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Pilot study of the Pb isotopic composition of detrital K-feldspar in Middle-Upper Jurassic sandstones of the northern Porcupine Basin, offshore western Ireland.

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Summary

The Pb isotopic composition of K-feldspar grains from prospective Upper Jurassic reservoir sandstones in the Northern Porcupine Basin identifies sources from at least two distinct basement terranes. The same two cryptic populations of grains occur within almost all the analysed Jurassic sandstones, irrespective of facies, environment or stratigraphy. The northern Porcupine Bank, to the west, and the area to the immediate north and east of the basin appear to represent appropriate sources for these sandstones, although, currently, the nature of these sources can only be indirectly constrained. Significant input from Archaean source areas farther to the north, from Variscan sources to the south, or recycling of Triassic sandstones appear to be ruled out. The data, although preliminary, are consistent with a drainage scale of less than 200 km, and may indicate that an area to the north of the Porcupine region, and south of the future Rockall Basin, was uplifted and shed sediment during the Upper Jurassic. These results imply a major re-organisation of the drainage system west of Ireland from Triassic to Jurassic times.

Origin, rationale and aims of pilot study:

This pilot study was conceived following discussions in October 2005 at Kilashee House Hotel, Kildare at a meeting hosted by the Petroleum Affairs Division involving academic, industrial and governmental representatives with interests in the Irish Offshore. Following a pilot provenance study assessing the Pb isotopic composition of K-feldspar grains from the Triassic Corrib gasfield sandstones in the Slyne Basin (carried out at UCD with Enterprise Ireland funding) it was felt that a similar approach could usefully be applied to prospective reservoir sandstones in the Porcupine Basin, given the current interest in sand supply and reservoir distribution in this basin. In the northern Porcupine Basin, Jurassic hydrocarbon reservoirs have long been identified (Connemara Field, quadrant 26, Spanish Point gas condensate discovery, quadrant 35) and are currently being developed, whereas the southern part of the basin is an area of current exploration. Evaluating the provenance of sandstones is an important element of basin analysis and in developing predictive models for sand fairways and the distribution and quality of potential hydrocarbon reservoirs. Provenance studies also offer key insights into palaeogeography and plate reconstructions over geological timescales. Conventional petrographic analysis, i.e., based on bulk detrital mineralogy, will provide only limited insight into provenance, as not all source blocks contribute unique mineral or rock fragment assemblages, and some potential source areas remain poorly characterised, particularly those that lie offshore (e.g., the basement to Porcupine Bank).

The aims of this pilot study were as follows:

- To petrographically examine a range of sedimentary rocks from core and cuttings samples from Middle and Upper Jurassic levels in both the North Porcupine and the Main Porcupine Basin to determine the suitability of the samples for a Pb K-feldspar provenance study. The screened wells were 35/8-2, 26/28-1, 26/28-2, 35/19-1, 34/15-1, 35/6-1, 35/30-1, 44/13-1 and 62/7-1. Petrophysical logs were used to identify potential 'sandy' intervals.
- To determine the Pb isotopic composition of detrital K-feldspar grains in both fluvial and turbidite sandstones in the northern Porcupine Basin (quadrants 26 and 35) in order to reveal whether single or multiple K-feldspar populations are present, whether there are different source areas in different parts of the basin, and to assess the potential for inter-well correlation using Pb isotopes.
- To determine the Pb isotopic composition of detrital K-feldspar grains from Middle-Upper Jurassic intervals from wells in the Main Porcupine Basin, if suitable samples were isolated during the screening process (see above).
- To attempt to constrain the composition of the basement on the Porcupine Bank by analysing feldspars from potentially locally-derived Cretaceous sandstones in RSG boreholes 83/20-sb01 and 16/28-sb01 on the western and northern flanks of the bank.
- To assess whether it is possible to retrieve reliable Pb data from feldspar in well cuttings from Late Jurassic-Cretaceous coarse-grained clastics in well 35/19-1 (a well that may also have a bearing on the composition of feldspars derived from Porcupine Bank).
- To assess if there is a component in the Jurassic that has been recycled from Triassic sandstones from the Slyne Basin. Triassic detrital grains have been characterised in a similar pilot study carried out on Corrib gasfield sandstones.
- To assess if Pb isotopic data provide constraints on the scale of drainage and the orientation of any drainage axes west of Ireland.

The project was framed as a six-month pilot study commencing on 10th January 2006, and was funded through the Irish Shelf Petroleum Study Group (ISPSG).

Approach

The Middle-Upper Jurassic sandstones of the northern Porcupine Basin contain relatively common detrital K-feldspar (typically 15-20%, Geraghty, 1999 and this study). K-feldspar sand grains have been shown to retain the common Pb isotopic composition of their source (Tyrrell *et al.*, 2006) and can thus provide a powerful indicator of provenance. K-feldspar is a likely first cycle component, and is arguably more representative of the source than relatively minor and potentially recycled, robust heavy mineral grains such as zircon. In addition, the Pb isotopic characteristics of the basement feldspar in potential source terranes show broad regional patterns that are easily characterised on the basis of a small number of samples. The assemblage of K-feldspar grain types can be used to assess whether a sandstone had multiple source areas, where these source areas lay and the extent of possible recycling. Such information is critical to establishing the distribution of reservoir sandstones, the scale of drainage systems, and the palaeogeography (Tyrrell *et al.*, 2006).

In order to link detrital K-feldspar to its source, Pb isotopic data from potential parent rocks need to be available for comparison. As part of the development of the Pb provenance tool at UCD, an extensive database of Pb isotopic data from the North Atlantic region has been compiled from the literature, and additional K-feldspar samples from exposed bedrock on the Irish Mainland have been analysed as part of the Triassic Corrib gasfield pilot study. Further potential K-feldspar sources were also analysed as part of the current study to fill some important gaps in coverage. These included granites from the Irish Mainland (Ox Mountains Granodiorite and Corvock Granite), arkosic Dalradian metasedimentary rocks from the Irish Mainland (the Keem Conglomerate) and Proterozoic crystalline basement from offshore (Rockall Bank and Rhinns Complex, Inishtrahull).

A key uncertainty relevant to sand supply to the Porcupine Basin is the composition of the adjacent Porcupine Bank. In the absence of samples from the Porcupine Bank or in the area of shelf to the north and east of the Porcupine Basin (the nature of which is discussed in more detail below) the possible Pb isotopic compositions in these areas can only be constrained indirectly. As well as sampling K-feldspars from potentially locally-derived Jurassic - Cretaceous sandstones in 35/19-1 and from RSG boreholes 83/20-sb01 and 16/28-sb01 on the western and northern flanks of the bank, boundaries between isotopically distinct crustal blocks from the Irish onshore and the broader North Atlantic region can be extended to the area surrounding the Porcupine Basin, taking into account the general structural trends and the crustal province types envisaged by Naylor and Shannon, 2005 (see below). It is thus possible to predict the likely regional variations in Pb isotopic composition, but this issue will need to be revisited should the Porcupine Bank basement be sampled directly in the future.

This pilot study employed the following work-flow:

- Review of log data to identify suitable Jurassic sandstone intervals for sampling.
- Identification of 'gaps' in the source terrane Pb isotopic coverage.
- Sampling of core and cuttings at the PAD core store, Sandyford.
- Preliminary petrographic assessment of sampled sandstones/cuttings.
- Detailed petrographic and SEM analysis of targeted samples (based on preliminary petrographic assessment) and imaging of individual K-feldspar grains from Jurassic and source targets.
- Pb isotopic analysis of characterised K-feldspar grains at the Geological Institute, Copenhagen.
- Upper Jurassic palaeogeographic reconstruction of the North Atlantic region, based on published work with particular reference to Pb basement domains.
- Interpretation of provenance based on Pb isotopic character of detrital K-feldspar and regional palaeogeographic reconstructions.
- Palaeodrainage modelling.

Geological Framework

In order to place the results and any interpretation in context it is necessary to summarise the geological framework of the region - specifically the development of the Porcupine Basin and the geological nature of the Porcupine Bank.

The Porcupine Basin

The Porcupine Basin (Figure 1), offshore western Ireland, is one of several basins along the North Atlantic margin that developed during multi-phase Mesozoic rifting and thermal subsidence. The sedimentary infill of the basin includes a syn-rift phase comprising both a thin and poorly constrained Triassic interval (restricted to the northern Porcupine Basin) and a thick Jurassic sequence, and a thermal-sag phase comprising Cretaceous to Tertiary sedimentary rocks (Crocker and Shannon, 1987, Naylor and Shannon, 2005).

Middle Jurassic (Bathonian - Bajocian) sandstones in quadrant 26 of the northern Porcupine Basin are interpreted to represent alluvial, fluvial and coastal plain channel deposits, interbedded with lacustrine shales and deltaics (Crocker and Shannon, 1987, Butterworth *et al.*, 1999). These grade upwards into an Upper Jurassic (Kimmeridgian-Tithonian) sequence of low-energy fluvial (meandering river) and marginal marine facies (Butterworth *et al.*, 1999). Toward the south, these Upper Jurassic sedimentary rocks grade into shallow marine sandstones and turbiditic fans (Quadrant 35; Figure 1; Butterworth *et al.*, 1999, Williams *et al.*, 1999). Both the Middle and Upper Jurassic sandstone intervals are prospective for hydrocarbons (MacDonald *et al.*, 1987). Conventional petrographic studies have shown that the sandstones had a varied provenance area including granites, basic intrusives and metasedimentary rocks (Geraghty, 1999). However, the location and affinities of the sources of these sandstones and, therefore, the sand routeways, remain unclear.

Nature of the Porcupine Bank and Irish Shelf Area:

The basement geology on the Porcupine Bank and within the area of continental shelf immediately to the north and east of the northern Porcupine Basin is poorly known. The region has been divided as follows into four broad provinces, based on seismic character and limited well/dredge data (Naylor and Shannon, 2005):

- 1) South of the Porcupine Fault (Figure 1), in the Goban Spur region, it is envisaged that the post-Variscan surface consists of Upper Palaeozoic strata, likely of Devonian age. In addition, *in-situ* Variscan granites have been dredged from sites on the margin of the Goban Spur (Naylor and Shannon, 2005).
- 2) North of the Porcupine Fault and extending to latitude 52°N, the Upper Palaeozoic cover is thought to be thinner, thus allowing for the possible emergence of Lower Palaeozoic and older lithologies. Metasedimentary rocks and gneisses have been reported from dredge samples in the east-central part of the Porcupine Bank (Auffret *et al.*, 1979).
- 3) Between latitudes 52°N and 54°40'N, the pre-Permian surface comprises a thick (perhaps up to 3 km) sequence of Upper Palaeozoic rocks. However a well in quadrant 26 (26/26-1) encountered schists and gneiss (of assumed Dalradian affinity) beneath Dinantian strata (Robeson *et al.*, 1988).

- 4) North of latitude 54°40'N, extending to the margins of the Rockall Trough and including the Erris and Slyne areas, the pre-Permian surface comprises Upper Palaeozoic sedimentary rocks, although metamorphic rocks (of assumed Dalradian affinity) have been dredged in the Erris-Slyne-Donegal basin area (Cole and Crook, 1910).

Sampling

Middle to Upper Jurassic sandstones were sampled from wells 26/28-1 (cores 1, 2 and 3), 26/28-2 (cores 2, 5 and 10) and 35/8-2 (cores 1, 4, 5, 6 and 7) in the northern Porcupine Basin (Figure 1, 2). Previous petrographic analysis (Geraghty, 1999) indicated a significant K-feldspar component in these sandstones. Bathonian – Bajocian fluvial sandstones were sampled from cores from well 26/28-2 (Figure 2). Upper Jurassic (Kimmeridgian to Tithonian) sandstones were sampled from well 26/28-1, and these have been interpreted to represent meandering river, deltaic and associated facies (Butterworth *et al.*, 1999; Figure 2). Farther to the south, Upper Jurassic (Kimmeridgian to Tithonian; Figure 2) sandstones were sampled from 35/8-2 and these intervals have been interpreted to represent the deposition of turbiditic fans (Butterworth *et al.*, 1999). In order to place the sampled sandstones in sedimentological context, the sampled intervals were logged (Figure 3 shows representative logs of a number of these intervals). Efforts were made to sample sandstones of suitable grain-size (see below) containing K-feldspar.

Middle Jurassic fluvial sandstones were sampled from core in well 35/6-1 (core 1; Figure 2) in order to assess if the provenance technique was applicable (K-feldspar had not previously been identified in these sandstones). Middle Jurassic sandstones were also sampled from well 62/7-1 (core 2) in the southern Porcupine Basin to assess if the provenance techniques were applicable and, if so, to determine if there was a contrast with the more northerly wells in the basin.

An important aim of the pilot study was to assess the application of the K-feldspar Pb isotopic provenance technique to well cuttings. Wireline log data (particularly gamma response) and well reports were used to locate “sandy intervals” from which cuttings were taken. Cuttings were sampled from wells 43/13-1, 35/30-1, 34/19-1, 35/6-1 and 34/15-1, in order to assess if material of sufficient quality for K-feldspar Pb analysis could be obtained. The positions of the sampled ‘sandy’ intervals from the northern Porcupine Basin wells are shown in Figure 2.

Cretaceous sands and sandstones, envisaged to have been derived from the Porcupine Bank and which, therefore, may constrain its Pb isotopic composition, were sampled from shallow boreholes 83/20-sb01 and 16/28-sb01 (Figure 1). A list of core and cutting samples is shown in Table 1.

Previous work evaluating the K-feldspar Pb-isotopic technique at UCD highlighted the difficulty of analysing grains with a long-axis less than 300 µm and has shown that altered K-feldspar grains can yield Pb isotopic data with higher analytical errors than fresh grains (Tyrrell *et al.*, 2006). Therefore, qualitative petrography and SEM work was carried out on the samples obtained from the cored intervals in order to

assess if the K-feldspar grains present fulfilled the criteria necessary for Pb analysis and to select the optimum material for analysis.

Geochemical Methods:

Pb isotopic analysis of the samples was carried out at the Geological Institute, Copenhagen between 19th and 21st May 2006. The analyses were performed on a Thermochemical Axiom multicollector mass spectrometer used in conjunction with a CETAC LSX-200 Nd-YAG 266nm laser. Problems with the ICPMS (a fault with a turbo-pump) resulted in a reduction in signal sensitivity and the laser-beam size had to be increased (from 100 μm to 200 μm) in order to compensate for this. This change in the operating conditions had the effect of increasing the minimum size of grain that could be analysed from $\sim 300\mu\text{m}$ long axis to $\sim 700\mu\text{m}$ long axis (upper medium-grained). For this reason, high precision analyses could not be obtained from $\sim 35\%$ of the desired grains. Laser-ablation tracks were chosen so as to avoid any heterogeneities identified using the SEM images. A typical analysis consisted of 60 measurements during which the thin section was rastered at a speed of 5 $\mu\text{m}/\text{s}$. These measurements can be examined in smaller groups in order to determine if there is any variation along the track during the analyses (a large variation in the measured isotopic ratios during an analysis would, in any case, result in a large standard deviation). With a laser pulse rate of 20 Hz and power of 5 mJ, the ^{204}Pb signal size was typically $>0.6\text{V}$, which was sufficient to allow measurements of all isotopes on the Faraday collectors. The signal strength is ultimately a function of the concentration of Pb in the sample but varied little throughout the analyses. Along with the Pb isotopes (^{204}Pb , ^{206}Pb , ^{207}Pb and ^{208}Pb), isotopes of Hg (^{200}Hg , ^{201}Hg , ^{202}Hg and ^{204}Hg) and Tl (^{203}Tl and ^{205}Tl) were also analysed. The monitoring of Hg allowed for three independent corrections for any isobaric interference on mass 204. Tl isotopes were monitored in order to identify and quantify any mass fractionation during analysis. This was achieved using the $^{205}\text{Tl}/^{203}\text{Tl}$ ratio of the NIST 610 standard (Pb=426 ppm, Tl=62 ppm), which was analysed upon changing thin section samples in the chamber and/or after every 6-8 analyses. Data obtained from the K-feldspar grains were subsequently corrected for incremental increases/decreases in fractionation and these corrected data are shown in Tables 2 and 3. These corrections for fractionation are very small, and in all cases they are less than the calculated real 2σ error (based on the measured analytical errors).

Results

1: Preliminary petrographic assessment of all samples:

Jurassic and Cretaceous core samples were processed in the same way. Two sections, orientated normal to bedding, were cut from each core sample, a thin section 30 μm thick for conventional petrographic analysis (impregnated with dyed resin in order to assess porosity/void space) and a thicker section ($\sim 300\mu\text{m}$) for SEM work and, ultimately, Pb analysis. Petrographic analysis has shown that Middle Jurassic samples from cores in wells 35/6-1 and 62/7-1 (Table 1) are either too fine-grained (in the case of sandstones from 35/6-1) or do not contain K-feldspar (sandstones from 62/7-1 are quartz arenites).

Cuttings from wells 35/19-1, 34/15-1, 35/6-1, 35/30-1, and 44/13-1 were also assessed (Table 1) but were not suitable for Pb isotopic analysis. After washing and sieving (to remove grains less than 200 μm), cutting samples were examined under a binocular microscope. Almost all consisted of dark shale fragments and grains smaller

than the minimum size required for Pb analysis (see above). Coarse cuttings were recovered from 34/19-1, but when sectioned, these grains were found to consist of fragmentary sedimentary rocks (carbonates and quartzites) and did not contain any feldspar. Despite this, more comprehensive sampling of cuttings at a higher stratigraphic resolution may provide adequate K-feldspar for analysis in the future.

Thin sections of ~300 µm thickness were cut from the potential K-feldspar source samples, and K-feldspar grains from these samples were characterised using backscattered scanning electron microscopy.

2: Detailed petrographic assessment of selected samples:

On the basis of the preliminary petrographic screening above, 29 samples from Jurassic sandstones in 35/8-2, 26/28-1 and 26/28-2 were selected for more detailed petrographic work (Table 1), involving optical microscopy and Scanning Electron Microscopy (SEM). K-feldspar grains were imaged from each of these samples. However, due to technical limitations of the ICPMS during the analytical session (see above), only the coarser K-feldspar grains yielded high precision Pb isotopic data (see below).

The petrography of Cretaceous sandstones from the RSG boreholes is detailed in Haughton *et al.*, 2005. In 83/20-sb01, the sampled sandstones are medium-grained, well-sorted and consist dominantly of monocrystalline quartz, with a significant K-feldspar component, a bioclastic component and minor plutonic igneous and sedimentary lithic components. The sandstones are cemented by poikilotopic calcite. The sampled sandstones in 16/28-sb01 are poorly cemented, well-sorted and coarse-grained. They consist dominantly of quartz with significant amounts of K-feldspar and bioclastic material. Lithic fragments are rarer and are of plutonic igneous and sedimentary origin. K-feldspar grains from these Cretaceous sandstones were characterised using SEM prior to Pb isotopic analysis.

The detrital modes of the 12 Jurassic sandstones analysed for Pb isotopes (Table 1) were determined by point counting. Most of these were from Upper Jurassic (Kimmeridgian – Tithonian) intervals from wells 26/28-1 and 35/8-2. Only one sample from the Middle Jurassic (Bajocian - Bathonian) interval in 26/28-1 (sample 10) was suitable for Pb analysis within the criteria discussed above. In general, all the sandstones examined are texturally immature and poorly sorted, ranging from medium- to coarse-grained and with grain shapes varying from angular to sub-rounded. The detrital framework mineralogy does not vary greatly within the sample set examined, either with geographical or stratigraphic position, although this may be due to the relatively small number of samples. These sandstones plot within the sub-arkosic arenite field on a QFL plot (Figure 4). Total quartz varies from 66.5 to 78.5% (expressed as a percentage of total framework mineralogy) with monocrystalline quartz always dominant, although the polycrystalline quartz component does show a wide variation from ~10 to 26.5% of total framework grains. The latter consists largely of vein quartz with minor amounts of chert and its variation explains the spread of points in the QmFLt ternary plot (Figure 4), though there is no discernable stratigraphic or geographical pattern to this variation. The feldspar component varies

from 9 to 15% with K-feldspar always dominant. Lithic fragments are rarer, never exceeding 7% of the total framework grains and more typically ~2%, although one sample contains a significant intraclastic component (~5%; sample 18 from 26/28-1). Igneous lithic fragments (dominantly plutonic) are dominant over sedimentary and metamorphic fragments. Calcite is present as a detrital phase (as well as an authigenic phase, see below) in micritic clasts and as single spar crystals (possibly replaced shell fragments). Detrital clay and chlorite form a minor component (>1.6%) and muscovite is always present, but does not exceed 2.6%.

Porosity in these sandstones varies greatly (0 to ~18%), a reflection of the texture and diagenesis. The total authigenic component varies from ~4 to 25% with no discernable correlation with geographic or stratigraphic position. Sandstones with very high total authigenic component have an early poikilotopic calcite cement and a correspondingly low porosity (~1%; sample 18, 26/28-1, sample 49, 35/8-2 (Figure 5c)). Other sandstones have clay cement, generally kaolinitic, which likely originates from the breakdown of feldspar. Dolomite forms an important authigenic component in some sandstones (particularly sample 30 from well 35/8-2, where dolomite rhombs form the dominant cement and are overgrown by kaolinite; Figure 5d) and is occasionally observed as zoned rhombs with a dolomitic core surrounded by an ankeritic (Fe-rich) rim. Syntaxial quartz overgrowths are observed in all sandstones as an early (pre-calcite, where observed), but relatively minor, diagenetic phase and there are also minor authigenic K-feldspar overgrowths (Figure 5f).

Backscattered scanning electron microscopy has been used to image the detrital K-feldspar grains in order to assess intra-grain heterogeneities (important during LA-ICPMS) but also to examine if there is any correlation between isotopically and petrographically distinct K-feldspar populations. K-feldspar grains vary in grain shape from sub-angular laths, to rhombic forms and rounded equant grains. There are also variations in perthite type, from grains with no visible perthite (dominant in the Jurassic sandstones of the northern Porcupine Basin), to very fine scale (~1µm) albitic lamellae to coarser (~10-20 µm) albitic lamellae and veins (Figure 5a, b, c). Common inclusions comprise albite and quartz, with rarer ferromagnesian minerals, apatite and zircon. The level of alteration in K-feldspar varies widely from unaltered pristine grains to grains with limited sericitisation and some rare grains showing extreme etching and dissolution (Figure 5, g and h). For the purposes of this study, pristine grains represent the optimum target for analysis, but given the nature of the laser-ablation technique, it is possible to analyse grains with discrete heterogeneities that can be avoided during laser ablation.

3: Pb isotope data:

A total of 44 high precision Pb isotopic analyses of detrital K-feldspar grains were obtained from cored intervals in 35/8-2, 26/28-1, 26/28-2, 16/28-sb01 and 83/20-sb01. These analyses are shown in Table 2, corrected for fractionation. Less precise data (those with errors larger than 0.2 2SE on $^{206}\text{Pb}/^{204}\text{Pb}$) were obtained from the analysis of smaller grains (<700 µm long axis; see above) and are not included in Table 2. The inability to analyse smaller grains allows for the possibility that an isotopically distinct population of sub 700 µm K-feldspar grains is present but unidentified. However, previous studies (the Triassic Corrib gas field pilot study and studies in the Pennine Basin, Northeast England; Tyrrell 2005) have indicated that distinct Pb

populations exist independently of grain size and grain shape. This would also be supported by the data in this study – there is no correspondence between isotopic composition and grain-size in the analysed K-feldspars (Figure 6).

- **Jurassic sandstones:** All of the analyses, bar one, are from the Upper Jurassic sequence in wells 26/28-1 and 35/8-2. Only one grain from the Middle Jurassic sequence in 26/28-2 yielded a high precision Pb isotopic analysis (sample reference 10, grain f2, Table 2), although this is due to the unusual ICPMS operating conditions (see above) rather than the quality of target grains. Taking all the Pb isotopic analyses together, two dominant populations of detrital K-feldspar can be distinguished on the basis of isotopic composition (Figure 7). Group 1 comprises a relatively unradiogenic population with $^{206}\text{Pb}/^{204}\text{Pb}$ ranging from 15.80 to 16.74 while Group 2 is the more radiogenic population with $^{206}\text{Pb}/^{204}\text{Pb}$ ranging from 16.93 to 17.83. These populations are not petrographically distinct - both show the same range of grain sizes and perthite types (Figure 6). Both Group 1 and Group 2 K-feldspars occur together in almost all the analysed samples, mixed at thin section scale. There is no correlation between stratigraphic position and K-feldspar type.
- **Cretaceous sands and sandstones:** Data for 8 grains from 83/20-sb01 form a radiogenic population ($^{206}\text{Pb}/^{204}\text{Pb}$ ranging from 17.35 to 18.30) with two outlying grains, a very unradiogenic grain (f6, Table 2) and an extremely radiogenic grain (f2, table 2). Analysis could only be obtained from two grains from 16/28-sb01 and these data are less radiogenic than the dominant population in 83/20-sb01 ($^{206}\text{Pb}/^{204}\text{Pb}$ ranging from 16.78 to 16.87). These data are plotted in Figure 8.
- **K-feldspar sources:** Table 3 shows Pb isotopic analyses for possible sources of K-feldspar carried out as part of this study. These data were obtained from the analysis of large K-feldspar grains/crystals and because more material could be ablated, the errors on these data are significantly lower. K-feldspars from gneisses and granitic rocks from the Rockall Bank are unradiogenic ($^{206}\text{Pb}/^{204}\text{Pb}$ ranging from 15.85 to 16.11) and almost indistinguishable from the Rhinns Complex (Figure 9). Detrital grains from the Dalradian Keem Conglomerate on Achill are less radiogenic than those from the Rockall Bank and the Rhinns Complex ($^{206}\text{Pb}/^{204}\text{Pb}$ ranging from 15.02 to 15.65), while K-feldspar from the Ox Mountain Granodiorite and the Corvock Granite are radiogenic ($^{206}\text{Pb}/^{204}\text{Pb}$ ranging from 17.14 to 17.80; Figure 9).

4: Palaeogeography and Pb Domains:

A palaeogeographic reconstruction for the North Atlantic region during the Upper Jurassic, based principally on the work of Scotese, 1998, Williams *et al.*, 1999, Butterfield *et al.*, 1999, and Eide, 2002 is shown in Figure 10. A preliminary map showing the distribution of Pb domains offshore west of Ireland during the Jurassic, based on this reconstruction and all available data is presented in Figure 11B. Related Pb compositional fields are shown in Figure 11C.

The four Pb basement domains are as follows:

- 1) In the north-west, an area of **Archaean** crust, similar to that of SE Greenland is envisaged (Figure 11).
- 2) Farther to the SW, the Pb data from Rockall Bank and the Rhinns Complex help constrain an area of basement with a distinct Pb character and with a Proterozoic affinity (Figure 11), that can be linked to similarly-aged rocks in Canada (**Proterozoic Type 1**, perhaps corresponding to province 4, outlined above). K-feldspar from 16/28-sb01, from north of the Porcupine Basin are relatively unradiogenic and resemble K-feldspar of Proterozoic Type 1 affinity (Figure 11).
- 3) Still farther to the SW a third basement block, also of Proterozoic affinity but with Pb isotopic composition more radiogenic than Proterozoic Type 1 (Figure 11), termed **Proterozoic Type 2** (equivalent to province 3, above). The boundary between Proterozoic Type 1 and 2 basements may correspond to the structural extension westward of the Great Glen Fault Zone. K-feldspar from 83/20-sb01, from the western flank of the Porcupine Bank (Figure 1) is relatively radiogenic and has a Proterozoic Type 2 affinity (Figure 11).
- 4) To south-west, a fourth basement type is likely (Figure 11), based on the presence of **Variscan** Granites in the vicinity of the Goban Spur and the presence of increased **Avalonian** crust south of the Iapetus Suture (equivalent to provinces 1 and 2 above).

5: Jurassic sandstone provenance

On comparison with the possible K-feldspar sources, Group 1 K-feldspars correspond well with those from Palaeoproterozoic rocks (the Rockall Bank and the Rhinns Complex) and, in general terms, with the Proterozoic Type 1 basement (Figure 12), but do not correspond with any sources on the Irish Mainland or with sources from Britain (which correlate with Proterozoic Type 2 basement), nor do they overlap with Archaean K-feldspar or with K-feldspar from the Variscides, Newfoundland or with grains recycled from Triassic sandstones in the Slyne Basin (Figure 13).

Group 2 K-feldspars have similar Pb isotopic compositions to K-feldspars from the Irish Mainland, and correspond particularly well with the Annagh Gneiss Complex, the Ox Mountain Granodiorite and the Donegal Granites (Figure 14). There is also reasonable correspondence with galena Pb isotopic data from Newfoundland and, in general terms, with K-feldspar from Proterozoic Type 2 basement. There is no correspondence with sources from Archaean rocks, Proterozoic Type 1 basement, the Variscides or with grains recycled from Triassic sandstones in the Slyne Basin (Figures 15).

No distinction can be made between the Middle Jurassic interval and the Upper Jurassic interval as there is insufficient data from the former. However the single analysis from the Middle Jurassic interval in 26/28-2 shows a Group 2 affinity (Figure 7).

The distribution of K-feldspar grains in each of the samples are illustrated in Figure 16 in terms of their likely sources. It can be seen that Proterozoic Type 1 basement was the dominant contributor of K-feldspar in all the Upper Jurassic cores and there is little difference between the distribution of isotopically distinct K-feldspar either within the stratigraphy in individual wells, or geographically between wells. This would imply that sandstones in 26/28-1 and 35/8-2 shared the same source areas and that these source areas remained the same through the sampled the Upper Jurassic interval.

6: Palaeodrainage reconstruction

Combining the palaeogeographic reconstruction, the Pb basement domain configuration and the interpretation of facies packages within the Upper Jurassic interval (from Butterworth *et al.*, 1999), it is possible to construct a tentative palaeodrainage model for the Upper Jurassic interval in the northern Porcupine Basin (the Middle Jurassic interval cannot be assessed due to lack of data). Sand was supplied by a fluvial system draining north to south, though some lateral input is also possible. The drainage scale may have been less than 200 km, and the model envisages the upper drainage zone (and principle source) as an area of uplift (Figure 17) that formed a drainage divide, north of which the fluvial systems drain northward into the proto-Rockall Basin. This divide is necessary to explain the absence of Archaean grains within the Jurassic sandstones. The Pb data would also allow for an alternative interpretation of the palaeodrainage in which a large scale (>500 km) drainage axis samples the Rockall Bank and drains into the northern Porcupine Basin. However, this configuration is considered very unlikely because of the absence of a significant Archaean component and it would require that the proto-Rockall Basin was somehow bypassed or was not a topographic low at this time.

It should be noted that the boundaries between Pb domains and the drainage divides remain only loosely constrained. However, what seems clear is that the drainage system operating during the Upper Jurassic is relatively small scale and that there is no indication of input of sediment from the south (Flemish Cap or a Variscan source) at least in the northern Porcupine Basin.

7: Implications of the pilot Pb study for Jurassic sand supply and reservoir distribution:

The main implications of the pilot Jurassic dataset are as follows:

- The source areas supplying sand grains to the northern Porcupine Basin appear to be constant during the Upper Jurassic.
- There is no requirement for significant far-travelled sand (from the Archaean of Greenland or from the Variscides) - all of the sources appear local and could have been derived from within 200km of the basin.
- No southern sources are indicated, at least in the northern Porcupine Basin.
- Derivation of K-feldspars from uplifted Triassic sandstones in the Slyne Basin is not indicated - although the present Triassic dataset is small and restricted to the Corrib gasfield, though this will be expanded as part of a broader Triassic study.

- Detrital K-feldspar grains from Cretaceous sands and sandstones on the flanks of the Porcupine Bank have similar Pb isotopic characteristics to detrital K-feldspars from the Upper Jurassic of the northern Porcupine Basin and are used to constrain the nature of the Porcupine Bank.
- The small-scale nature of the drainage system implies that there has been a major rearrangement since Triassic times when a large-scale system (drainage scale in excess of 500 km), feeding the Slyne Basin, operated. This contrast in drainage scale from Triassic to Jurassic times is consistent with textural evidence from both sandstone sequences. Triassic sandstones in the Slyne Basin are texturally mature and very well sorted, in contrast to the Upper Jurassic sandstones from the northern Porcupine Basin (Tyrrell, 2005).
- Given that it is now clear that Triassic and Upper Jurassic sandstones have contrasting K-feldspar populations, it may be possible to distinguish sandstones of unknown age in the basins offshore Ireland, in the absence of biostratigraphic or other control, using the Pb isotopic technique.

Conclusions

Middle - Upper Jurassic sandstone samples from cored intervals in the northern Porcupine Basin (quadrants 26 and 35) have yielded sufficient K-feldspar for Pb isotopic analysis. These sandstones are poorly-sorted and texturally immature sub-arkosic arenites. Middle Jurassic sandstones from cores in wells 35/6-1 and 62/7-1 were either too fine-grained for Pb isotopic analysis of their K-feldspars or they did not contain K-feldspar. Cuttings samples examined as part of this pilot study did not contain adequate K-feldspar for Pb isotopic analysis.

Two isotopically distinct populations of K-feldspar are identified in Upper Jurassic sandstones from 26/28-1 and 35/8-2. The two populations (Group 1 and 2) occur independently of geographic location and stratigraphic position, although this needs to be tested with additional data. There are insufficient data from Middle Jurassic sandstones in 26/28-2 (one analysis).

The Pb isotopic character of the Porcupine Bank and the area to the north and east of the Porcupine Basin has been constrained by analysis of crystalline basement from both onshore and offshore Ireland and locally-derived Cretaceous sands and sandstones from RSG shallow boreholes. Group 1 K-feldspar grains in Upper Jurassic sandstones in the northern Porcupine Basin are dominant over Group 2 K-feldspars and are likely sourced from Proterozoic Type 1 basement. Group 2 K-feldspar grains are likely to have been derived from Proterozoic Type 2 basement. Combining detrital K-feldspar Pb data, Pb domain maps and palaeogeographic reconstructions, Upper Jurassic drainage can be reconstructed. This reconstruction evokes drainage scales less than 200 km, with drainage direction from north to south, and an uplifted upper drainage area comprising Proterozoic Type 1 basement. These results indicate that there was a major reconfiguration of the drainage system between Triassic and Jurassic times.

Recommendations for further work

This pilot study has led to a tentative model of palaeodrainage, based on the analysis of relatively few grains and there is scope to expand the dataset and test this model in a full-blown study. The areas which need addressing are as follows:

- 1) Additional Pb isotopic data from the wells in the northern Porcupine Basin should be collected and the study extended into the southern Porcupine Basin should suitable material become available. This pilot study has revealed some intriguing patterns and additional data will test whether the bimodal grain distribution is robust and will help greatly in testing/refining the palaeodrainage model. This should also include more detailed sampling and analysis of Middle Jurassic targets. It should also be noted that K-feldspar grains from these targets were imaged, but Pb isotopic analyses could not be undertaken for technical reasons (see above). These imaged grains can still be analysed under normal instrumental operating conditions. Comparison of the K-feldspar populations from Middle and Upper Jurassic sandstones will provide important constraint on the evolution of the drainage system during syn-rift extension.
- 2) A detailed assessment of the diagenetic history of the Middle and Upper Jurassic sandstone intervals, to examine for biasing due to feldspar dissolution.
- 3) More detailed sampling of cuttings material. The sampling of cuttings in this study did not yield grains of sufficient size or quality to enable analysis, but the utility of using cuttings has not been adequately explored.
- 4) Constraining the nature of the Porcupine Bank and the area of continental shelf to the north and east of the Porcupine Basin through direct sampling, especially as it is anticipated that such material may be available in the near future.
- 5) Linking the possible uplift of an area to the north of the Porcupine Bank with the regional tectonic development. Is this uplifted area a source for potential reservoir sandstones in the Rockall Basin? If these sandstones have the same provenance as those in the Porcupine Bank and have experienced a similar burial history, then it is possible that they share the same reservoir characteristics.

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Table 1: List of core and cutting samples obtained from Middle and Upper Jurassic intervals in the Porcupine Basin. All samples underwent preliminary petrographically assessment and those samples which were assessed in greater detail are indicated, as are the samples which were analysed using LA-ICPMS.

Core Intervals:

Sample	Well	Core	Depth (m)	Depth (ft)	Detailed petrography and SEM	Pb analysis
1	26/28-2	2	2093.25	6867.95		
2	26/28-2	2	2092.95	6866.97		
3	26/28-2	2	2092.10	6864.18		
4	26/28-2	5	2151.40	7058.74		
5	26/28-2	5	2150.25	7054.97		
6	26/28-2	5	2149.88	7053.76		
7	26/28-2	10	2188.75	7181.29		
8	26/28-2	10	2188.84	7181.58		
9	26/28-2	10	2187.48	7177.12		
10	26/28-2	10	2183.85	7165.21	y	y
11	26/28-1	1	2258.00	7408.50		
12	26/28-1	1	2256.82	7404.63		
13	26/28-1	1	2255.83	7401.38		
14	26/28-1	3	2419.95	7939.86	y	
15	26/28-1	3	2419.60	7938.71	y	
16	26/28-1	2	2272.40	7455.74	y	
17	26/28-1	2	2270.75	7450.33	y	
18	26/28-1	2	2268.65	7443.44	y	y
19	26/28-1	2	2268.07	7441.54	y	y
20	26/28-1	2	2267.70	7440.32	y	
21	26/28-1	2	2266.45	7436.22	y	
22	26/28-1	2	2265.55	7433.27		
23	35/6-1	1	3953.70	12972.09		
24	35/8-2	7	4281.55	14047.75		
25	35/8-2	7	4284.29	14056.75		
26	35/8-2	7	4293.33	14086.42		
27	35/8-2	7	4296.38	14096.42		
28	35/8-2	6	4212.59	13821.50		
29	35/8-2	6	4212.13	13820.00	y	y
30	35/8-2	6	4211.22	13817.00	y	y
31	35/8-2	6	4209.21	13810.42	y	y
32	35/8-2	6	4207.23	13803.92	y	y
33	16/28	sb01	147.30	483.29	y	y
34	83/20	sb01	155.42	509.93	y	y
35	62/7-1	2	3124.58	10251.75		
36	62/7-1	2	3122.24	10244.08		
37	62/7-1	2	3120.14	10237.17		
38	35/8-2	1	3996.65	13113.00	y	y
39	35/8-2	1	3995.22	13108.33		y
40	35/8-2	4	4106.98	13475.00	y	
41	35/8-2	4	4109.82	13484.33	y	y
42	35/8-2	4	4111.04	13488.33	y	
43	35/8-2	4	4111.83	13490.92		y
44	35/8-2	4	4113.86	13497.59	y	
45	35/8-2	5	4139.19	13580.67	y	
47	35/8-2	5	4141.01	13586.67	y	
48	35/8-2	1	3993.90	13104.00	y	
49	35/8-2	1	3993.01	13101.08	y	y

Cuttings:

Reference	Well	Depth (m)	Depth (ft)
C1	43/13-1	5035.00	16519.84
C2	43/13-1	5050.00	16569.05
C3	35/30-1	5024.38	16485.00
C4	35/30-1	4846.08	15900.00
C5	35/30-1	4751.60	15590.00
C6	34/19-1	2901.00	9518.18
C7	34/19-1	2829.00	9281.95
C8	34/19-1	2682.00	8799.64
C9	35/6-1	3920.00	12861.52
C10	35/6-1	3870.00	12697.47
C11	35/6-1	3760.00	12336.56
C12	34/15-1	3865.00	12681.07
C13	34/15-1	3400.00	11155.40
C14	34/15-1	3125.00	10253.13

Table 2: Lead isotopic analyses of detrital K-feldspar from Jurassic sandstones in the northern Porcupine Basin and from Cretaceous sands/sandstones from the flanks of the Porcupine Bank. Lead isotopic data have been corrected for fractionation taking into account incremental changes in measured Ti-based fractionation, using NIST-610 Pb standard.

Sample	Well	Core #	Depth (m)	Grain #	$^{207}\text{Pb}/^{206}\text{Pb}$	$^{208}\text{Pb}/^{206}\text{Pb}$	$^{207}\text{Pb}/^{206}\text{Pb}$	$^{208}\text{Pb}/^{206}\text{Pb}$	$^{207}\text{Pb}/^{206}\text{Pb}$	$^{208}\text{Pb}/^{206}\text{Pb}$	2SE	$^{207}\text{Pb}/^{206}\text{Pb}$	$^{208}\text{Pb}/^{206}\text{Pb}$	2SE	$^{207}\text{Pb}/^{206}\text{Pb}$	$^{208}\text{Pb}/^{206}\text{Pb}$	2SE	$^{207}\text{Pb}/^{206}\text{Pb}$	$^{208}\text{Pb}/^{206}\text{Pb}$	2SE
18/26/28-1		2	2268.65	f11	16.078113	0.041779	15.325622	0.038769	35.363862	0.088794	0.005558	0.961834	2.201642	0.000938						
18/26/28-1		2	2268.65	f5	15.951683	0.050569	15.300598	0.048536	35.358583	0.114574	0.002310	0.961834	2.219631	0.003014						
18/26/28-1		2	2268.65	f4	16.413481	0.186135	15.469719	0.070620	36.092958	0.264547	0.007535	0.947095	2.204964	0.009477						
18/26/28-1		2	2268.65	f7	17.530906	0.033830	15.625760	0.030465	36.436054	0.070887	0.000281	0.893958	2.082398	0.000321						
18/26/28-1		2	2268.65	f3	16.637604	0.036786	15.492284	0.031712	36.167656	0.075206	0.000639	0.934074	2.178762	0.000906						
18/26/28-1		2	2268.65	f8	17.177505	0.028003	15.541365	0.020844	36.104616	0.053131	0.000966	0.907737	2.107276	0.000792						
19/26/28-1		2	2268.07	f1	17.631087	0.133909	15.455495	0.086763	37.328330	0.235788	0.001115	0.877115	2.111528	0.003868						
10/26/28-2		10	2183.85	f2	17.831731	0.069671	15.426326	0.057806	36.972645	0.144943	0.000896	0.865015	2.068768	0.000919						
38/35/8-2		1	3996.65	f5	15.802378	0.085028	15.087861	0.080691	34.979055	0.187817	0.000466	0.955625	2.213005	0.000832						
38/35/8-2		1	3996.65	f1	16.631820	0.190042	15.203597	0.095683	36.548539	0.245003	0.007642	0.916583	2.199895	0.004328						
39/35/8-2		1	3995.22	f1	16.939638	0.133861	15.376942	0.101408	36.415139	0.252718	0.003539	0.908709	2.148666	0.004959						
49/35/8-2		1	3993.01	f2	16.192477	0.096571	15.221273	0.065018	35.483615	0.161668	0.003715	0.940524	2.192494	0.005863						
49/35/8-2		1	3993.01	f7	17.213997	0.165957	15.505226	0.094558	36.616881	0.243405	0.005943	0.902144	2.130471	0.009843						
49/35/8-2		1	3993.01	f9	15.938879	0.030830	15.366118	0.029617	35.328957	0.068133	0.000403	0.964634	2.219119	0.000617						
41/35/8-2		4	4109.82	f3	17.450749	0.061209	15.519619	0.053485	36.622668	0.125945	0.000356	0.890423	2.099557	0.000558						
41/35/8-2		4	4109.82	f4	14.917786	0.038163	14.911290	0.028906	35.022063	0.068202	1.030143	0.1030143	2.418115	0.003052						
41/35/8-2		4	4109.82	f5	17.365156	0.077168	15.469319	0.068788	35.981956	0.158375	0.000494	0.892295	2.074792	0.000826						
41/35/8-2		4	4109.82	f8	15.908164	0.068143	15.280510	0.065848	35.344528	0.150739	0.000371	0.962337	2.225657	0.000712						
41/35/8-2		4	4109.82	f7	16.947960	0.052110	15.400773	0.048177	36.152547	0.110965	0.000277	0.910901	2.137789	0.000530						
41/35/8-2		4	4109.82	f9	15.986215	0.103382	15.327008	0.095033	35.429337	0.212753	0.001493	0.961036	2.222156	0.001995						
43/35/8-2		4	4111.83	f2	15.958305	0.051402	15.438832	0.050479	35.560129	0.112798	0.000702	0.967607	2.229049	0.001618						
43/35/8-2		4	4111.83	f5	16.078861	0.066513	15.450660	0.056419	35.577349	0.132163	0.001705	0.961320	2.214219	0.002365						
43/35/8-2		4	4111.83	f3	16.267423	0.088614	15.503427	0.038256	36.051364	0.108797	0.004209	0.954002	2.219102	0.000665						
43/35/8-2		4	4111.83	f1	17.283683	0.075999	15.481711	0.061953	36.694017	0.149459	0.001619	0.896536	2.126567	0.002497						
43/35/8-2		4	4111.83	f4	16.334201	0.064004	15.437419	0.060505	35.550234	0.141183	0.000897	0.946043	2.180680	0.001526						
29/35/8-2		6	4212.13	f3	17.441114	0.068594	15.604090	0.062065	36.851412	0.143779	0.000788	0.895687	2.117675	0.000970						
30/35/8-2		6	4211.22	f3	16.096049	0.037116	15.387079	0.033376	37.411742	0.180161	0.003361	0.887247	2.144672	0.005846						
30/35/8-2		6	4211.22	f2	16.127544	0.036882	15.490029	0.069712	35.533431	0.078318	0.000623	0.955539	2.205642	0.000878						
31/35/8-2		6	4209.21	f1	16.147971	0.066281	15.422395	0.049496	35.300948	0.065977	0.001067	0.952692	2.186022	0.002335						
31/35/8-2		6	4209.21	f6	16.010616	0.025197	15.379693	0.020587	35.646888	0.122756	0.001869	0.954337	2.203766	0.002649						
31/35/8-2		6	4209.21	f4	16.741491	0.013017	15.513446	0.012291	35.433635	0.049412	0.000687	0.959323	2.207255	0.000927						
31/35/8-2		6	4209.21	f2	16.44206	0.046723	15.422352	0.039362	36.426171	0.028235	0.000161	0.925201	2.169037	0.000204						
32/35/8-2		6	4207.23	f2	16.344206	0.046723	15.422352	0.039362	35.403657	0.089421	0.001274	0.943428	2.165258	0.002759						
34a/83/20		sb01	155.42	f9	18.130765	0.095055	15.482661	0.080852	37.796901	0.197733	0.000379	0.853845	2.084187	0.000667						
34a/83/20		sb01	155.42	f10	18.101987	0.073386	15.346444	0.062537	36.503554	0.146602	0.000382	0.847574	2.015591	0.000524						
34a/83/20		sb01	155.42	f7	18.144265	0.145376	15.419488	0.122622	37.761557	0.301509	0.000562	0.849431	2.079200	0.001169						
34a/83/20		sb01	155.42	f6	15.498556	0.040619	15.507889	0.040092	37.863269	0.097678	0.000219	0.855268	2.086926	0.000388						
34a/83/20		sb01	155.42	f2	23.596911	0.138878	16.379451	0.049325	36.628361	0.101751	0.003985	0.693985	1.550900	0.006852						
34a/83/20		sb01	155.42	f3	18.314663	0.055326	15.639845	0.036473	38.211224	0.093834	0.001816	0.853318	2.083004	0.003304						
34a/83/20		sb01	155.42	f4	18.194106	0.018122	15.642556	0.015379	38.124872	0.037304	0.000156	0.858930	2.091970	0.000285						
34a/83/20		sb01	155.42	f1	17.355546	0.044714	15.497317	0.040038	37.587564	0.097752	0.000278	0.891963	2.161048	0.000605						
33/16/28		sb01	147.30	f2	16.872475	0.167004	15.017457	0.147742	35.391985	0.348186	0.000630	0.891849	2.097656	0.001229						
33/16/28		sb01	147.30	f3	16.785739	0.192297	15.148180	0.173538	35.908472	0.414025	0.000931	0.904329	2.139229	0.001673						

Table 3. Lead isotopic analyses of K-feldspar grains from possible K-feldspar sources, onshore Ireland and the Rockall Bank. Lead isotopic data have been corrected for fractionation taking into account incremental changes in measured Th-based fractionation, using NIST-610 Pb standard.

Sample	Type	Grain #	²⁰⁶ Pb/ ²⁰⁸ Pb	2SE	²⁰⁶ Pb/ ²⁰⁷ Pb	2SE										
KR1p	Dalladian Keem Conglomerate, Achill	f1	15.629981	0.015256	15.15036173	0.013971	35.50393326	0.033593	0.9693716	0.000368	2.2717247	0.000354	0.9693716	0.000368	2.2717247	0.000354
		f1a	15.62396434	0.018627	15.14990615	0.011547	35.52328243	0.035536	0.9697613	0.000867	2.2740443	0.000605	0.9697613	0.000867	2.2740443	0.000605
		f3	15.60055609	0.022722	15.11783738	0.013432	35.516156659	0.043573	0.9692559	0.001109	2.2773959	0.000697	0.9692559	0.001109	2.2773959	0.000697
		f4	15.62203795	0.016004	15.09493185	0.008066	35.54841897	0.029531	0.9694838	0.000802	2.276517	0.000537	0.9694838	0.000802	2.276517	0.000537
		f5	15.53104117	0.013923	15.06513132	0.010252	35.40291374	0.068710	0.9702587	0.000499	2.2806729	0.000456	0.9702587	0.000499	2.2806729	0.000456
		f6	15.45731768	0.018684	15.04525534	0.018041	35.31225469	0.042497	0.9736354	0.000191	2.2858722	0.000247	0.9736354	0.000191	2.2858722	0.000247
		f7	15.06117197	0.020256	15.0559974	0.016609	35.40891532	0.041344	0.970153	0.000685	2.2823873	0.001004	0.970153	0.000685	2.2823873	0.001004
RP8	Dalladian Keem Conglomerate, Achill	f1	15.50271502	0.017083	15.0303957	0.007425	35.46155524	0.025601	0.9695413	0.000795	2.2873688	0.001020	0.9695413	0.000795	2.2873688	0.001020
		f1a	15.41790601	0.019702	15.02322138	0.009854	35.44344273	0.034445	0.9743831	0.000869	2.2986762	0.000898	0.9743831	0.000869	2.2986762	0.000898
		f2	15.32509963	0.010665	15.02524863	0.007211	35.36427412	0.019162	0.9803762	0.000425	2.3073156	0.000572	0.9803762	0.000425	2.3073156	0.000572
		f3	15.40721687	0.008904	15.04540021	0.007370	35.48780141	0.020292	0.9764354	0.000361	2.3029305	0.000530	0.9764354	0.000361	2.3029305	0.000530
		f5	15.58531125	0.029543	15.07081468	0.015488	35.79103792	0.053520	0.9669402	0.001404	2.2960148	0.001244	0.9669402	0.001404	2.2960148	0.001244
		f1	17.87678376	0.023770	15.53277734	0.018936	37.07624211	0.048989	0.868877	0.000235	2.0734576	0.000481	0.868877	0.000235	2.0734576	0.000481
		f3	17.891696	0.024883	15.52525906	0.018932	37.0460846	0.044503	0.867613	0.000493	2.0704763	0.001139	0.867613	0.000493	2.0704763	0.001139
A	Rockall Bank	f4	17.92562391	0.019640	15.56516904	0.016739	37.26027202	0.043044	0.8681715	0.000219	2.0779169	0.000727	0.8681715	0.000219	2.0779169	0.000727
		f1	15.89586738	0.021301	15.28875031	0.019540	35.39028682	0.048506	0.9618266	0.000298	2.226464	0.000450	0.9618266	0.000298	2.226464	0.000450
		f2	15.9589044	0.051998	15.29873294	0.017993	35.4382733	0.051251	0.958849	0.002405	2.2211	0.004689	0.958849	0.002405	2.2211	0.004689
		f4	15.93191551	0.020459	15.33957391	0.019853	35.49247262	0.045937	0.9628719	0.000277	2.2279939	0.000428	0.9628719	0.000277	2.2279939	0.000428
S1A	Rockall Bank	f5	15.85796778	0.027438	15.29308293	0.022180	35.38314528	0.051320	0.9644684	0.000816	2.2216909	0.001366	0.9644684	0.000816	2.2216909	0.001366
		f1	16.00409795	0.013638	15.35566748	0.011428	35.55314003	0.027883	0.959572	0.000407	2.2218959	0.000475	0.959572	0.000407	2.2218959	0.000475
		f2	16.03492676	0.012061	15.37679506	0.010090	35.63355394	0.025738	0.9590617	0.000276	2.2227188	0.000218	0.9590617	0.000276	2.2227188	0.000218
		f4	15.97496047	0.008661	15.36585008	0.008055	35.567437	0.019002	0.9619898	0.000173	2.2269959	0.000563	0.9619898	0.000173	2.2269959	0.000563
R11B	Rockall Bank	f2	16.082792	0.049840	15.30958663	0.019483	35.35221132	0.043511	0.9522323	0.002247	2.1982251	0.005568	0.9522323	0.002247	2.1982251	0.005568
		f4b	15.99405093	0.028090	15.34212377	0.023264	35.44427811	0.052759	0.9593389	0.000917	2.2165052	0.002079	0.9593389	0.000917	2.2165052	0.002079
		f4c	16.09794642	0.083351	15.32296299	0.019133	35.47798321	0.058649	0.9525182	0.004025	2.2055588	0.007817	0.9525182	0.004025	2.2055588	0.007817
		f1	16.04740881	0.045501	15.34927282	0.017143	35.47154588	0.040620	0.9568728	0.002155	2.2118629	0.005375	0.9568728	0.002155	2.2118629	0.005375
D	Rockall Bank	f3	16.03523866	0.063028	15.33125595	0.017096	35.4232228	0.035541	0.9566981	0.003019	2.2112622	0.007611	0.9566981	0.003019	2.2112622	0.007611
		f4	16.01374285	0.081482	15.32503364	0.075002	35.50035354	0.175165	0.9574204	0.000850	2.2187523	0.001544	0.9574204	0.000850	2.2187523	0.001544
		f5	16.11441841	0.102235	15.33161246	0.021466	35.48910458	0.058816	0.9526426	0.004853	2.2060928	0.010294	0.9526426	0.004853	2.2060928	0.010294
		f2	15.99584242	0.031440	15.29472413	0.029490	35.27706165	0.069818	0.9554535	0.000369	2.2049312	0.000401	0.9554535	0.000369	2.2049312	0.000401
		f3	16.21802799	0.064098	15.31538799	0.029019	35.45569525	0.072337	0.9444039	0.003128	2.1857223	0.005762	0.9444039	0.003128	2.1857223	0.005762
RMIN-7	Rhinnis Complex, Inisitraill	f6	16.15135109	0.038946	15.37763214	0.035985	35.52923437	0.082317	0.9515786	0.000567	2.19737	0.001231	0.9515786	0.000567	2.19737	0.001231
		f7	15.96532837	0.042381	15.29544274	0.040513	35.3339981	0.093316	0.9561801	0.000402	2.2074157	0.000631	0.9561801	0.000402	2.2074157	0.000631
		f1	17.14123518	0.075455	15.40760277	0.068930	36.77404729	0.160037	0.8988645	0.000372	2.1453471	0.000648	0.8988645	0.000372	2.1453471	0.000648
		f4	17.16802571	0.014043	15.4530307	0.012733	36.86311268	0.030373	0.9000908	0.000108	2.1471268	0.000210	0.9000908	0.000108	2.1471268	0.000210
		f5	17.15433379	0.035954	15.44637656	0.032250	36.85284018	0.075837	0.9004174	0.000209	2.1482237	0.000361	0.9004174	0.000209	2.1482237	0.000361
OX13	Ox Mountain Granodiorite	f2b	17.47532439	0.043147	15.42534458	0.037815	37.19887742	0.090913	0.8837668	0.000295	2.1295049	0.000554	0.8837668	0.000295	2.1295049	0.000554
		f2c	17.49310955	0.031962	15.44292086	0.028658	37.22973982	0.067990	0.8839517	0.000210	2.1295502	0.000298	0.8839517	0.000210	2.1295502	0.000298
		f2d	17.5021221	0.029112	15.45188474	0.025805	37.24063749	0.061622	0.8841001	0.000164	2.12951	0.000290	0.8841001	0.000164	2.12951	0.000290
		f2e	17.51983574	0.047773	15.47183037	0.042396	37.28091165	0.101761	0.8844363	0.000246	2.1300999	0.000430	0.8844363	0.000246	2.1300999	0.000430
		f1a	17.47387081	0.020365	15.42345978	0.018017	37.1446207	0.042970	0.8840806	0.000170	2.1283174	0.000260	0.8840806	0.000170	2.1283174	0.000260
OX51	Ox Mountain Granodiorite	f1b	17.49272455	0.027293	15.43582134	0.022709	37.15850106	0.054854	0.8839299	0.000355	2.127259	0.000770	0.8839299	0.000355	2.127259	0.000770
		f1c	17.45833635	0.016228	15.41947129	0.014437	37.09849733	0.034466	0.884847	0.000127	2.128426	0.000204	0.884847	0.000127	2.128426	0.000204
		f2	17.76134152	0.024509	15.46417489	0.021586	37.59642903	0.051727	0.8706415	0.000205	2.1166442	0.000449	0.8706415	0.000205	2.1166442	0.000449
CG1	Convock Granite	f3	17.80556057	0.027490	15.51265757	0.024321	37.71255236	0.058749	0.871197	0.000179	2.1178845	0.000318	0.871197	0.000179	2.1178845	0.000318
		f1	17.7971338	0.026765	15.50528759	0.021426	37.7013819	0.052849	0.8711962	0.000308	2.1182479	0.000686	0.8711962	0.000308	2.1182479	0.000686
		f4	17.80342451	0.021683	15.50677022	0.018327	37.72275146	0.044882	0.8709639	0.000282	2.1186701	0.000481	0.8709639	0.000282	2.1186701	0.000481
		f2	17.80342451	0.021683	15.50677022	0.018327	37.72275146	0.044882	0.8709639	0.000282	2.1186701	0.000481	0.8709639	0.000282	2.1186701	0.000481

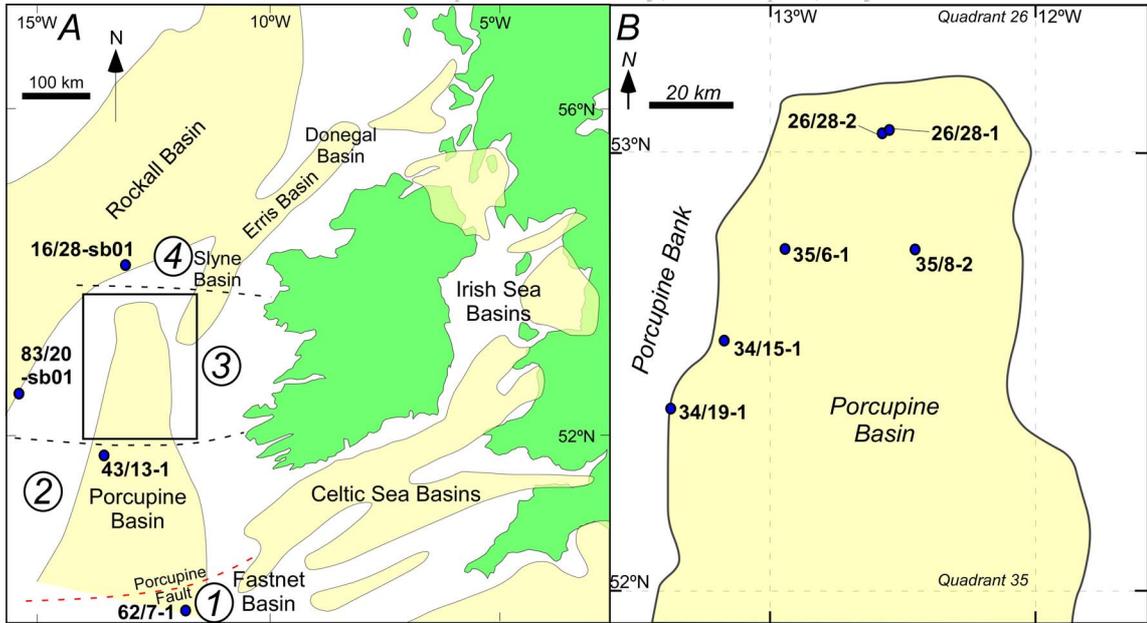


Figure 1: Sketch maps: (A), showing the location of the Porcupine Basin and the four basement provinces (circled numerals) after Naylor and Shannon (2005); (b) showing the location of the wells referred to in the text.

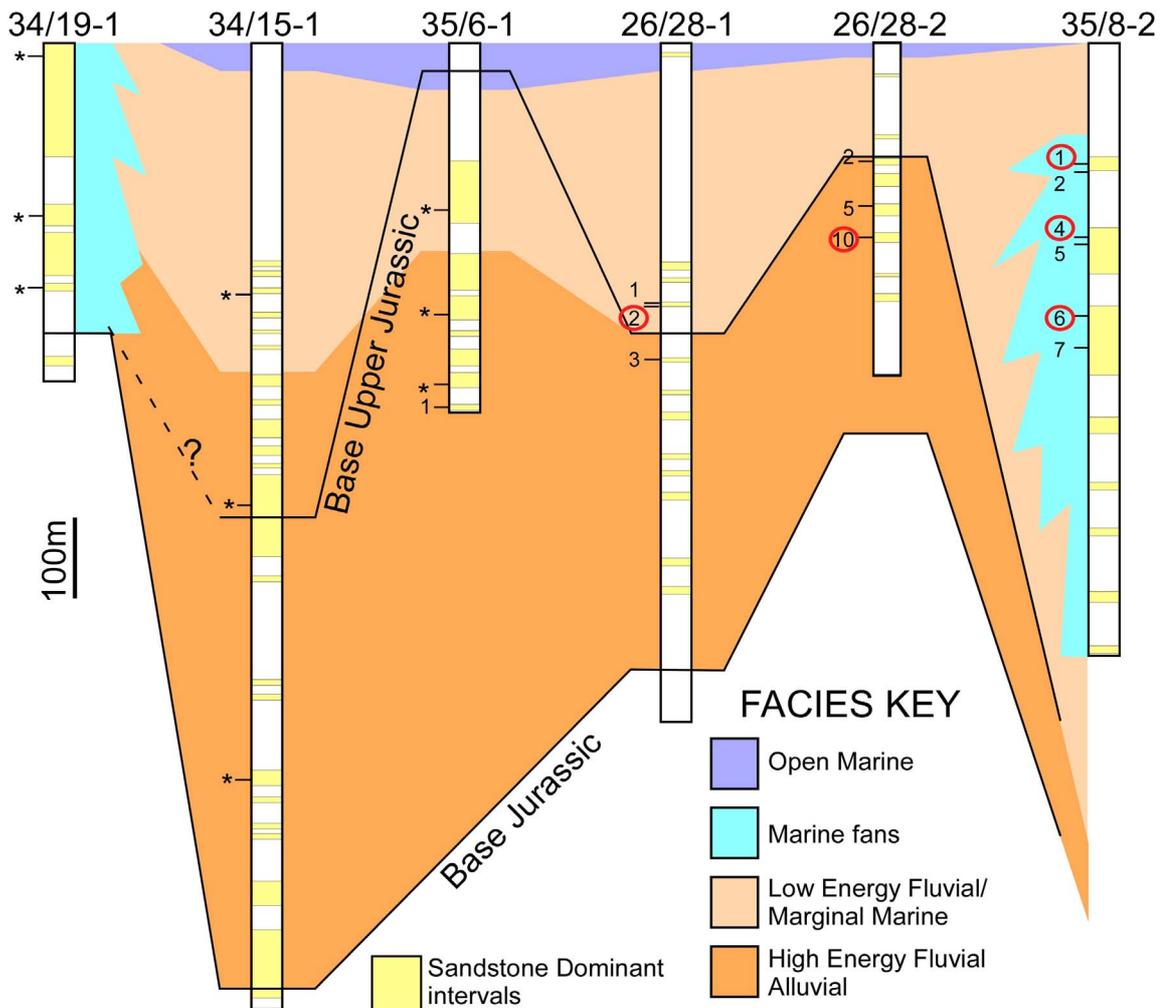


Figure 2: Simplified Jurassic correlation (adapted from Croker and Shannon, 1987) of wells in the northern Porcupine Basin showing the positions of sampled core intervals (indicated with core numbers) and cuttings (*) in this study. Red circles indicate cores from which Pb isotopic analyses were obtained.

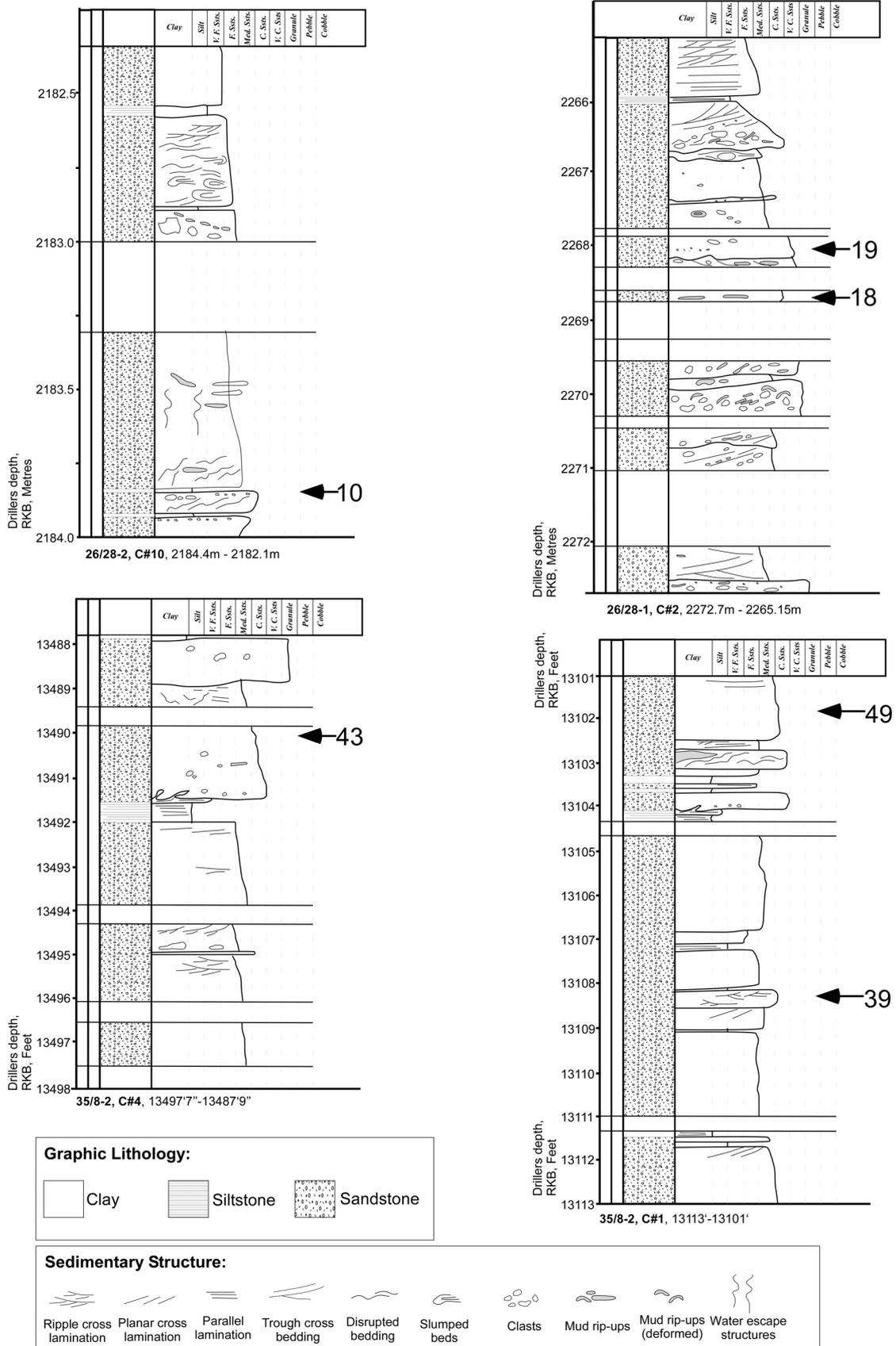


Figure 3: Representative graphic logs of some of the logged intervals in 26/28-2, 26/28-1 and 35/8-2 showing the position of the samples selected for Pb isotopic analysis.

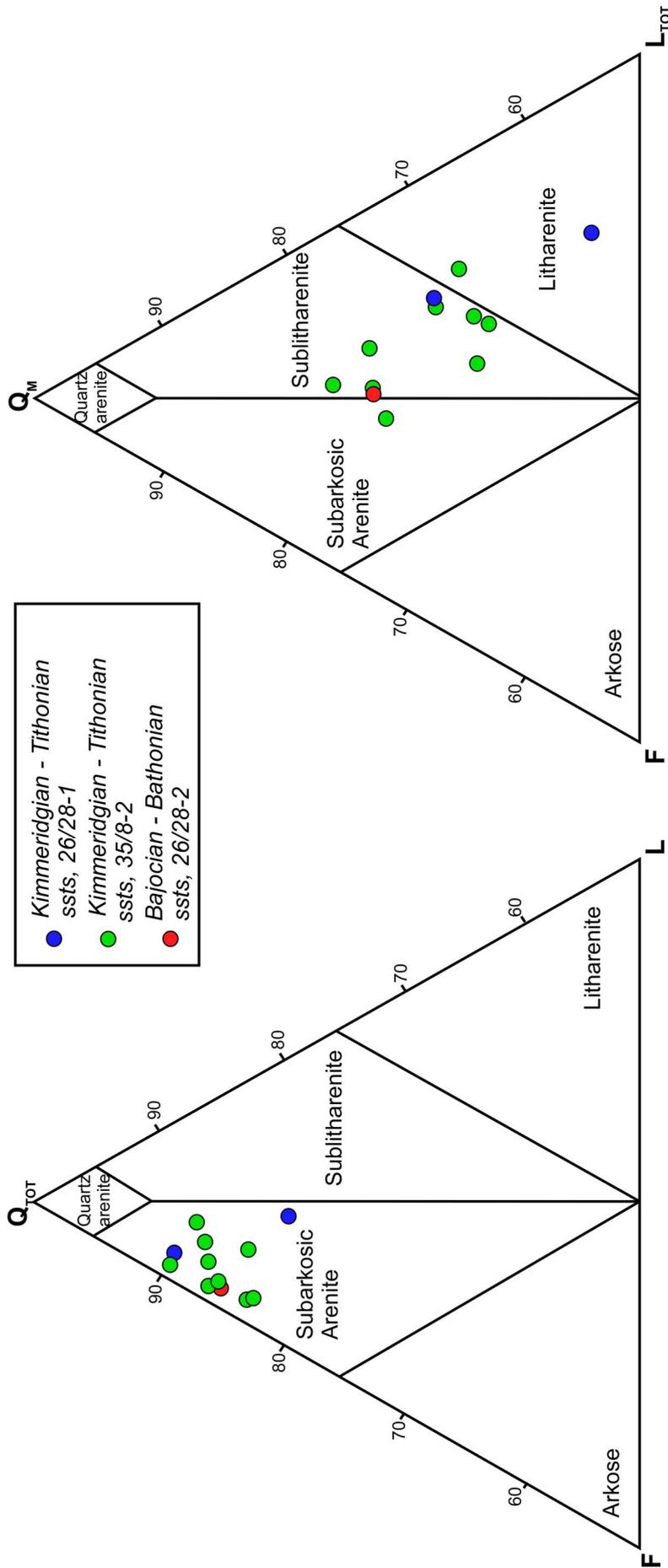


Figure 4: QFL (Total quartz, total feldspar and lithic) and QmFLtot (Monocrystalline quartz, total feldspar and lithic + polycrystalline quartz) ternary plots (after Pettijohn *et al.*, 1987) showing the mineralogy of Middle – Upper Jurassic sandstones from the analysed samples from wells 26/28-1, 26/28-2 and 35/8-2, northern Porcupine Basin.

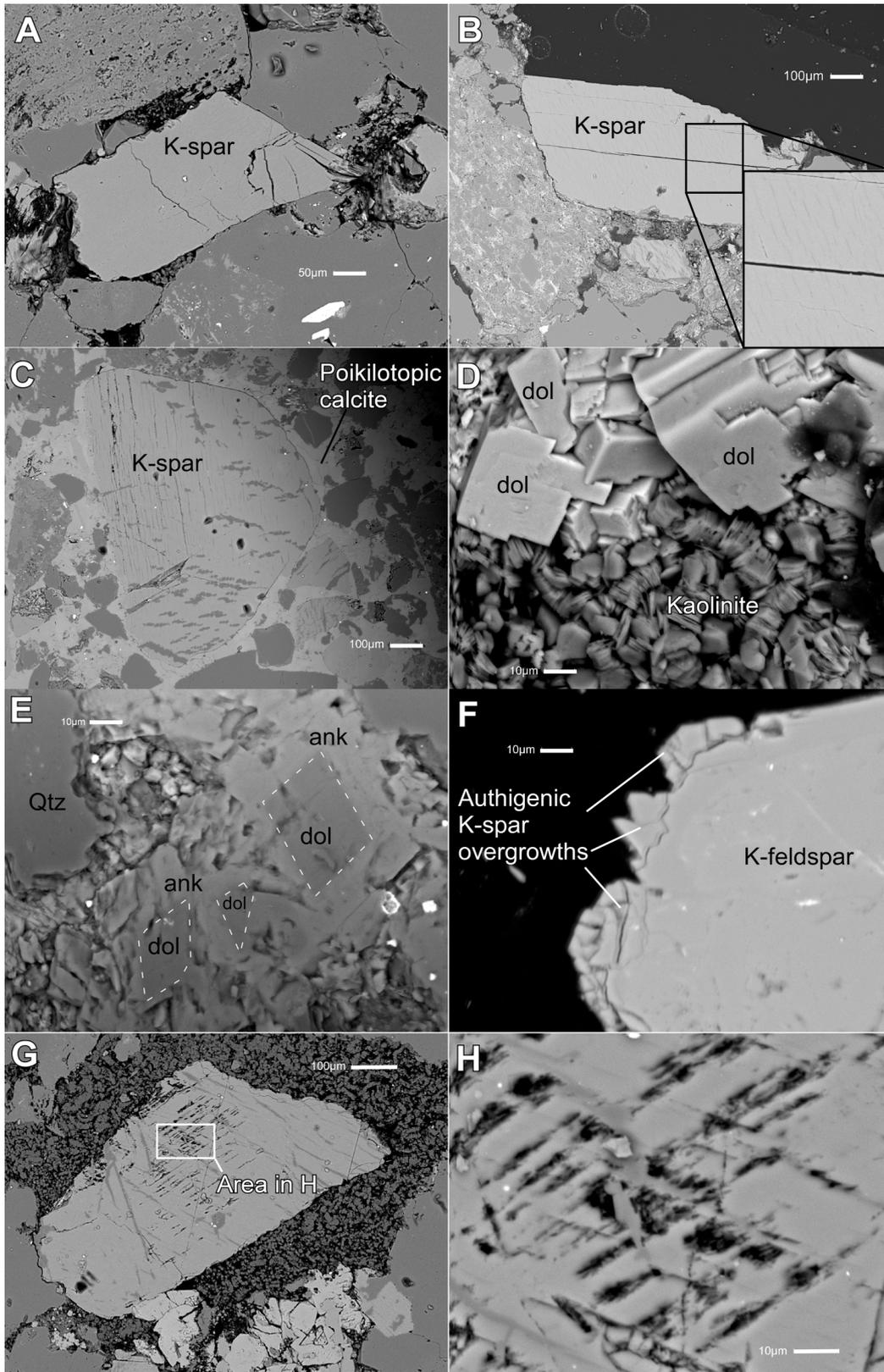


Figure 5: Backscattered SEM images of a) K-feldspar grain with no visible perthite, b) K-feldspar grain with very fine scale perthites, c) K-feldspar with albite lamellae and albite veins and surrounded by poikilotopic calcite cement, d) authigenic dolomite rhombs and kaolinite from sandstones in 35/8-2 (sample 30), e) authigenic zoned dolomite/ankerite (dashed line represents transition from dolomite to ankerite), f) authigenic K-feldspar overgrowth from Cretaceous sandstones in 83/20-sb01, g and h) etched and partially dissolved K-feldspar grain from Jurassic sandstones in 35/8-2 (sample 48).

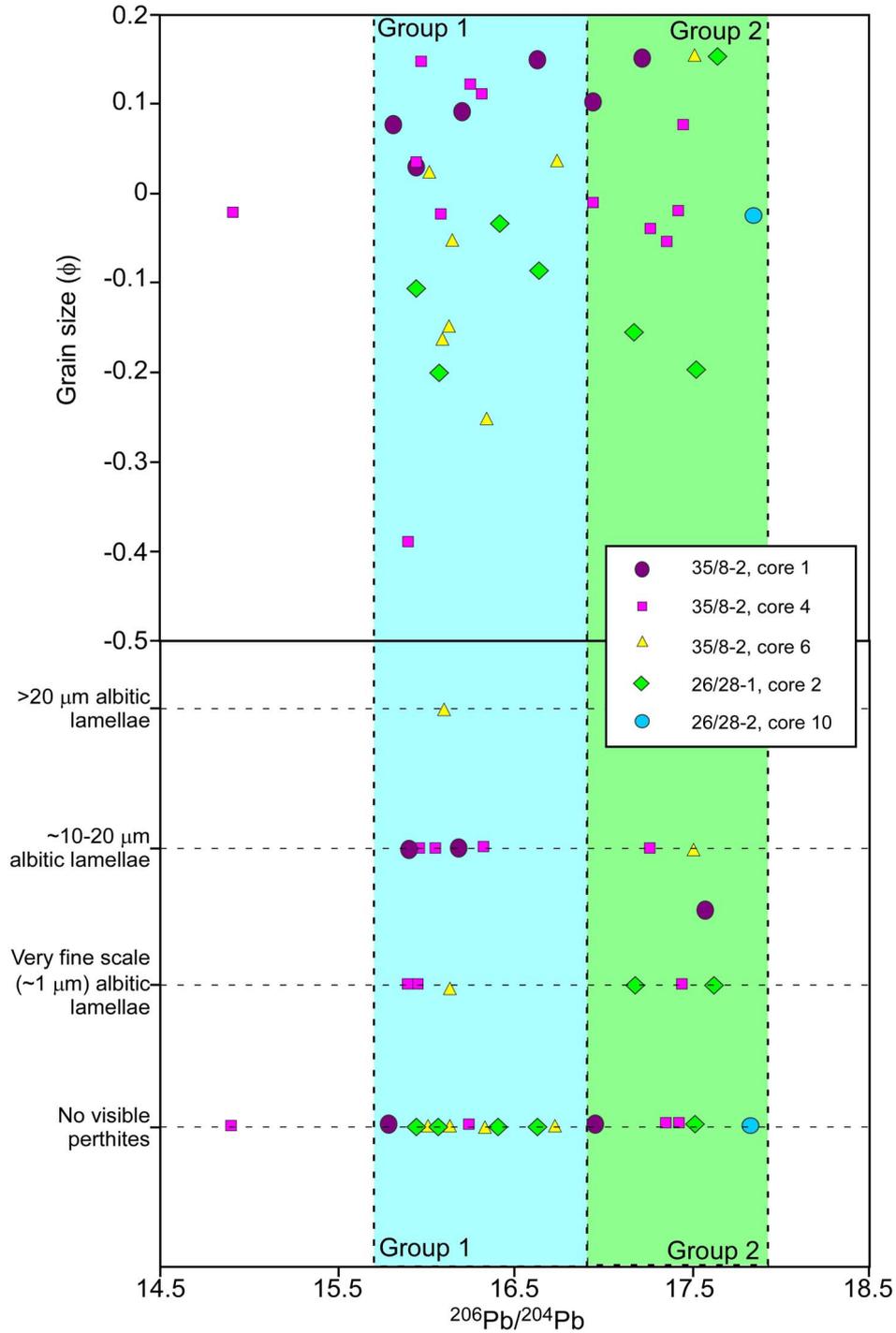


Figure 6: Plots of Pb isotopic composition of K-feldspar grains from the Middle (26/28-2, core 10) and Upper Jurassic sandstones in the northern Porcupine Basin, indicating that the distinct groups (1 and 2) exist independent of grain-size and perthite type.

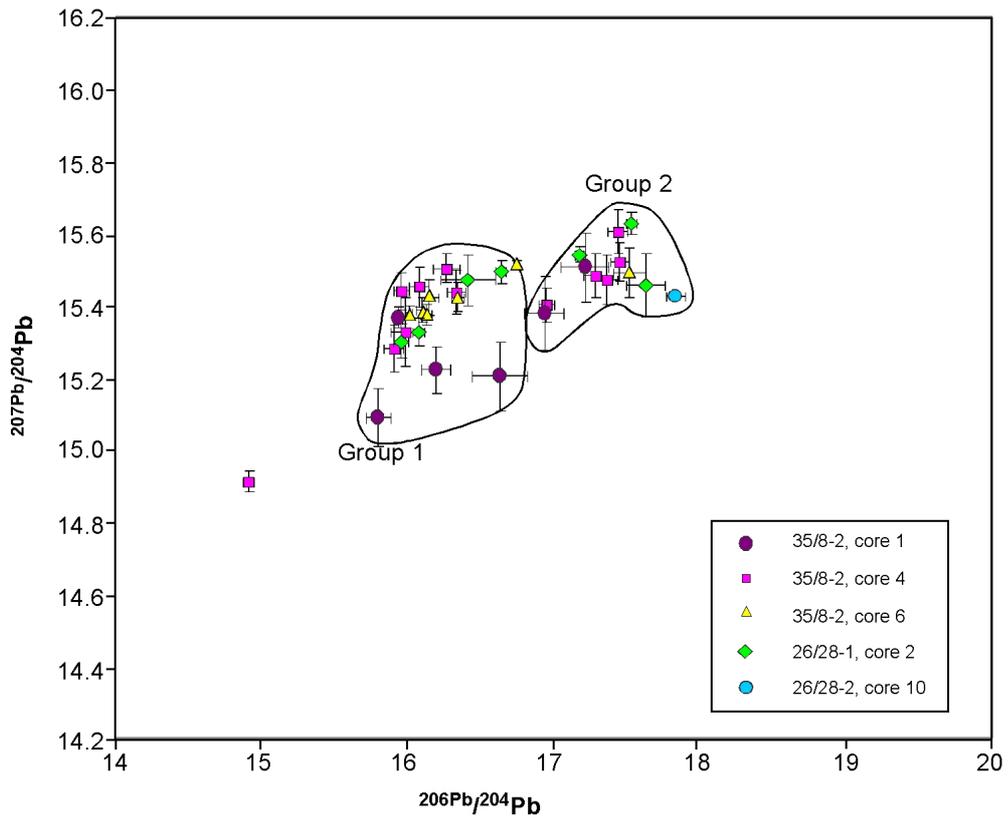


Figure 7: Pb isotopic data for detrital K-feldspar grains from Jurassic sandstones from wells in the northern Porcupine Basin. Individual analyses are plotted with 2σ analytical error bars. The plot displays a strongly bimodal distribution (groups 1 and 2).

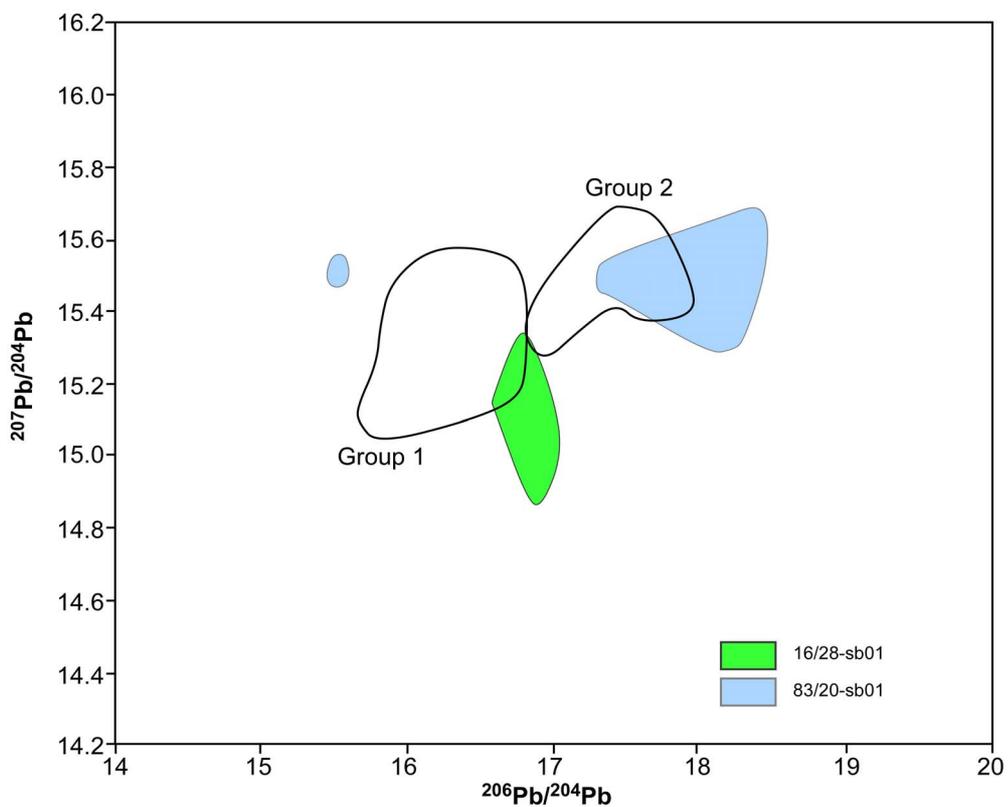


Figure 8: Pb isotopic data for Group 1 and 2 Jurassic K-feldspars, northern Porcupine Basin, compared with K-feldspars from Cretaceous sandstones from the flanks of the Porcupine Bank.

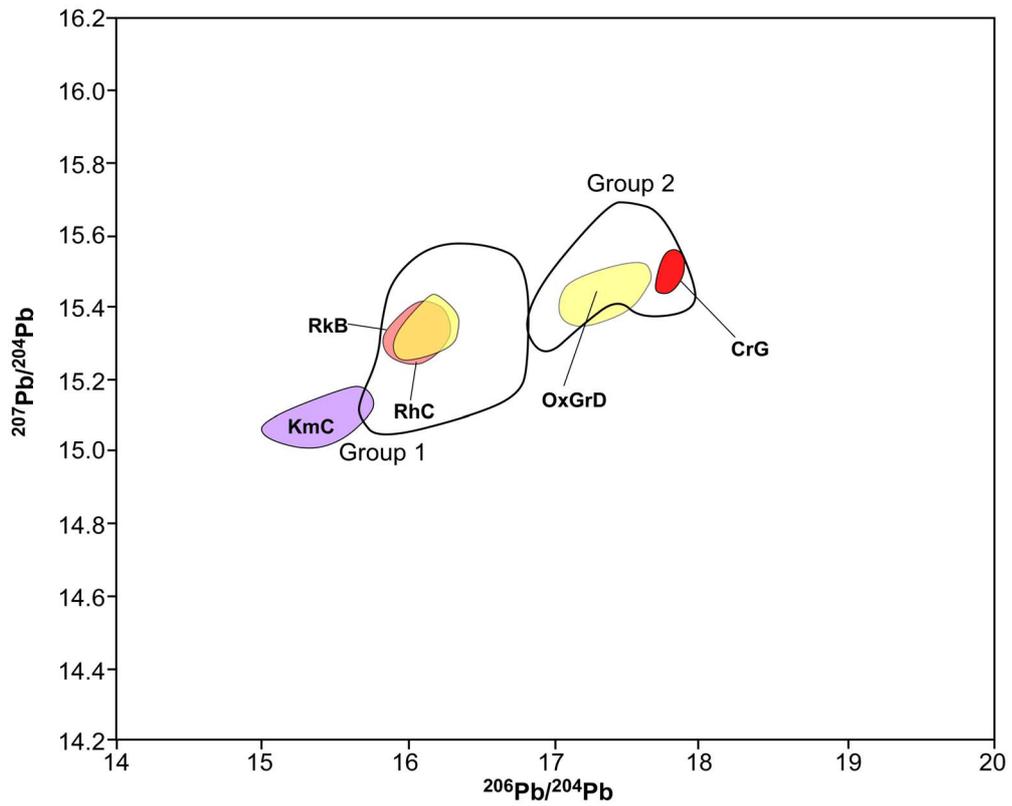


Figure 9: K-feldspar Pb isotopic data for Group 1 and 2 Jurassic K-feldspar, northern Porcupine Basin, compared with possible sources from onshore and offshore Ireland. RkB = Rockall Bank, RhC = Rhinn's Complex, OxGrD = Ox Mountains Granodiorite, KmC = Keem Conglomerate, CrG = Corvock Granite.

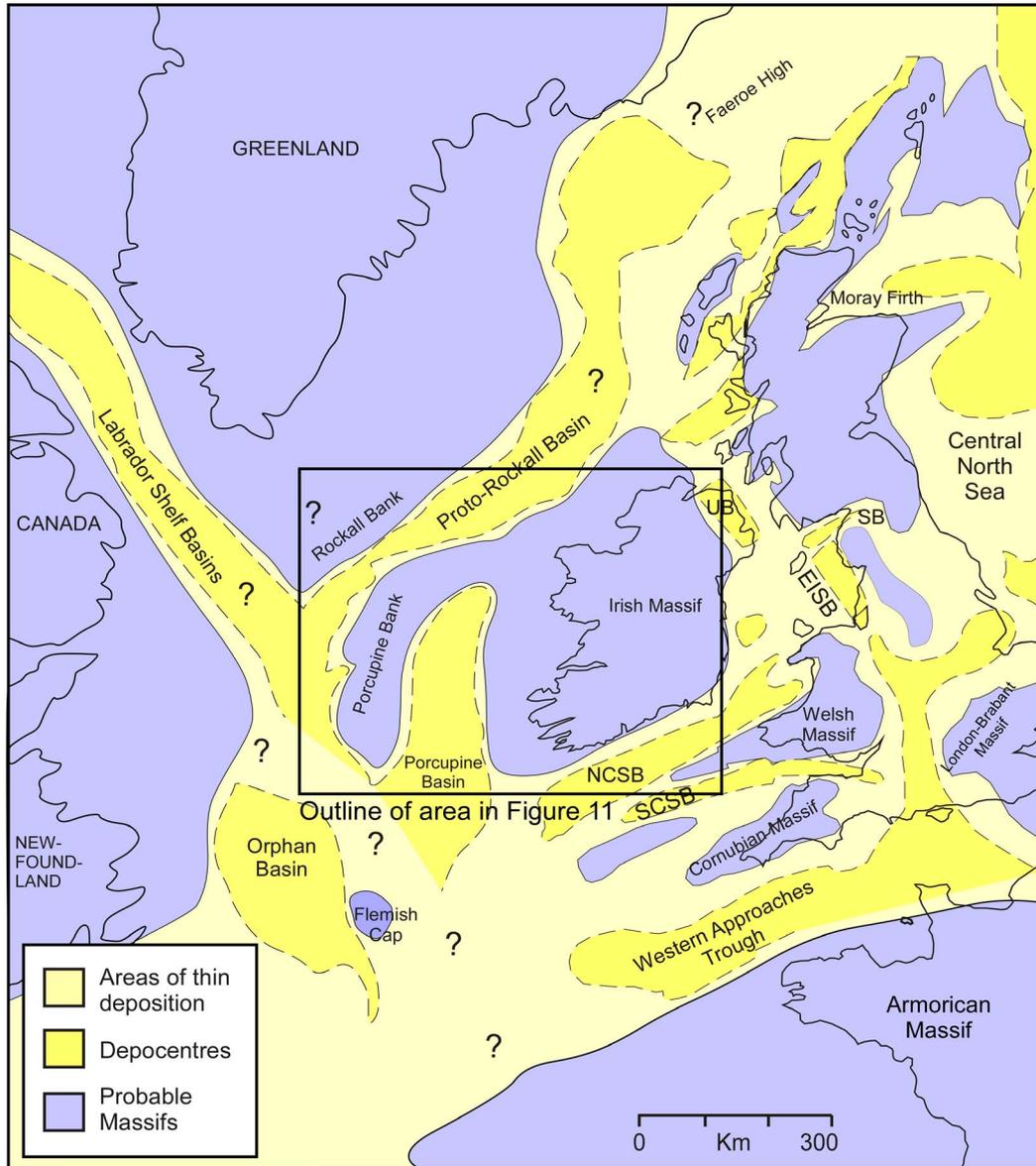


Figure 10: Palaeogeographic reconstruction of the north Atlantic region during the Upper Jurassic adapted from Croker and Shannon (1987), Ziegler (1990), Scotese (1998), Williams *et al.* (1999), Butterfield *et al.* (1999) and Eide (2002). NCSB = North Celtic Sea Basin, SCSB = South Celtic Sea Basin, EISB = East Irish Sea Basin, UB = Ulster Basin, SB = Solway Basin.

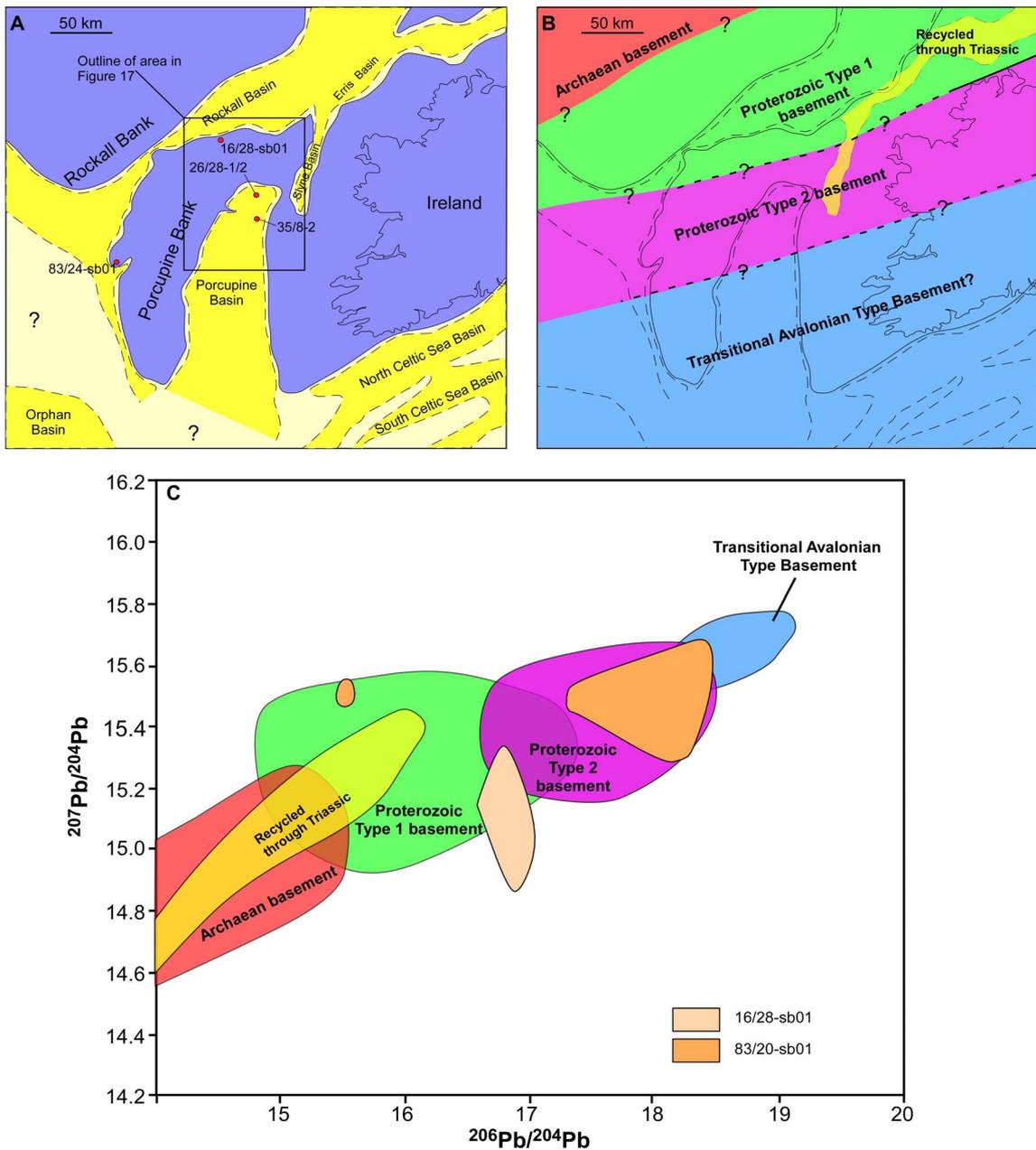


Figure 11: (A) Palaeogeographic reconstruction of the Porcupine area during the Upper Jurassic, after Ziegler (1990), Scotese (1998), Williams *et al.* (1999), Butterfield *et al.* (1999) and Eide (2002); (B) showing the possible configuration of basement Pb domains and (C) the Pb isotopic characteristics of those Pb domains, compared with overlying Triassic and Cretaceous sands and sandstones. Additional data from DeWolf and Mezger (1994), Kalsbeek *et al.* (1993) and Tyrrell (2005).

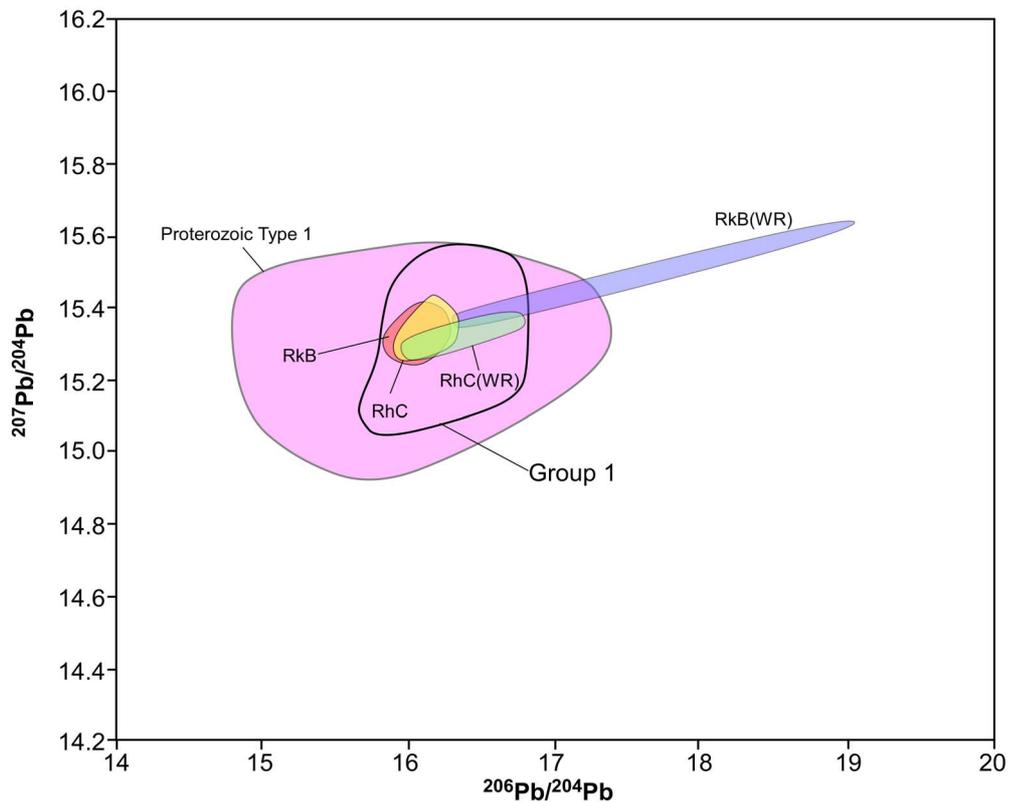


Figure 12: Pb isotopic data for Group 1 Jurassic K-feldspar, northern Porcupine Basin and possible K-feldspar source rocks. RkB =Rockall Bank, RkB(WR) = Rockall bank whole-rock data, RhC = Rhinns Complex, RhC(WR) = Rhinns Complex whole-rock data. Additional data from Morton and Taylor (1991), DeWolf and Mezger (1994) and Loewy *et al.* (2003).

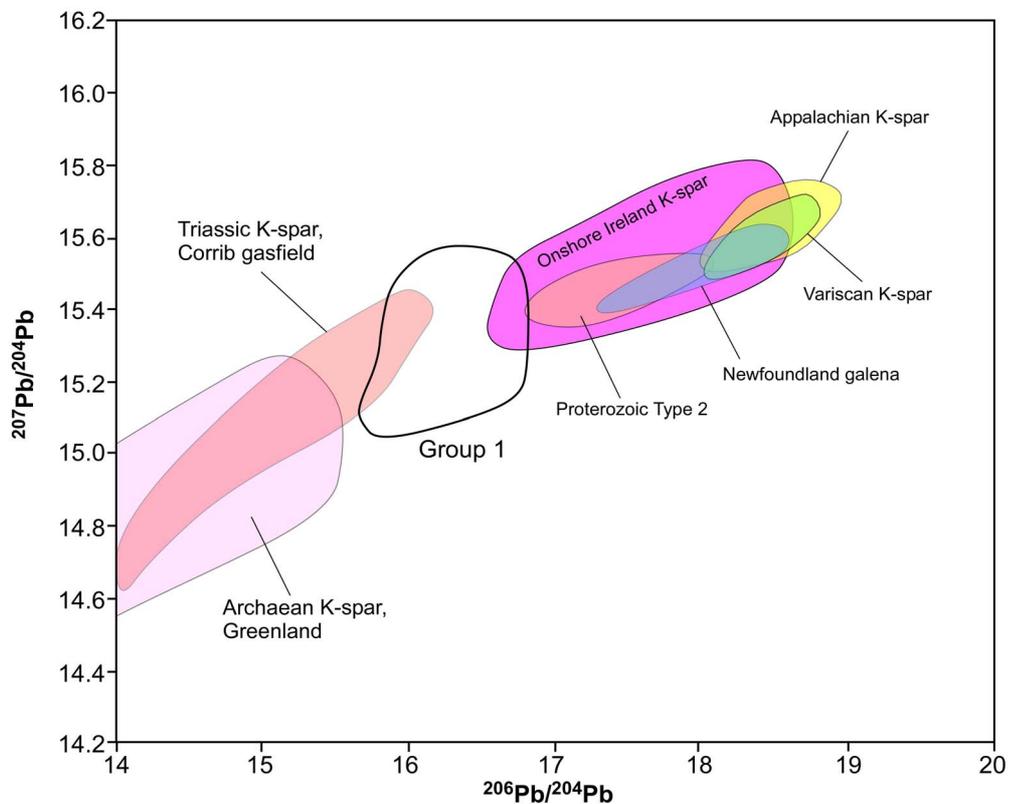


Figure 13: Pb isotopic data for Group 1 Jurassic K-feldspar, northern Porcupine Basin, compared with potential regional K-feldspar sources. Additional data from Vitrac *et al.* (1981), Ayuso *et al.* (1991), Kalsbeek *et al.* (1993), DeWolf and Mezger (1994) and Tyrrell (2005).

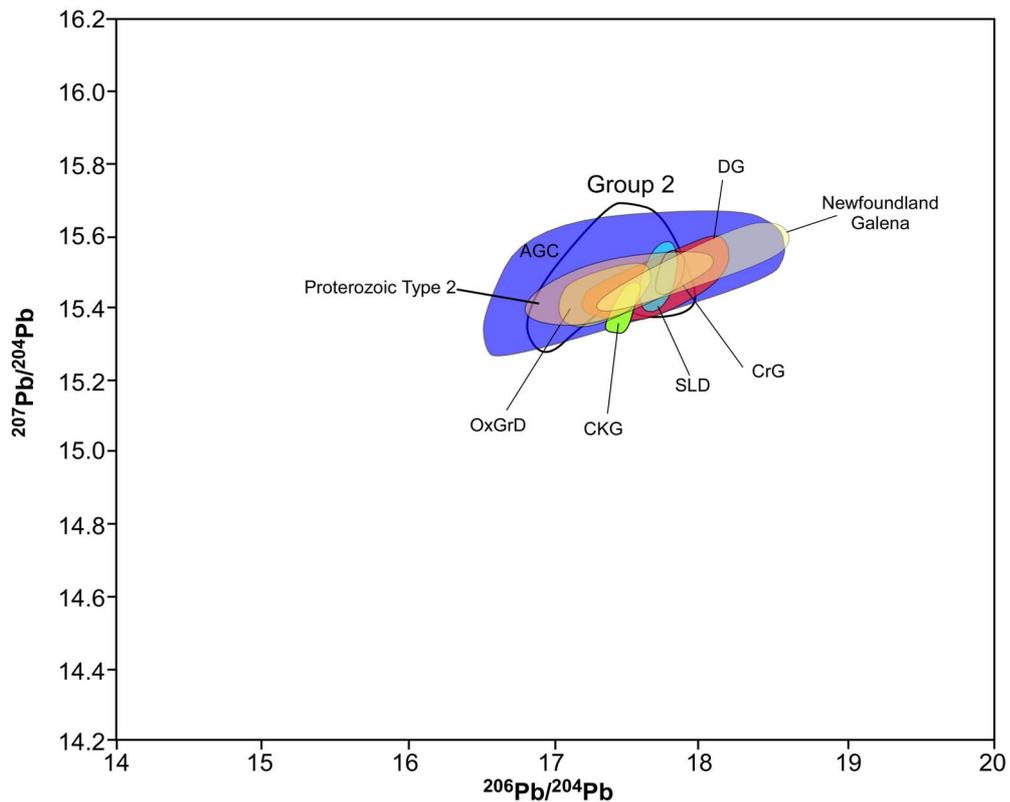


Figure 14: Pb isotopic data for Group 2 Jurassic K-feldspar, northern Porcupine Basin compared with possible K-feldspar sources (this study). AGC = Annagh Gneiss Complex, DG = Donegal Granite, OxGrD = Ox Mountain Granodiorite, CrG = Corvock Granite, SLD = Sliswood Division, CKG = Connemara K-feldspar gneiss. Additional data from DeWolf and Mezger (1994) and Tyrrell (2005).

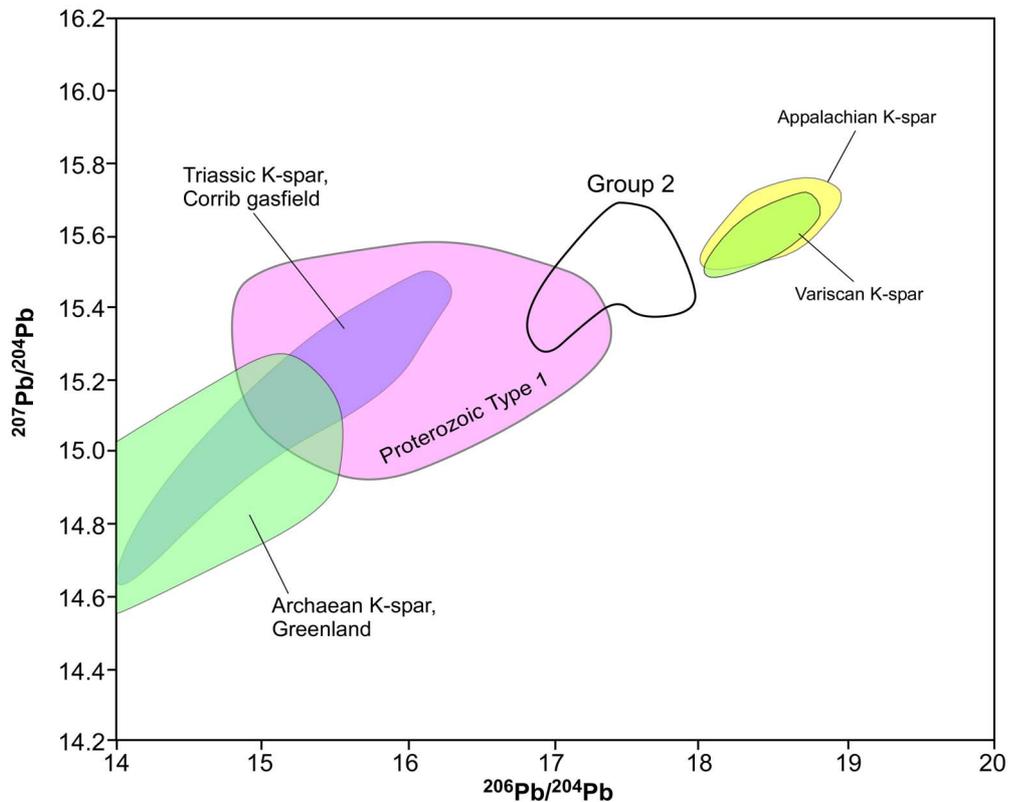


Figure 15: Pb isotopic data for Group 2 Jurassic K-feldspar, northern Porcupine Basin compared with potential regional K-feldspar sources. Additional data from Vitrac *et al.* (1981), Ayuso *et al.* (1991), Kalsbeek *et al.* (1993), DeWolf and Mezger (1994) and Tyrrell (2005).

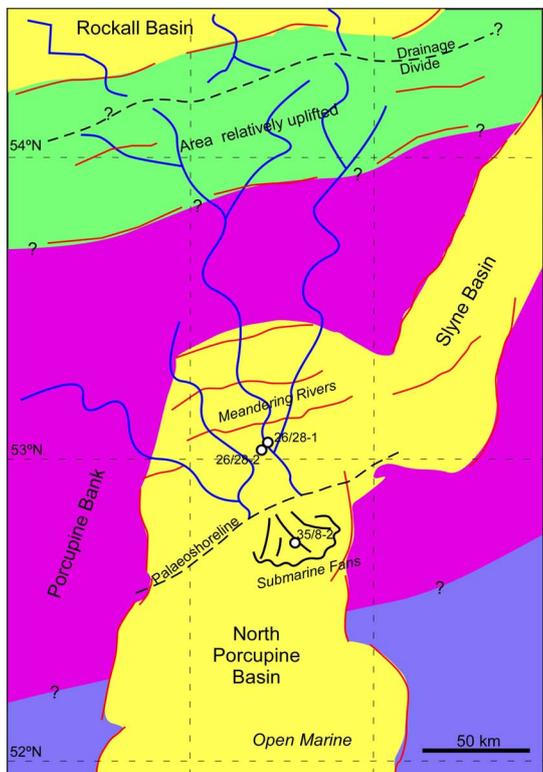
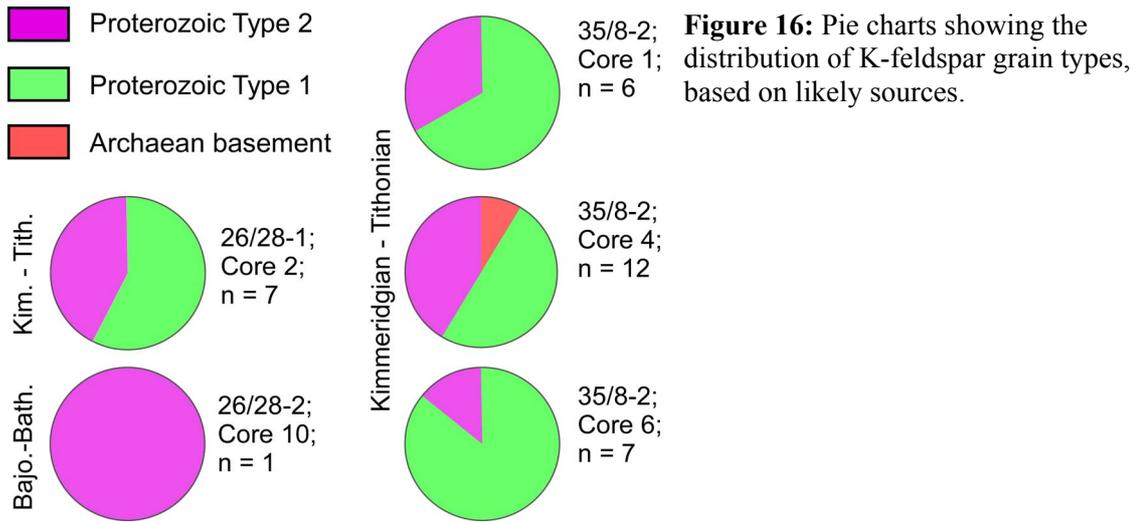


Figure 17: Schematic palaeogeographic reconstruction of the Porcupine region, in plan view and in block diagram, based on Pb isotopic character of detrital K-feldspar grains and general facies distribution (Butterworth *et al.*, 1999)

