternatively, these areas may have been buried beneath now-eroded
488 sedimentary rocks so as not to have been available as a source for K-feldspar-bearing siliclastic
489 sediments during the Triassic. It is possible that there were significant uplands, but that these
490 dominantly comprised carbonates. However, apatite fission track data (Allen *et al.* 2002) suggest
491 low denudation rates during the Triassic and similar data from the Scottish Massif suggests that
492 significant post-Caledonian uplift did not take place until the Cenozoic (Lewis *et al.* 1992; Hall &
493 Bishop 2002), supporting the idea that these areas remained relatively tectonically quiescent and
494 topographically subdued during much of the early Mesozoic.

495

496 It is clear that climate and topography played an important role in sediment dispersal and mixing,
497 but these must have also impacted on sediment release rates. In the envisaged arid environment,
498 low humidity and presumed minimal biogenic activity would result in slow rates of chemical
499 weathering, as suggested by the overall abundance of K-feldspar in the preserved sedimentary
500 products. Mechanical weathering was most likely the dominant process of rock disaggregation.
501 Sediment can be 'stored' and 'pre-sorted', perhaps in areas more proximal to their ultimate
502 source (e.g. as alluvial fans), prior to ultimate deposition (Figure 8). Alternatively, the textural
503 maturity may simply be due to repetitions of aeolian winnowing and fluvial transport during
504 downstream migration of sediment. Dryland systems typically show the progressive sorting
505 producing the mineralogically sub-mature, texturally mature sandstones ubiquitous in both the
506 Lower and Middle Triassic basins of NW Europe.

507

508

509 **Conclusions:**

510 K-feldspar sand grains in Middle Triassic sandstones in the Wessex and East Irish Sea basins
511 appear to share the same sources, indicating that the drainage system supplying these sands
512 was through-going and extended northward from the SW England to offshore North Wales. The
513 sand grains were likely derived from the Variscan Uplands to the south, implying drainage length
514 scales in excess of 400 km. Populations are mixed at thin section scale and different facies
515 display the same populations, perhaps indicating that some or possibly all of the sediment was

516 mixed and reworked by fluvial and/or aeolian processes and accumulated in intermediate storage
517 areas prior to final deposition. These observations agree with the current understanding of
518 Triassic palaeogeography and climate models, where both topography and flooding associated
519 with an annual monsoon are thought to have been responsible for the transport of sediment from
520 the uplands. This combination of processes can also account for the overall textural maturity and
521 mineralogical sub-maturity of the sandstones. Comparison with K-feldspar provenance data from
522 Atlantic Margin basins show that the latter sandstones have a different provenance, were
523 dominantly supplied from Archaean and Proterozoic rocks from the north and west, and that there
524 was no input from the Variscan Uplands. The Triassic K-feldspar provenance data collected to
525 date from all basins in the region indicate the presence of two drainage domains (the
526 'Budleighensis' and the Atlantic Margin basins), separated by a NE-SW oriented drainage divide.
527 The drainage divide comprised the Irish-Scottish massifs and, although these areas were of
528 sufficient topography to act as a barrier to evolving drainage, they themselves were not a
529 significant source of K-feldspar detritus. Carboniferous arkosic sandstones from the Irish Massif
530 and from the Pennine Basin, Northern England can also be ruled out as sources in both drainage
531 regimes, supporting the idea that detrital K-feldspar in sandstones cannot readily survive
532 reworking and is, therefore, likely first-cycle detritus.

533

534

535

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548

549 **Figure 1:** Schematic palaeogeographic reconstruction of the Middle Triassic (right) after Scotese
550 2002; Eide 2002; McKie & Williams 2009; Bourquin *et al.* 2011; McKie & Shannon 2011) showing
551 the distribution of massifs and sedimentary basins with summarised Triassic stratigraphy of some
552 NW European basins (left, after McKie & Williams 2009, Tyrrell *et al.* 2010). Also shown are the

553 locations (geographic and stratigraphic) from which Pb K-feldspar provenance data have been
554 obtained, and a map of the East Irish Sea Basin (EISB; inset; after Meadows 2004) showing the
555 location of wells sampled in this study. AM = Armorican Massif; CM = Cornubia Massif; FC =
556 Flemish Cap; HP = Hebridean Platform; IM = Irish Massif; LB = London-Brabant High; PH =
557 Porcupine High; RB = Rockall Bank; SM = Scottish Massif; SP = Shetland Platform. ChB =
558 Chesire Basin; CNB = Central North Sea Basin; CSB = Celtic Sea Basins; EISB = East Irish Sea
559 Basin; FSB = Faeroe Shetland Basin, NNB = Northern North Sea Basin; RBa = Rockall Basin; SB
560 = Slyne Basin; SNB = Southern North Sea Basin; WB = Wessex Basin; WoB = Worcester Basin;
561 ggf = Great Glen Fault.

562

563 **Figure 2:** Stratigraphic panel for the Middle - Upper Triassic from the Wessex Basin northward
564 through the East Irish Sea Basin and into the Ulster Basin adapted from McKie & Williams (2009)
565 and based on their correlation of 10 wireline logs. The datum is the top Triassic. The line of
566 section is shown on Figure 1.

567

568 **Figure 3:** Backscatter electron (A, C, D) and cathodoluminescence (B) images of K-feldspar
569 grains from East Irish Sea and Wessex basins illustrating, A) authigenic overgrowths on K-
570 feldspar which are only visible in CL (B), modifying the primary rounded grain shape; C)
571 authigenic overgrowth on K-feldspar grain (from Wessex Basin), visible in backscatter; and D)
572 three K-feldspar grains (each with visible overgrowths), with laser ablation pits shown on the
573 largest grain.

574

575 **Figure 4:** $^{206}\text{Pb}/^{204}\text{Pb}$ vs. $^{207}\text{Pb}/^{204}\text{Pb}$ plots showing A) K-feldspar data from the East Irish Sea
576 Basin (EISB) Ormskirk Sandstone Formation sandstones; B) K-feldspar data from the Wessex
577 Basin (WB) Otter Sandstone Formation; C) the enclosed range of Pb isotopic composition of all
578 K-feldspar grains from EISB and WB sandstones, illustrating clear overlap between the two and
579 suggesting that the sandstones from each basin have the same provenance; and D) the Pb
580 isotopic composition of all K-feldspar grains analysed from EISB fluvial facies, EISB aeolian
581 facies and WB fluvial facies sandstones, indicating that there are no significant differences in the
582 Pb composition of K-feldspar grains from either facies. 'Far.' indicates grains analysed using
583 Faraday collector configuration, 'IC' indicates ion counter collector configuration used. When not
584 indicated, the IC configuration was used.

585

586 **Figure 5:** $^{206}\text{Pb}/^{204}\text{Pb}$ vs. $^{207}\text{Pb}/^{204}\text{Pb}$ plots of EISB and WB K-feldspars against A) new data from
587 Variscan granites (Brittany, Normandy and Cornwall), Cadomian Granite and a single clast of
588 feldspar porphyry from the Budleigh Salterton Pebble Beds (BSPB) ; B) published data from
589 Variscan Granites from Brittany, Cornwall, the French Massif Central and the Pyrennes; C) new

590 and published data from Irish Massif granites, granitic veins (cutting the Rosslare Complex) and
591 galena; D) published data from Scottish granites and granitic rocks and granites from northern
592 England; E) summary of potential groupings and suggested sources for the feldspars. Pb
593 basement data from Blaxland *et al.* 1979; Vitrac *et al.* 1981; Kinnaird *et al.* 2002; Tyrrell *et al.*
594 2006. New basement data are shown in Table 2.

595

596 **Figure 6:** $^{206}\text{Pb}/^{204}\text{Pb}$ vs. $^{207}\text{Pb}/^{204}\text{Pb}$ plot showing the Pb isotopic composition of all K-feldspar
597 grains analysed from the East Irish Sea (EISB) and Wessex (WB) basin Triassic sandstones.
598 Also shown is the range of compositions found in detrital K-feldspars Permo-Triassic and Triassic
599 sandstones in basins more marginal to NW Europe, from Upper Carboniferous sandstones in the
600 Pennine Basin (Data from Tyrrell *et al.* 2006, 2007, 2009, 2010) and Lower Carboniferous
601 sandstones in the Irish NW Carboniferous Basin (Data in table 2).

602

603 **Figure 7:** Schematic palaeogeographic reconstruction of the Middle Triassic (after Scotese 2002;
604 Eide 2002; McKie & Williams 2009; Bourquin *et al.* 2011; McKie & Shannon 2011) showing the
605 distribution of massifs and sedimentary basins, with potential K-feldspar sources highlighted. Also
606 highlighted are potential drainage directions and sedimentary input points for the 'Budleighensis'
607 system, as suggested by the data presented in this paper, and for the Triassic basins more
608 marginal to NW Europe (after Tyrrell *et al.* 2010). Abbreviations are listed in caption figure 1. The
609 approximate palaeogeographic location of Pb basement data in Figure 4 is shown; B&C =
610 Brittany and Cornwall granites; BfG = Barfleur Granite; BrG = Brech Granite; CG = Carnsore
611 Granite; CIG = Carrolles Granite; FIG = Flamanville Granite, FMC = French Massif Central
612 granites; LEG = Land's End Granite; LnG = Leinster Granite; MmS =Mullaghmore Sandstone
613 Formation. PY = Pyrennes Granites; ShG = Shap Granite; Slga = southern Ireland Galena data;
614 SUG = Southern Uplands granites; RC = Rosslare Complex.

615

616

617 **Figure 8:** Schematic block diagram showing the distribution of uplands in the Middle Triassic,
618 with suggested drainage routes and sediment storage areas highlighted. The block diagram
619 shows that there is major topography within the remnant Variscan Uplands and perhaps within
620 the Greenland Massif, but that the topography of the Scottish and Irish Massifs is relatively
621 subdued. The Scottish and Irish massifs act as a drainage divide separating systems influenced
622 by the Variscan Uplands from those with no Variscan input.

623

624

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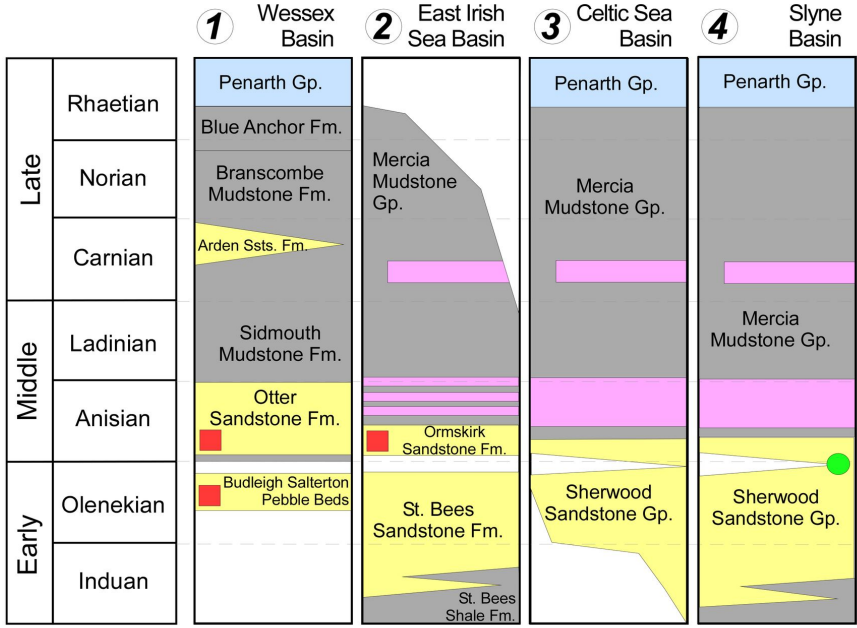
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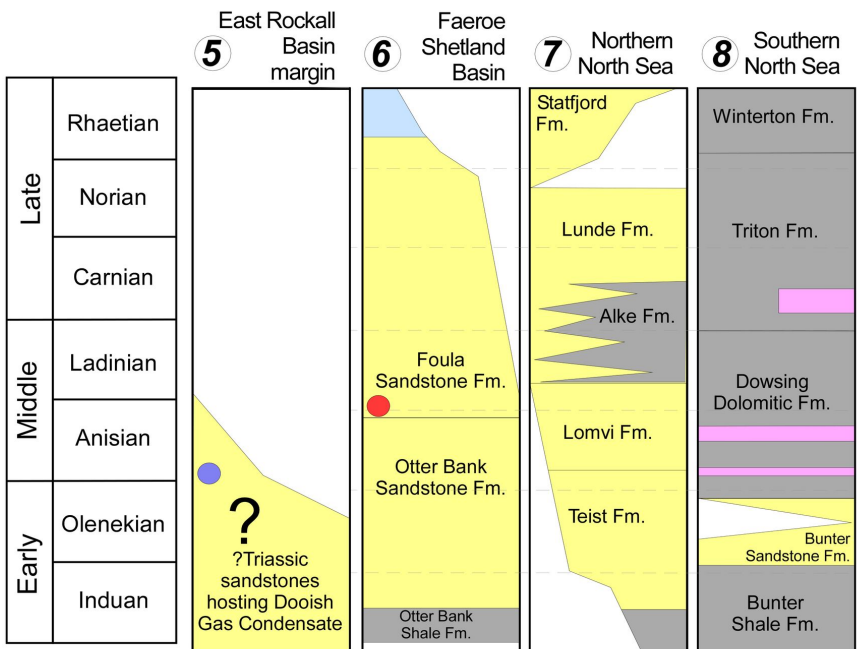
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TRIASSIC



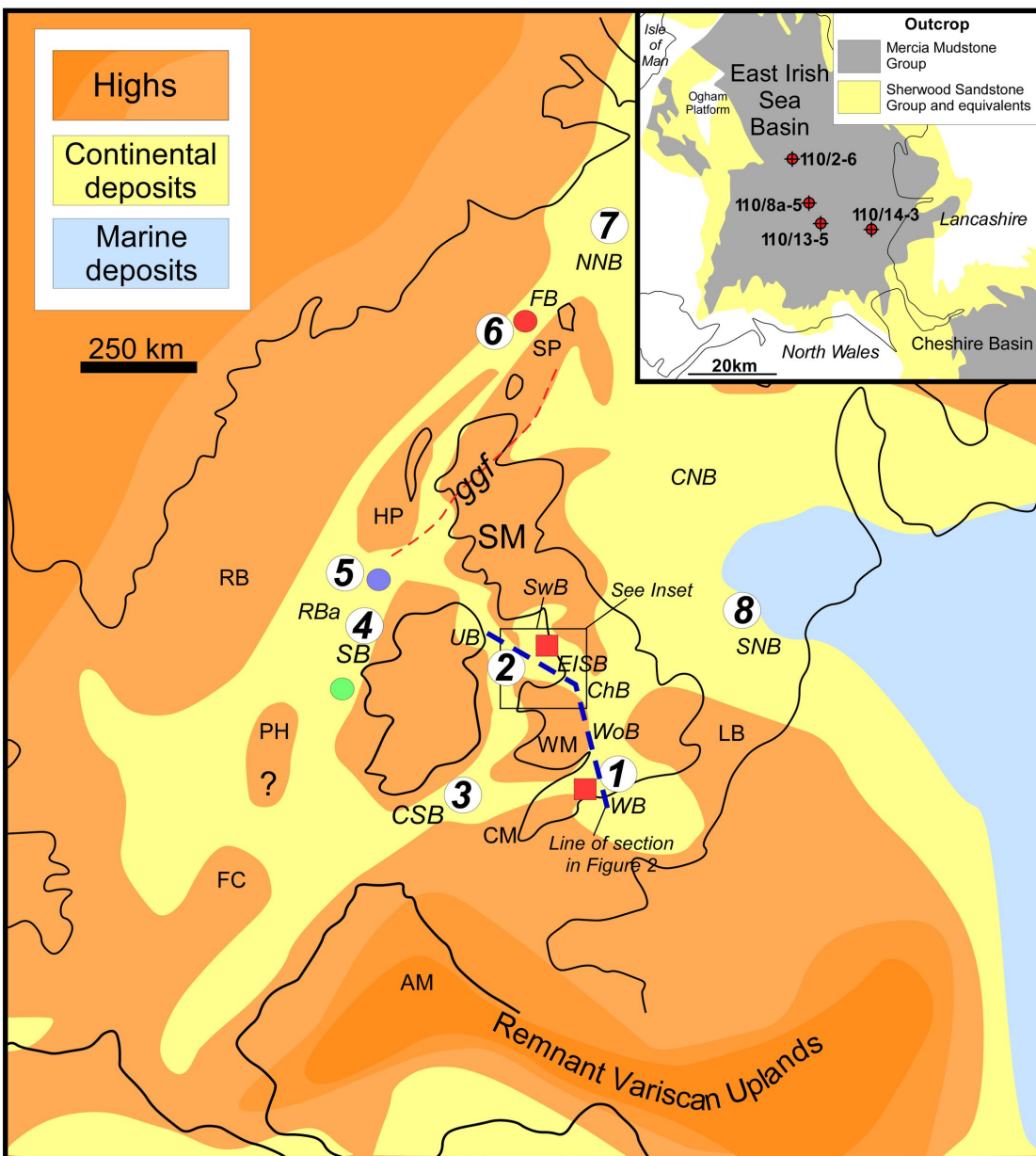
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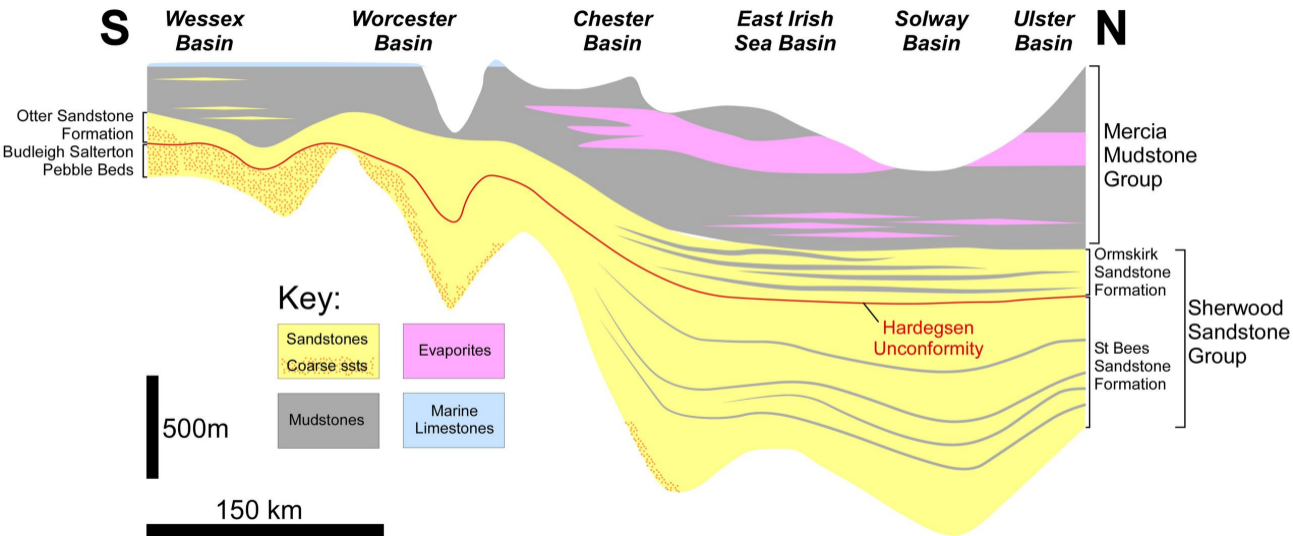


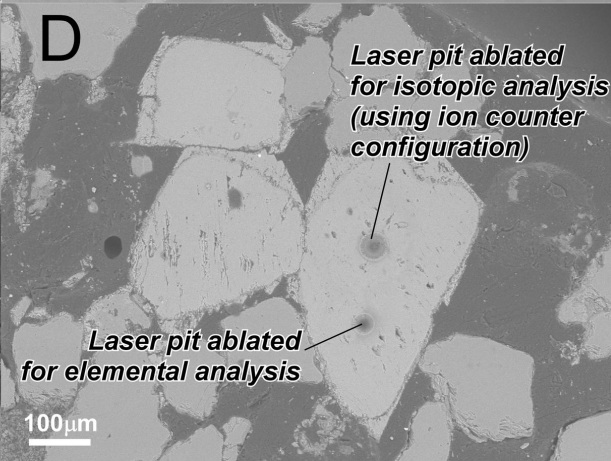
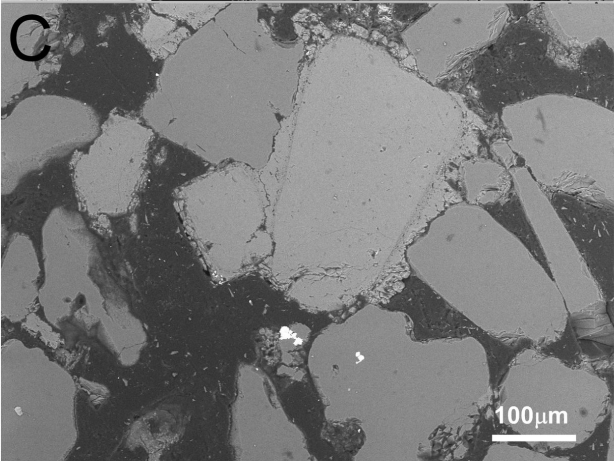
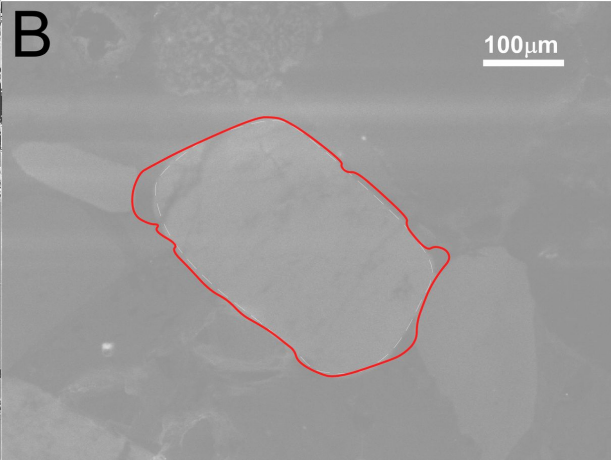
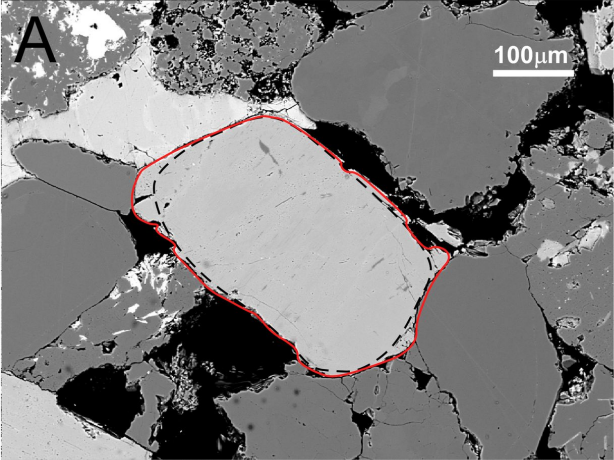
Key to Basin Stratigraphy:

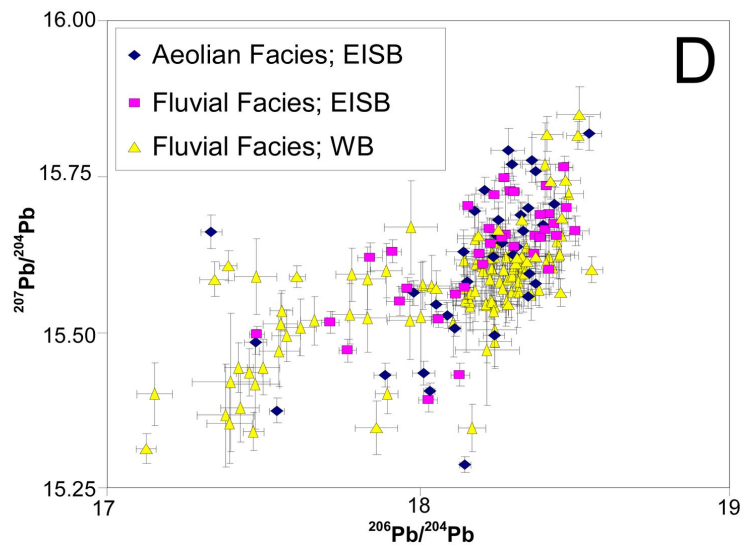
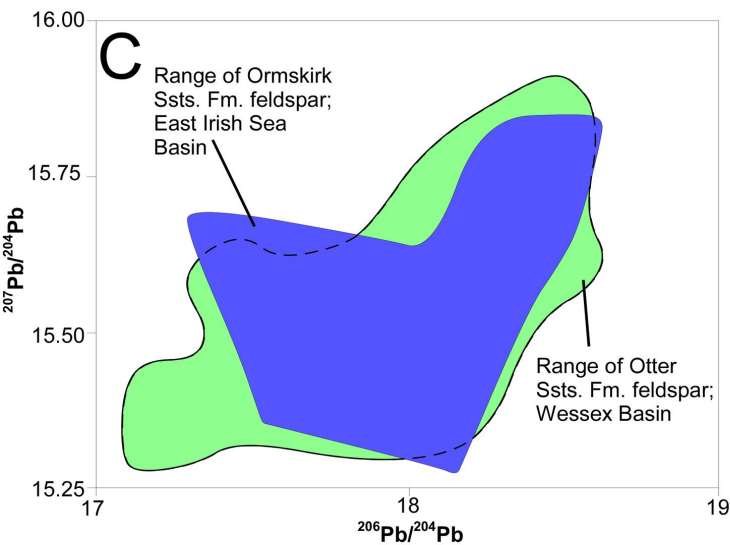
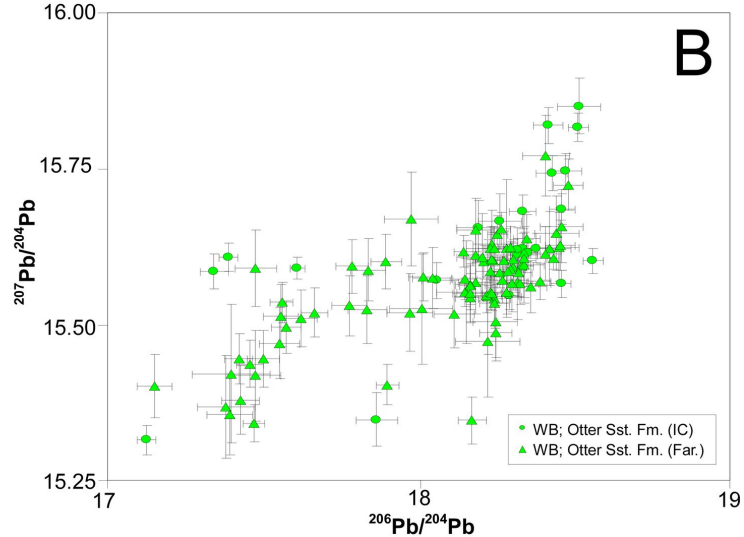
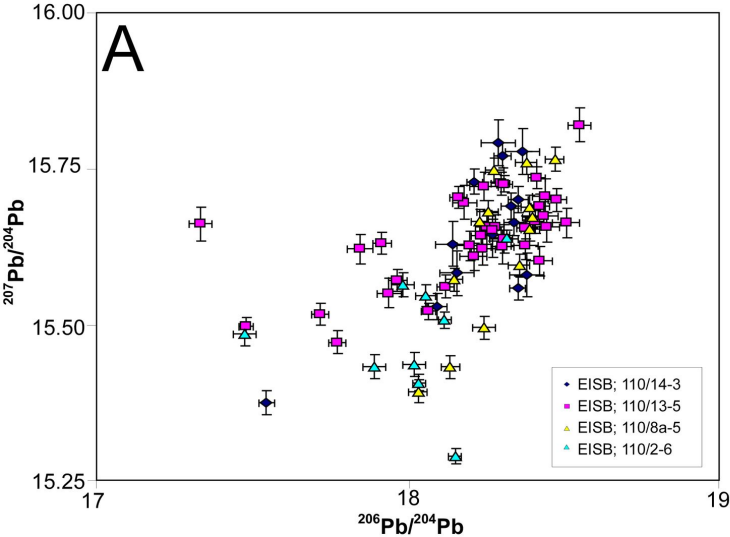


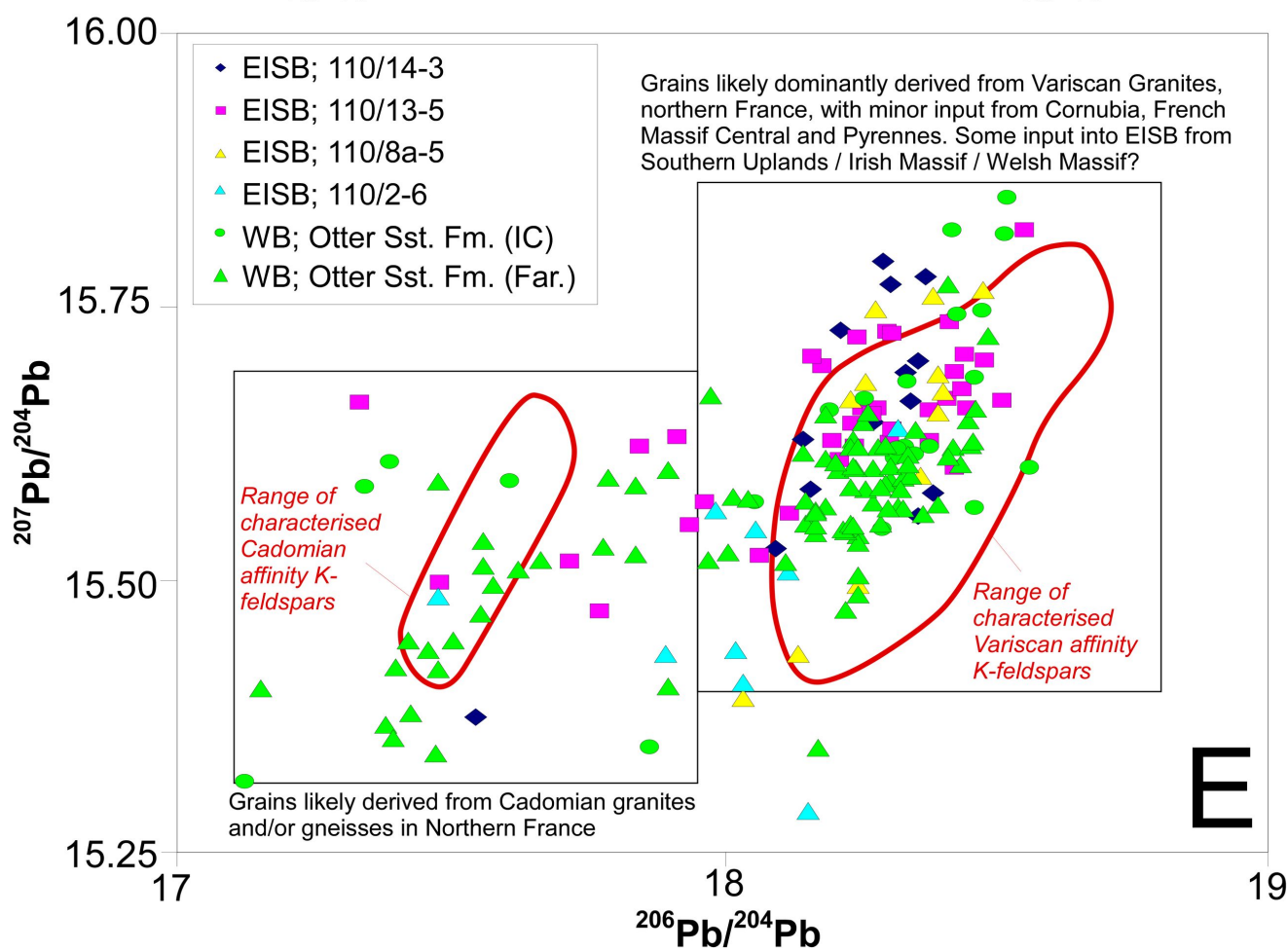
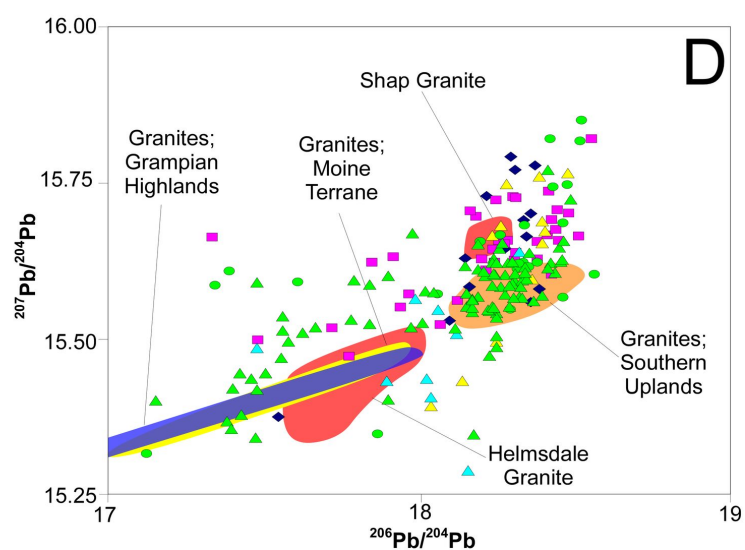
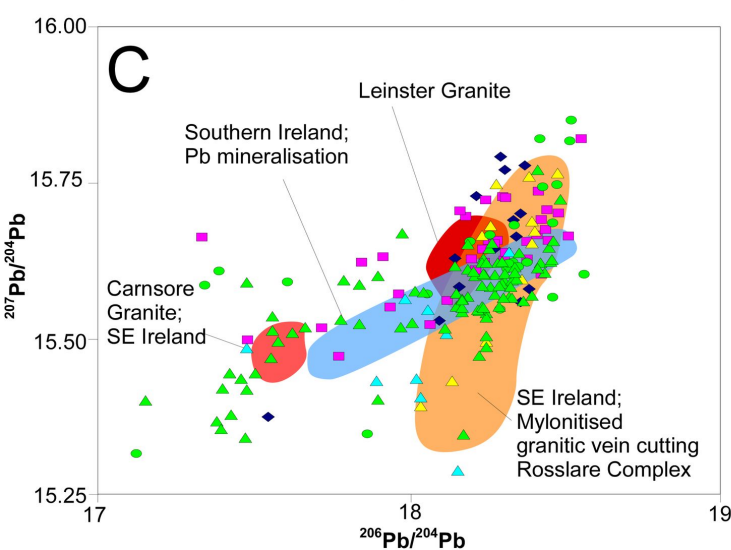
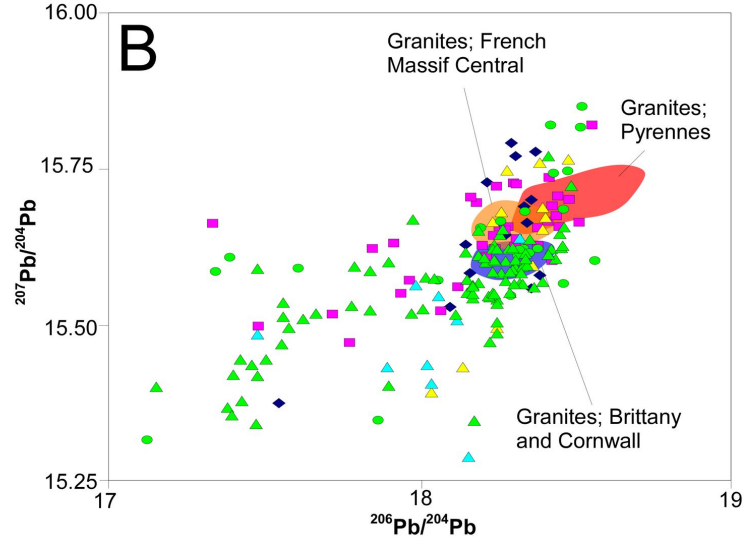
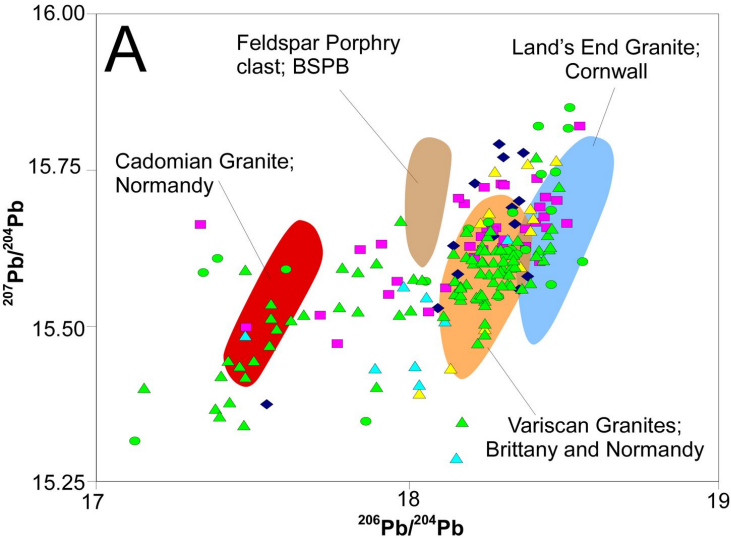
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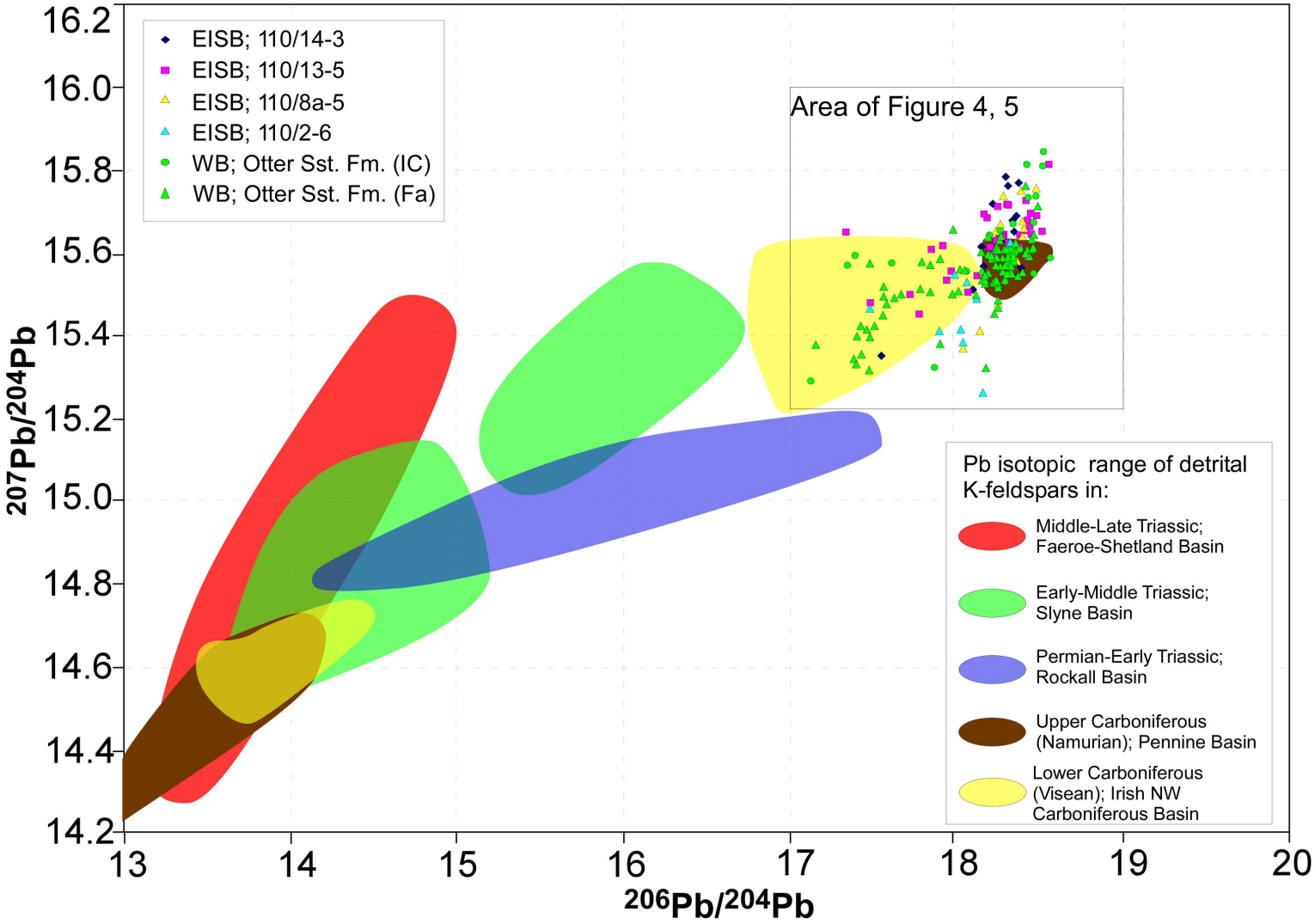












Highs

Continental
deposits

Marine
deposits

250 km

Palaeodrainage routes / Sediment
input directions

- Major
Minor
- 'Budleighensis' system;
Wessex and East Irish
Sea basins
- Foula Sandstone Fm.;
Faeroe-Shetland Basin
- Sherwood Sandstone
Group; Slyne Basin
- ?Permo-Triassic
sandstones; Rockall
Basin

NNB

FB

SP

HP

ggf

SM

CNB

RB

RBa

PH

FC

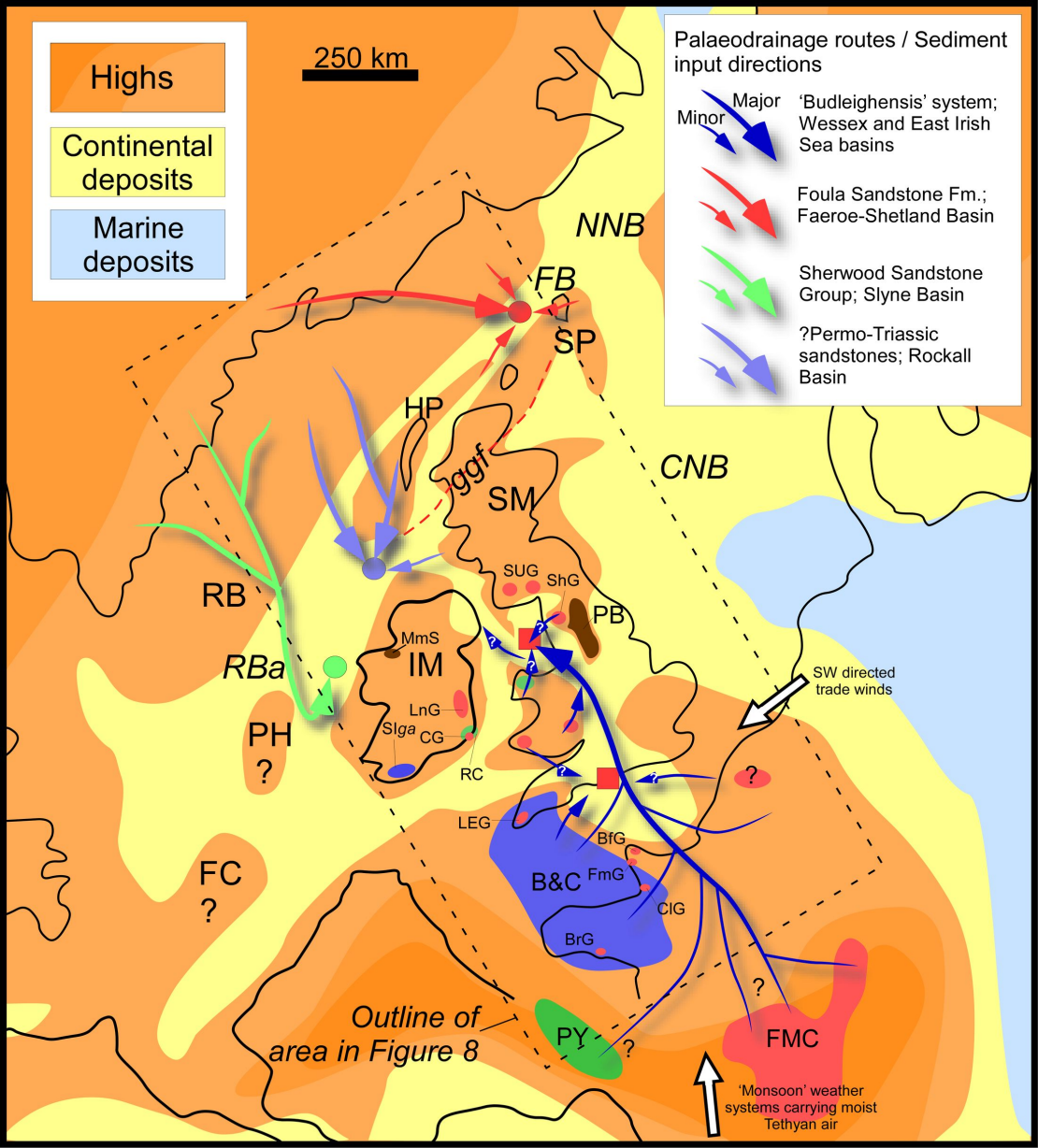
Outline of
area in Figure 8

PY

FMC

'Monsoon' weather
systems carrying moist
Tethyan air

SW directed
trade winds



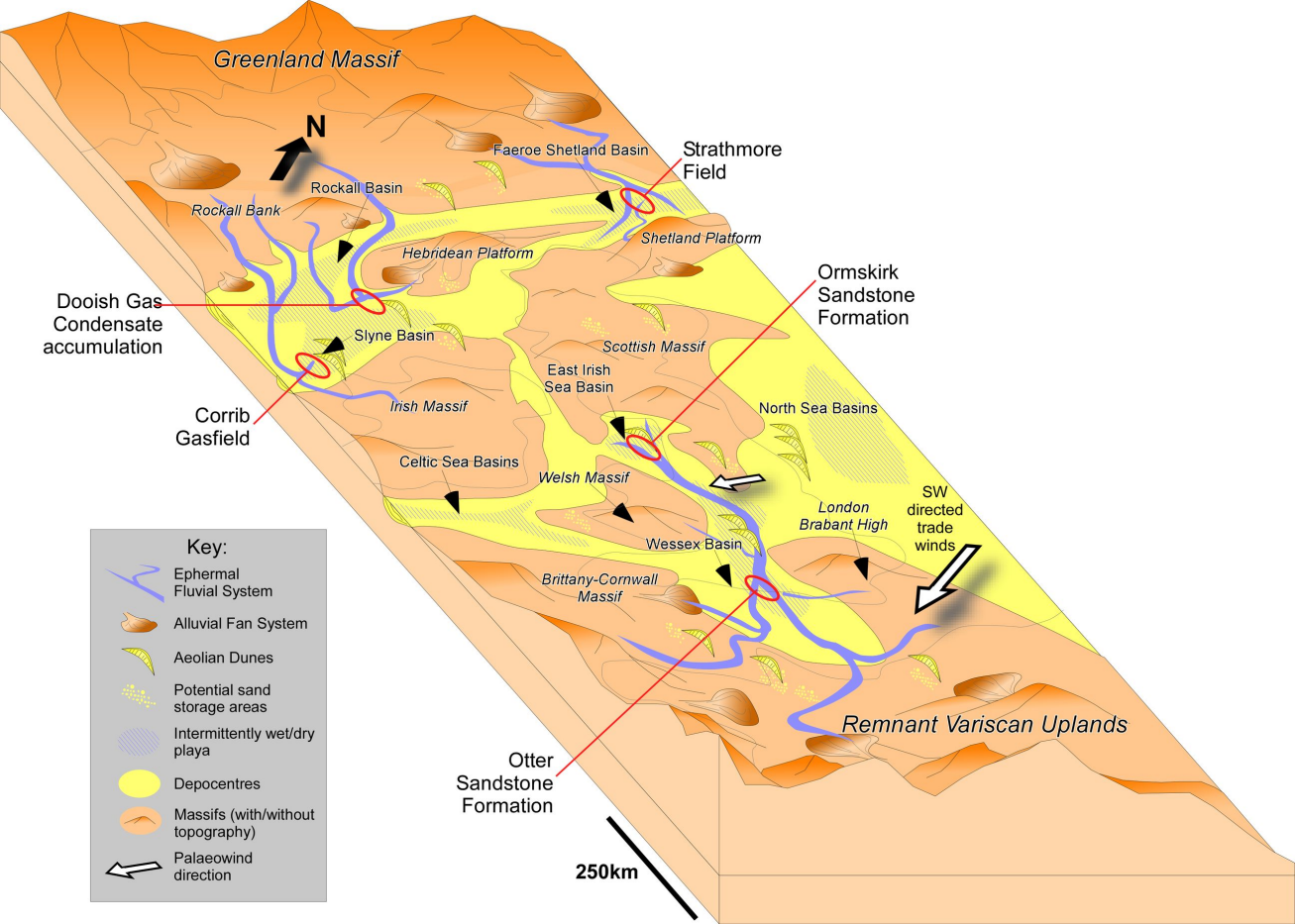


Table 1: Pb, U and Th concentration and Pb isotopic data from feldspars from Triassic sandstones (and one diast) in the East Irish Sea (EIS) and Wessex (WB) basin. Also shown are the stratigraphic nomenclature, the age, depths, wells and facies interpretation of individual sandstone samples. EIS facies interpretations from Meadows, 2004

Area	Well	Sample Ref.	Stratigraphy	Age	Facies	Depth (m)	Grain Ref.	Pb (ppm)	Th (ppm)	U (ppm)	²⁰⁶ Pb/ ²⁰⁸ Pb	²⁰⁶ Pb/ ²³⁸ U	²⁰⁷ Pb/ ²³⁵ U	²⁰⁶ Pb/ ²⁰⁷ Pb	²⁰⁶ Pb/ ²⁰⁸ Pb	²⁰⁷ Pb/ ²³⁵ U				
East Irish Sea Basin, 11913-5	2	Omskik Sandstone Fm.	Anisian	Aeolian sandstone	1584.77	1	65.5	< 0.01	0.016	18.145	0.054	15.620	0.036	38.146	0.238	0.241				
					2	11.6	0.005	0.996	18.271	0.052	15.644	0.036	38.097	0.241						
					3	56.3	< 0.01	0.012	18.258	0.037	15.626	0.036	38.014	0.238						
					4	66	0.457	3.870	18.485	0.036	15.736	0.037	38.446	0.175						
					6	124	0.021	0.063	18.551	0.038	15.820	0.037	38.829	0.179						
					8	72.4	< 0.01	0.012	18.381	0.032	15.720	0.036	38.036	0.241						
	3	Omskik Sandstone Fm.	Anisian	Aeolian sandstone	1085.85	1	81.7	< 0.01	0.012	18.599	0.031	15.720	0.031	37.887	0.238					
					2	81.2	< 0.01	0.012	18.334	0.032	15.705	0.031	38.461	0.203						
					3	148	0.141	0.038	18.341	0.032	15.694	0.032	38.461	0.203						
					4	81.2	< 0.01	0.012	18.334	0.032	15.688	0.031	38.487	0.203						
					5	28.1	0.003	0.989	18.214	0.032	15.730	0.032	38.275	0.154						
					6	5.02	0.012	0.036	18.353	0.036	15.509	0.032	37.822	0.148						
East Irish Sea Basin, 11913-5	7	Omskik Sandstone Fm.	Anisian	Aeolian sandstone	885.6	1	71.2	0.003	0.044	18.242	0.037	15.622	0.027	38.156	0.173					
					2	67.6	0.004	0.011	18.262	0.037	15.691	0.027	38.365	0.174						
					3	68.2	< 0.01	0.012	18.258	0.037	15.626	0.027	38.322	0.172						
					4	66	0.457	3.870	18.485	0.036	15.736	0.027	38.446	0.175						
					5	124	0.021	0.063	18.551	0.038	15.820	0.027	38.829	0.179						
					6	96.2	< 0.01	0.002	18.305	0.037	15.625	0.027	38.352	0.172						
	9	Omskik Sandstone Fm.	Anisian	Stacked fluvial channels	902.21	7	46.3	1.670	0.041	17.334	0.036	15.661	0.027	37.592	0.173					
					8	46	0.002	0.036	18.187	0.042	15.626	0.027	38.116	0.164						
					9	45.7	0.113	0.347	18.375	0.042	15.627	0.025	38.345	0.165						
					10	27	0.002	0.028	17.862	0.041	15.500	0.025	37.864	0.162						
					11	143	< 0.01	< 0.01	18.422	0.042	15.602	0.025	38.293	0.164						
					12	167	0.006	0.106	18.486	0.042	15.604	0.025	38.222	0.162						
10	Omskik Sandstone Fm.	Anisian	Stacked fluvial channels	904.95	1	79.2	< 0.01	< 0.01	17.866	0.041	15.621	0.025	38.071	0.164						
				2	82.7	< 0.01	< 0.01	18.038	0.042	15.603	0.025	38.066	0.167							
				3	88.8	0.032	0.022	17.718	0.039	15.516	0.018	38.052	0.165							
				4	85.4	0.011	0.019	18.301	0.039	15.702	0.018	38.264	0.161							
				5	85.1	0.011	0.019	18.319	0.039	15.625	0.018	38.295	0.163							
				6	35.8	0.036	< 0.01	17.916	0.039	15.638	0.018	37.987	0.111							
11	Omskik Sandstone Fm.	Anisian	Stacked fluvial channels	918.2	1	138	0.004	0.462	18.281	0.038	15.657	0.018	38.403	0.164						
				2	67.5	0.018	< 0.01	18.272	0.038	15.602	0.018	38.270	0.163							
				3	11.3	0.001	0.001	17.869	0.038	15.621	0.018	38.218	0.164							
				4	7.04	0.024	0.053	17.774	0.038	15.471	0.018	37.609	0.114							
				5	75.8	0.014	0.028	18.234	0.038	15.642	0.018	38.404	0.164							
				6	67.7	0.038	< 0.01	18.410	0.038	15.666	0.018	38.369	0.166							
12	Omskik Sandstone Fm.	Anisian	Stacked fluvial channels	919.58	7	64	0.011	0.031	18.040	0.038	15.707	0.018	38.418	0.166						
				8	76.4	0.283	0.920	18.413	0.038	15.728	0.018	38.463	0.162							
				9	132	0.003	0.003	18.040	0.038	15.602	0.018	38.294	0.164							
				10	131	0.186	0.024	18.122	0.038	15.581	0.018	38.031	0.112							
				11	103	2.420	0.116	18.311	0.024	15.726	0.013	39.191	0.062							
				12	66.8	< 0.01	< 0.01	17.481	0.023	15.497	0.013	37.468	0.098							
16	Omskik Sandstone Fm.	Anisian	Stacked fluvial channels	960.73	6	43	< 0.01	< 0.01	18.088	0.023	15.521	0.013	37.815	0.137						
				7	40.1	0.007	0.002	18.311	0.046	15.638	0.022	38.168	0.173							
				8	71.6	0.021	< 0.01	18.246	0.046	15.721	0.022	38.005	0.167							
				9	161	0.191	0.026	18.211	0.042	15.606	0.022	38.101	0.164							
				10	58.3	< 0.01	< 0.01	18.498	0.046	15.674	0.022	38.477	0.169							
				11	78.6	0.001	0.001	18.498	0.046	15.674	0.022	38.477	0.169							
East Irish Sea Basin, 11918-6	20	Omskik Sandstone Fm.	Anisian	Aeolian sandstone	1274.47	1	67.3	0.007	0.031	18.240	0.036	15.496	0.018	37.960	0.134					
					2	78.6	0.012	0.112	18.257	0.034	15.481	0.018	38.470	0.163						
					3	77.1	< 0.01	< 0.01	18.306	0.035	15.596	0.018	38.222	0.128						
					4	81.1	< 0.01	0.008	18.381	0.035	15.736	0.018	38.247	0.123						
					5	118	0.017	0.015	18.150	0.039	15.672	0.018	38.154	0.156						
					6	83.4	< 0.01	< 0.01	18.231	0.039	15.666	0.018	38.475	0.156						
	21	Omskik Sandstone Fm.	Anisian	Stacked fluvial channels	1283.12	1	55	0.011	0.011	18.020	0.038	15.625	0.018	37.876	0.168					
					2	83.4	< 0.01	< 0.01	18.231	0.039	15.666	0.018	38.475	0.156						
					3	55	0.011	0.011	18.020	0.038	15.625	0.018	37.876	0.168						
					4	57.1	< 0.01	0.015	18.136	0.039	15.432	0.018	37.869	0.155						
					5	138	0.001	0.001	18.306	0.039	15.618	0.018	38.681	0.169						
					6	75.1	0.013	< 0.01	18.278	0.038	15.747	0.018	38.487	0.157						
East Irish Sea Basin, 11924-6	25	Omskik Sandstone Fm.	Anisian	Aeolian sandstone	955.33	1	202	0.048	< 0.01	17.680	0.036	15.564	0.020	38.143	0.124					
					2	70.5	< 0.01	< 0.01	18.018	0.037	15.430	0.018	37.876	0.144						
					3	48.8	< 0.01	< 0.01	17.882	0.036	15.432	0.018	37.436	0.146						
					4	124	0.022	0.011	17.478	0.036	15.485	0.030	37.274	0.146						
					5	97.1	< 0.01	< 0.01	18.139	0.036	15.507	0.018	38.034	0.091						
					6	75.3	0.008	0.007	18.317	0.018	15.638	0.013	38.275	0.088						
	28	Omskik Sandstone Fm.	Anisian	Aeolian dunes	965.61	1	30.2	0.008	< 0.01	18.302	0.018	15.289	0.013	37.416	0.097					
					2	75.3	0.008	0.007	18.317	0.018	15.638	0.013	38.275	0.088						
					3	30.2	0.008	< 0.01	18.302	0.018	15.289	0.013	37.416	0.097						
					4	127	0.191	0.026	18.098	0.018	15.406	0.013	37.852	0.098						
					5	78.6	0.071	0.166	18.066	0.033	15.648	0.017	37.858	0.098						
					6	78.6	0.071	0.166	18.066	0.033	15.648	0.017	37.858	0.098						
Wessex Basin, Budleigh Salterton Outcrop	104	Other Sandstone Fm.	Anisian	Damp sandflat	1118.48	1	83.7	< 0.01	1.000	18.517	0.069	15.840	0.040	38.826	0.200					
					2	81.6	0.070	0.045	18.194	0.069	15.650	0.044	38.446	0.201						
					3	83	0.060	0.011	18.260	0.069	15.664	0.044	38.362	0.200						
					4	85.1	< 0.01	< 0.01	17.866	0.067	15.347	0.043	37.560	0.272						
					5	88.2	0.006	0.005	18.116	0.066	15.419	0.044	38.274	0.270						
					F1	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
					F2	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
					F3	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
					F4	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
					F5	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
					F6	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
					F7	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
F8	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na					
F9	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na					
F10	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na					
F11	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na					
F12	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na					
F13	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na					
F14	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na					
F15	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na					
F16	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na					
F17	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na					
F18	na	na	na	na																

Table 2: New Pb isotopic K-feldspar data from crystalline basement rocks in northern France, Cornwall and southeast Ireland, and Lower Carboniferous sandstones in NW Ireland.

Unit Name	Location	Age	Grain	$^{206}\text{Pb}/^{204}\text{Pb}$	2σ	$^{207}\text{Pb}/^{204}\text{Pb}$	2σ	$^{208}\text{Pb}/^{204}\text{Pb}$
Barfleur Granite	Near Barfleur, Normandy, Northern France	Variscan	F1	18.240	0.047	15.528	0.040	38.008
			F2	18.198	0.097	15.499	0.083	37.931
			F3	18.316	0.051	15.602	0.044	38.192
			F4	18.306	0.053	15.591	0.045	38.170
			F5	18.281	0.073	15.581	0.063	38.156
Carolles Granite	Cliff below tower, Carolles, Normandy, Northern France	Cadomian	F1	17.495	0.054	15.483	0.048	37.461
			F2	17.484	0.053	15.456	0.047	37.435
			F3	17.621	0.082	15.598	0.072	37.759
Flamanville Granite	Anse De Sciotot, Normandy, Northern France	Variscan	F1	18.275	0.079	15.573	0.068	38.087
			F3	18.304	0.056	15.606	0.048	38.157
Leinster Granite	Dalkey Quarry, Co. Dublin, Ireland	Caledonian	F2	18.135	0.080	15.612	0.070	38.076
			F3	18.144	0.045	15.623	0.039	38.095
Brech granite	Near Brech, Brittany, Northern France	Variscan	F1	18.192	0.048	15.608	0.041	38.220
			F2	18.159	0.055	15.583	0.047	38.156
			F4	18.195	0.060	15.613	0.051	38.234
			F5	18.217	0.068	15.633	0.058	38.272
Lands End Granite	Cape Cornwall, SW United Kingdom		F1	18.388	0.038	15.597	0.032	38.277
			F2	18.408	0.139	15.591	0.118	38.270
			F3	18.535	0.102	15.715	0.088	38.553
			F4	18.470	0.087	15.642	0.074	38.425
			F5	18.469	0.105	15.668	0.090	38.437
Leinster Granite	Wicklow Gap, Co. Wicklow, Ireland	Caledonian	F1	18.190	0.052	15.609	0.045	38.072
			F2	18.157	0.030	15.575	0.026	37.992
			F3	18.275	0.036	15.647	0.031	38.196
			F4	18.173	0.025	15.582	0.021	38.009
Carnsore Granite	Carnsore Point, Co. Wexford,	Caledonian	F1	17.603	0.023	15.500	0.019	37.156

	Ireland		F2	17.587	0.022	15.467	0.011	37.089
			F3	17.541	0.015	15.473	0.010	37.092
Mylonitised vein cutting Kilmore Quay Group	Kilmore Quay, Co. Wexford, Ireland	?Precambrian	F1	18.423	0.070	15.713	0.061	38.302
			F2	18.422	0.047	15.715	0.039	38.288
			F3	18.116	0.075	15.392	0.066	37.490
			F4	18.246	0.060	15.615	0.050	38.019
			F5	18.146	0.069	15.515	0.064	37.756
			F6	18.219	0.081	15.407	0.069	37.522
Mullaghmore Sandstone Formation	Mullaghmore strand, Co. Sligo, Ireland	Lower Carboniferous	F1	14.330	0.028	14.716	0.025	34.656
			F2	17.926	0.021	15.550	0.019	37.560
			F3	17.946	0.036	15.548	0.031	37.565
			F4	17.967	0.032	15.590	0.028	37.661
			F5	16.948	0.063	15.279	0.058	36.254
			F6	18.032	0.022	15.575	0.019	37.697
			F8	16.845	0.051	15.579	0.047	34.148
			F10	14.229	0.026	14.701	0.020	34.603
			F11	17.720	0.067	15.549	0.059	36.458
			F12	16.886	0.068	15.411	0.050	36.304
			F13	17.318	0.024	15.440	0.022	36.708
			F14	13.724	0.032	14.493	0.027	33.808
			F15	13.778	0.025	14.520	0.026	33.181
			F16	13.470	0.030	14.603	0.033	33.298
			F17	13.975	0.024	14.618	0.025	33.388
			F18	15.713	0.048	15.094	0.036	33.910
F19	17.781	0.056	15.420	0.050	37.267			
F20	17.493	0.076	15.528	0.067	37.096			
F21	14.099	0.032	14.659	0.030	34.390			
F22	14.158	0.050	14.701	0.038	34.177			

and

2σ
0.100
0.204
0.108
0.110
0.156
0.117
0.114
0.178
0.167
0.120
0.173
0.095
0.102
0.116
0.127
0.145
0.080
0.293
0.216
0.184
0.222
0.110
0.064
0.077
0.052
0.045

0.028

0.024

0.149

0.097

0.162

0.123

0.151

0.170

0.061

0.046

0.075

0.069

0.135

0.047

0.104

0.050

0.140

0.128

0.052

0.065

0.061

0.076

0.059

0.093

0.121

0.159

0.072

0.094