ISPSG Project Number IS06/19

Interim report II

Provenance of Jurassic sandstones in the Porcupine Basin – new insights into sediment sources, palaeogeography and palaeodrainage.

by

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Executive summary

There are significant issues in Jurassic basins west of Ireland in relation to sand-entry points, sediment routing within and between basins and the location of sand-source areas. ISPSG project IS06/19 is focusing on the Pb isotopic composition of detrital K-feldspar as this can give key insight represents a powerful provenance tool in regional palaeodrainage reconstructions. The project is using in-situ laser ablation multi-collector inductively coupled mass spectrometry (LA-MC-ICPMS) and has initially focused on a thick sand-prone interval in well 35/8-2 in the northern Porcupine Basin. The aim of the study is to investigate whether the Pb isotopic signal is consistent between different depositional elements recognised in the cores and across a wider stratigraphic interval than previously examined in a recent pilot study. Project IS06/19 is also investigating extensively cored reservoir sandstones in the Upper Jurassic Fulmar Formation in the

Central North Sea in order to (1) further develop the Pb-in-K-feldspar tool, (2) better understand potential limitations of the technique and (3) inform parallel Pb studies in the Irish offshore basins. K-feldspar abundance is known to decrease with depth in the Fulmar Formation.

A previous study of K-feldspar from Upper Jurassic sandstones in well 35/8-2 (Spanish Point) suggested derivation from the North Porcupine High but was based on only a few (~25) analyses. New common Pb isotopic data for 334 K-feldspar grains from 15 samples have been acquired from well 35/8-2. K-means cluster analysis was used to identify four clusters, each attributed to discrete basement sources and including previously unrecognised grain populations and source contributions. The Pb isotopic and conventional petrographic data have also been integrated with MLA (Mineral Liberation Analysis) tallies of the grain types to provide a more robust interpretation. The results confirm that detrital K-feldspar in Upper Jurassic sandstones in well 35/8-2 in the northern Porcupine Basin were likely derived from a small- to modest-scale hinterland drainage system with three main catchment areas: (a) the Rockall High (less likely) or Rhinns Complex (or possible along strike equivalents = Cluster 1), (b) the North Porcupine High (and/or its along strike equivalent = Cluster 2) and (c) the Central Porcupine High (and/or its along strike equivalent found onshore in NW Ireland = clusters 3 and 4). A significant outcome of the new work is the demonstration that the provenance signal evolved through time. Although the same source areas persisted through at least two phases of deep-water fan activity, the relative contribution of each changed suggesting increasing input through time from clusters 2, 3 and 4. The new isotopic dataset appears to rules out recycling of K-feldspar from Triassic sandstones in the Slyne Basin or elsewhere implying that areas that subsided in the Triassic must have remained low lying in the Upper Jurassic. The mix of sources suggest transport distances were probably less than 250 km. Significantly, far traveled transport from the Archaean to the north or sand from the Variscides to the south can be ruled out.

1. Project Rationale and Aims

The Irish offshore region contains a number of large Mesozoic sedimentary basins similar in age and geological history to the basins on the Canadian conjugate margin although the palaeogeographic assembly and potential links between the basins prior to Atlantic opening remain unclear. The Irish basins are relatively lightly explored and sediment source areas, sand-entry points and the pattern of regional drainage are poorly constrained. ISPSG Project Number IS06/19 is applying an integrated provenance approach incorporating the Pb isotopic composition of detrital K-feldspar, sandstone petrography and Mineral Liberation Analysis (MLA) to investigate the sediment source, palaeogeography and palaeodrainage of Upper Jurassic sandstones in well 35/8-2 in the northern part of the Main Porcupine Basin. The Pb isotopic composition of detrital K-feldspar has proved to be a useful tool in provenance characterisation. Analyses are carried out *in-situ* using laser ablation multi-collector inductively coupled mass spectrometry (LA-MC-ICPMS). This approach can help overcome some of the inherent limitations with single grain studies using other techniques and is useful in cases where limited material is available (e.g. subsurface core, plug offcuts or cuttings). As sediment is transferred from source to sink the provenance signal(s) may be masked by mixing of sediment contributed from multiple sources, merging of dispersal systems and incorporation of recycled grains. Improved source discrimination can be achieved by interrogating the provenance signal in more labile mineral grains like K-feldspar that are more likely to be first cycle components and hence derived directly from their source. The use of common Pb isotopic compositions thus represents a significant advance in provenance characterisation. Pilot Pb data from 25 K-feldspar analyses in well 35/8-2 identified two distinct Pb isotopic populations (Tyrrell et al. 2007). The small sample number prevented robust statistical analysis of the data or any assessment of temporal changes in sand supply. Tyrrell et al. (2007) interpreted these data to represent hinterland drainage from a northern source, probably from an uplifted section of the North Porcupine High with a dispersal distance of c.100 km.

The *in-situ* Pb isotopic study of K-feldspar grains reported here focuses on several thick sand-prone intervals (separate sandbodies representing phases of deep water fan sedimentation) in well 35/8-2 (the Spanish Point Discovery well) in the northern Porcupine Basin. The Pb isotopic and conventional petrographic data have also been integrated with MLA tallies of the grain types to provide a more robust characterisation. The aim of this study is to investigate whether the Pb signal is consistent between different depositional elements recognised in the cores and across a wider stratigraphic interval than previously examined. The latter is important for inferring the continuity of supply during several cycles of deposition, for assessing the potential for multiple sand supply points to the basin, and for constraining hinterland evolution during syn-rift extension. By sampling throughout the cored Late Jurassic stratigraphy it is possible to investigate the potential of the Pb-in-K-feldspar provenance approach for constraining sediment supply and drainage evolution. Ultimately, vertical trends may aid field-scale correlation in the event that further wells are drilled on the Spanish Point prospect.

Five principal Pb basement source domains (Fig. 1) are identified in the North Atlantic region on the basis of compiled published Pb data (Fig. 1; Tyrrell et al. 2007 and references therein). Note offshore basement highs remain poorly constrained due to sparse sampling and the Pb domains are thought to extend along strike into these poorly uncharacterised zones albeit with some uncertainty. Domain continuity is likely because they correspond to large-scale basement terranes that ultimately owe their origin to the assembly of Laurentia and Rodina (Karlstrom et al., 2001), the Caledonian collision of Laurentia with Avalonia and the Variscan Orogen. Although second-order isotopic variations occur within each of the domains (and are useful for higher resolution provenance work), there is a progression towards more radiogenic Pb towards the SE, reflecting the history of crustal growth. Pb domain 1 comprises Archaean and Palaeoproterozoic basement and has the least radiogenic Pb. Pb domain 2 corresponds mainly to older basement reworked during the Meso- and Palaeoproterozoic. Pb domain 3 largely comprises Mesoproterozoic basement with Neoproterozoic metasedimentary rocks and younger Caledonian granites. Pb domain 4a corresponds to Avalonian basement and has a large overlap with Pb domain 4b, which corresponds with the

Variscan and contains radiogenic Pb remobilized from Avalonian basement during end-Palaeozoic closure of the Rheic Ocean (Tyrrell et al. 2007).

1.2 Project staffing

This PhD project commenced in October 2008 with the appointment of grad uate student Andreas Siemes. However, some 9 months into the project, and having completed detailed logging, sampling and initial petrographic work on the 35/8-2 cores, Mr. Siemes decided against continuing his studies. At this point (June 2009) a suitable replacement candidate was sought. Áine Mc Elhinney was subsequently appointed and commenced working on the project in September 2009.

1.3 Porcupine Basin

The Porcupine Basin (Fig. 1) includes an Upper Jurassic sequence deposited in a multiphase rift setting (Croker & Shannon 1987; Naylor & Shannon 2005). The Porcupine Basin contains up to 10 km of strata of Late Palaeozoic to Cenozoic age (Naylor and Shannon, 2005) and basin development was linked to the northward propagation of the Atlantic Rift system (Naylor & Shannon, 1999 and 2005). In the Upper Jurassic low-energy fluvial (meandering river) and marginal marine sequences grade southwards into shallow marine sandstones and then deep-water turbidites (Butterworth et al. 1999; Williams et al. 1999) that form the principal reservoir in the Spanish Point gas condensate discovery (well 35/8-2). The Porcupine Basin has seen only modest exploratory drilling with some 30 exploration and appraisal wells to date. As a result, sediment sources, palaeodrainage and palaeogeographic reconstructions are poorly constrained, particularly for the Jurassic interval. Butterworth et al. (1999) suggested north-to-south drainage in the Upper Jurassic section in the Main Porcupine Basin. Published pilot Pb data from Tyrrell et al. (2007) imply that the drainage axis that supplied the non-marine reservoir sandstones in Quadrant 26 in the north shared the same source as the marine sandstones in Quadrant 35 in the south. The two areas may have been up-dip and down-dip, respectively, along the same depositional profile. Grains derived from Archaean and Palaeoproterozoic sources were very rare in this dataset which suggested that the drainage axis did not extend beyond the developing Rockall Basin at this time.

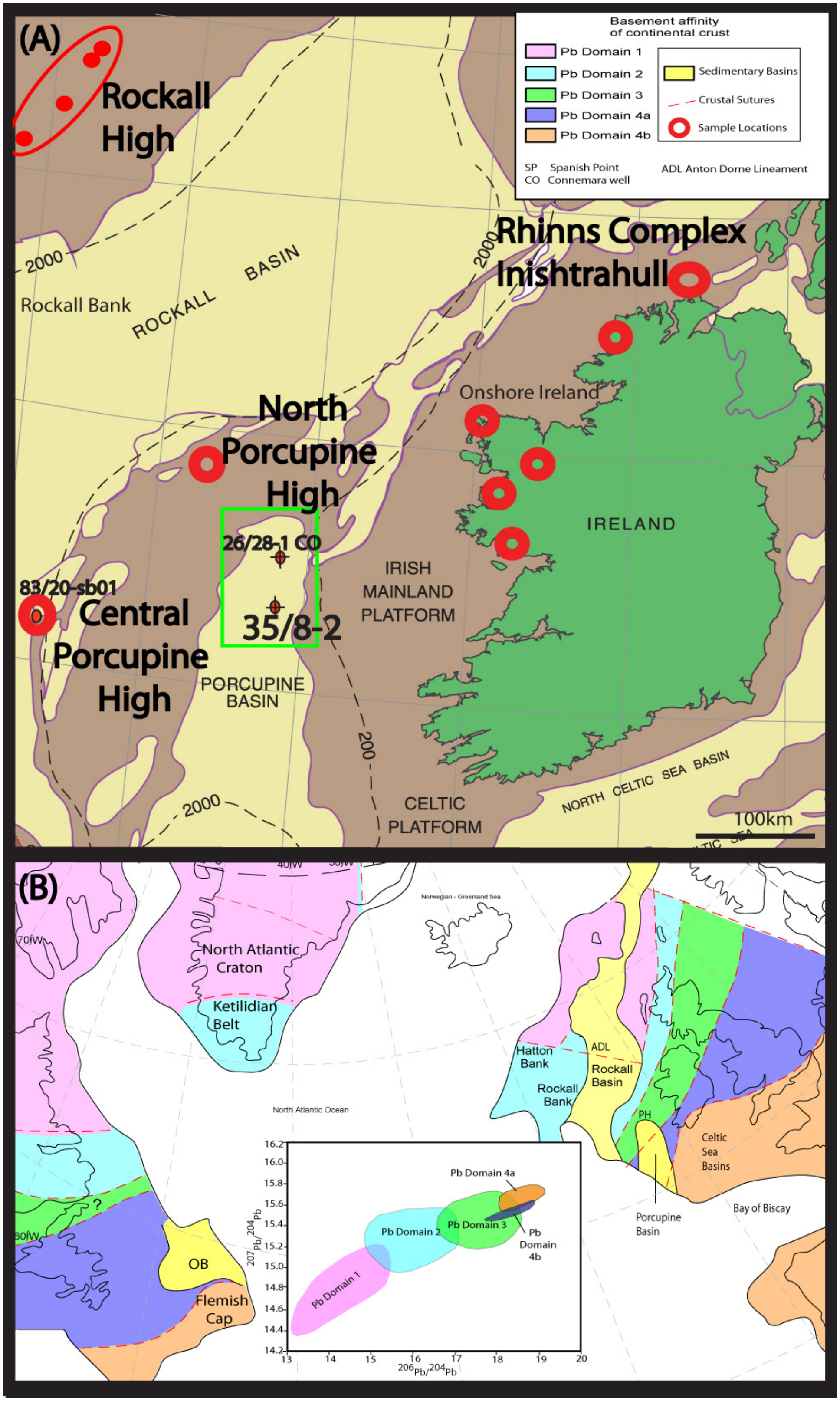

Figure 1 : (a) Porcupine Basin showing well 35/8-2 location and local Pb domain sample locations b) Pb domain map for the broader North Atlantic region after Tyrrell et al. (2007).

1.4 Depositional Environment

The 35/8-2 gas condensate discovery well (Fig. 1) is located in the Main Porcupine Basin 150 km west of Ireland in a water depth of 422 m, and 30 km south of non-marine/marginal marine reservoir sandstones in Quadrant 26 (the Connemara prospect). Drilled by Philips Petroleum in 1981, an over-pressured c.1400 ft (426 m) gross gas condensate column was encountered in Late Jurassic Volgian-aged stacked turbidite sandstones (Pugliese et al. 2009). The discovery was not appraised due to the lack of gas infrastructure and a viable market in Ireland at the time. The Upper Jurassic section consists of hemipelagic claystones and bituminous shales in which four significant sandstone intervals are developed (A, B, C and D) varying from 37-60 m thick. The cored section is sandstone dominated, with a local component of gravel, the latter sourced both extra- and intraformationally. The A sandstone interval (13101-13215 ft l.d.) consists of a basal 10 ft of claystones deposited by suspension fallout and distal silty turbidites together with mud-supported debris flows. Above this, a stacked sequence of overall coarsening-upward sandy units is present. Each unit consists of individual beds that fine upwards. The units are dominated by massive sandstones (Fig. 2) which display abundant dewatering structures, indicating high pore-fluid pressure and interpreted to represent significant upward migration of depositional waters from loosely packed sand in response to increased depositional overburden. Overall the A sequence is interpreted to represent fan lobe progradation in an outer to middle fan environment. The B sandstones (13415-13595 ft l.d.) comprise a basal interval with an overall coarsening-upward sequence comprising interbedded sandy turbidites and mudstones which grade upwards into thicker, sand-dominated turbidites. Above this a sandy sequence fines upwards over a 137 ft interval. Thickly bedded granule conglomerates and sandstones, interpreted as possible channelised high-density turbidites, grade upwards into more ‘classical’ sand-dominated turbidites which become progressively thinner and finer grained (Fig. 4). The overall fining-up sequence of the B sandstones is interpreted to represent a gradation from inner to outer fan (Robinson and Canham, 2001).

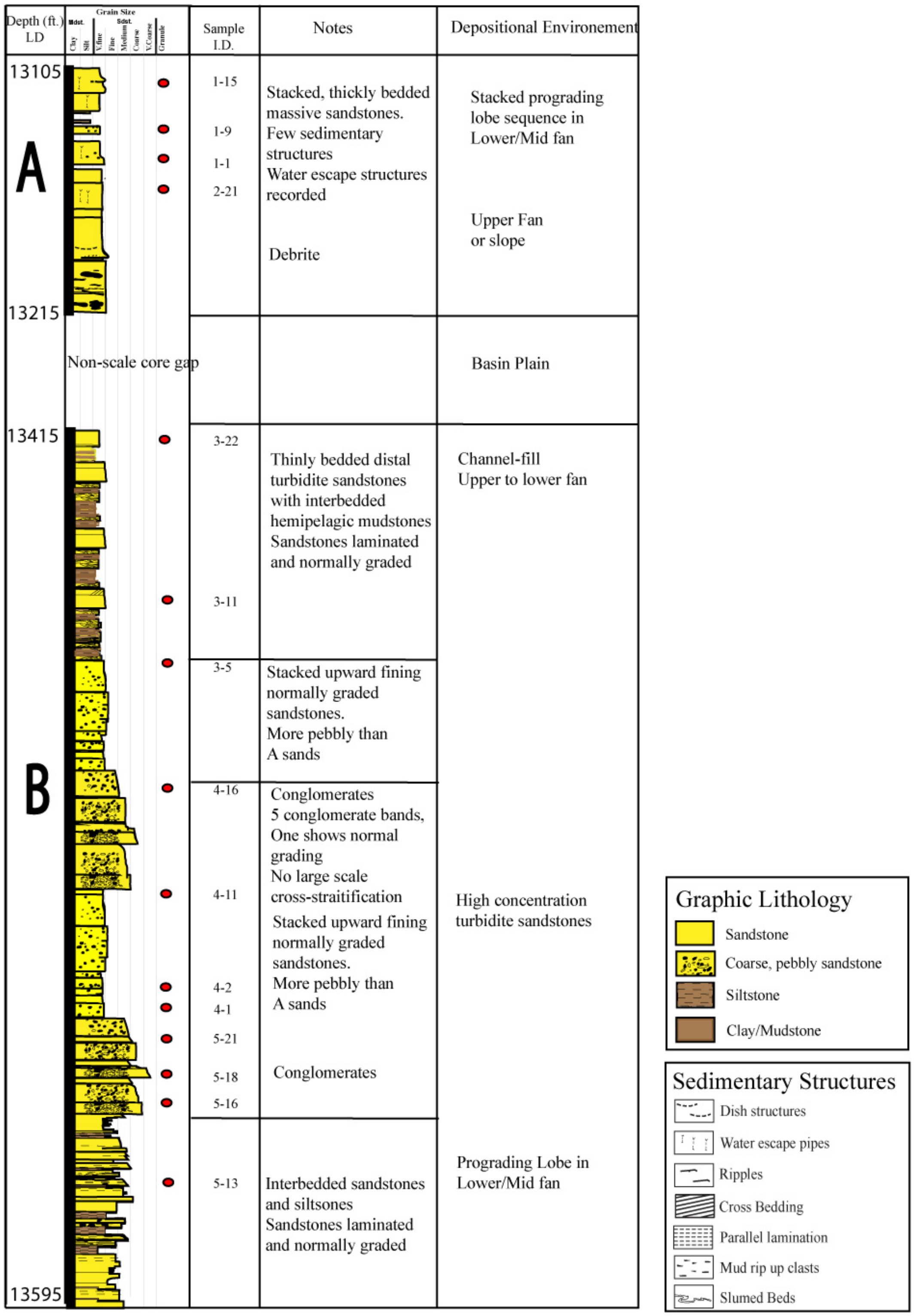

Figure 2 – Summary sedimentological log of well 35/8-2, based partly on a core description undertaken by Andreas Siemes. Samples for which the Pb composition of K-feldspar have been analysed are highlighted with red circles.

The sandbodies are separated by relatively thick mudstone-dominated intervals inferred to represent a basin plain setting. The former correspond to individual submarine fan lobes with the intervening mudstones reflecting a return to quiet basinal conditions suggesting repeated episodes of fan activity and abandonment (Robinson and Canham, 2001). Relatively high depositional gradients (indicated by the debris flow and channelised high-density turbidity current deposits), high ratios of sand to mud, the scale of the sequence development and the limited basin size all suggest an immature, actively-faulted basin margin setting. The overall fan morphology is uncertain as only a single well has penetrated the fan succession – the possibilities include a single point-sourced fan issuing from a slope canyon/channel or a laterally-coalescing fan apron with multiple sources active along the shelf break. Croker and Shannon (1987) suggest that a fan apron setting is the more likely. These Upper Jurassic sediments coincide with the last major phase of syn-rift faulting in the basin. A similar pattern of fan activity separated by fine grained facies have been identified in the South Viking Graben (North Sea) with the latter interpreted as tectonically-enhanced maximum flooding surfaces (Partington & Underhill, 1993).

2. Methodology

2.1 Sampling and Petrography

Provenance studies need to be underpinned by petrological investigations in order to establish the bulk sediment composition and to classify the sandstones being analysed. A total of 105 thin sections were prepared from cores 1-5, with 40 from cores 1-2 (A sandbody) and 65 from cores 3-5 (B sandbody). Standard optical petrography has been used to determine the nature of the framework grains. A subset of 15 samples was then selected for more detailed characterisation and Pb isotopic analysis; 4 samples from cores 1-2 and 11 from cores 3-5 (Table 3). Point counting of the framework grains (Table 1) was carried out according to the Gazzi-Dickinson method (Gazzi 1966; Dickinson 1970) with the K-feldspar being divided into different categories on the basis of internal texture and extent of alteration. K-feldspar grains were also characterised in terms of microstructure following Parsons et al. (2005) with the following categories distinguished: fractured, patch perthite, fine-film perthite, optically featureless and heavily dissolved K-feldspar grains. Grain percentages were quantified by counting 300 points in each thin section including porosity.

2.2 Laser Ablation - Multi Collector-Inductively Coupled Plasma Mass Spectrometry

The Pb isotopic composition of fine to medium sand-sized K-feldspar grains were analysed using LA-MC-ICPMS with Faraday collectors at the National Centre for Isotope Geochemistry, UCD, following the analytical techniques described in Tyrrell et al. (2009). Prior to analysis, grains were imaged using Backscattered-Electron Microscopy (BSE) so as to avoid intragrain heterogeneities during ablation as these might have compromised the Pb signal. Polished K-feldspar surfaces were ablated along predetermined 100-400 μm tracks, guided by the BSE imaging. In previous LA-MC-ICPMS Pb K-feldspar work (Tyrrell et al. 2007; Tyrrell et al. 2006) data could only be retrieved from grains larger than c. 300 μm long axis, but refinement of the technique has allowed for Pb analysis of very fine-grained sand (100 μm long axis). Analytical uncertainties (2δ $^{206}Pb/^{204}Pb$) are typically 0.1% for the Faraday configuration. ^{204}Pb, ^{206}Pb, ^{207}Pb and ^{208}Pb were measured. ^{202}Hg was also measured during analysis in order to correct for isobaric interference of ^{204}Hg on ^{204}Pb. Standard-sample bracketing, using NIST standard glass 612 ($^{206}Pb/^{204}Pb$ = 17.099) was carried out in order to monitor and correct for mass bias fractionation during analysis.

2.3 Mineral Liberation Analysis (MLA)

It is possible to overcome the limitations of point counting such as its semi-quantitative nature and the variable objectivity of different operators by comparing it with Mineral Liberation Analysis (MLA) on the same sample. Mineral identification and quantitative estimates of the type, proportions, sizes and shapes of all the grains in a sample have been acquired automatically using a SEM (Scanning Electron Microscope) equipped with an Energy Dispersive X-ray (EDX) spectrometer and Mineral Liberation Analysis software at the Microanalysis Facility SEM/MLA Laboratory, Memorial University, St. Johns, Newfoundland. The SEM can undertake image and feature analyses using the University of Queensland JK Tech Mineral Liberation Analysis acquisition and processing software. It is also equipped with a Roentec SDD EDX X-ray detector for acquiring elemental X-ray spectra with high efficiency. Six samples, three from the A sandbody (1-1, 1-15 & 2-21) and three from the B sandstones (3-22, 4-16 & 5-16) were analysed using MLA in order to acquire quantitative modal abundances and investigate the bulk mineralogy and petrography in more detail (Table 2). Automated EDX analysis of specific features in a sample requires there to be a consistent detectable difference in brightness of the feature in the image. By using the BSE detector, particles or phases with a different atomic/molecular weight to the background or bulk of the sample can be seen as either bright or dark features, and this can be used to specify to the system what features to detect and analyse (Gu 2003). Lithic fragments are identified as mixtures of compositions by creating a standard library of their EDX spectra. The EDX system can also produce X-ray maps of the surface to highlight differences in elemental or phase distribution in the field of view, and X-ray line scans. MLA is one of the few techniques that allows the retrieval of a detailed breakdown of the bulk mineralogy at the scale of a thin section sample, while retaining the grain context.

2.4 K-means Cluster Analysis

Cluster analysis creates groups or clusters of data in such a way that objects in the same cluster are very similar and objects in different clusters are distinct. K-means clustering is a partitioning method (Hartigan and Wong 1979; MacQueen, 1967). An iterative algorithm partitions data into k mutually exclusive clusters, and returns the index of the cluster to which it has assigned each observation. Operating on actual observations (rather than the larger set of dissimilarity measures used in hierarchical clustering), k-means creates a single level of clusters. This distinction means that k-means clustering is often more suitable than hierarchical clustering when dealing with large amounts of data. The numbers of clusters (k) is an input parameter and is identified by running the k-means with values of k between 1 and 25 until the optimal number of clusters is identified. The centroid for each cluster is the point to which the sum of distances from all data points in that cluster is minimised. K-means operates by identifying a grouping in which data points within each cluster are as close to each other as possible, and as far from data points in other clusters as possible. Each cluster in the partition is defined by its member data points and by its centroid. The algorithm minimises the Euclidean distances from each data point to its cluster centroid over all clusters. Observations are moved from one group to another iteratively, starting from an initial partition, until the sum cannot be decreased further. The result is a set of clusters that are as compact and well-separated as possible.

Clusters in this study possess positive intercluster and negative intracluster similarity values, such that data points within a cluster are very similar to each other and dissimilar to data points in different clusters. It is possible for ambiguity to exist over which cluster an observation belongs to when the distance to cluster centers is similar. The output for each observation can be inspected for such ambiguity. It is possible different sources may have overlapping compositions falling on linear arrays and in these cases cluster analysis would not be able to distinguish the contributing sources. However, in this study, the spread of Pb isotopic composition within potential sources is such that it is possible to identify and distinguish individual populations that are likely to represent discrete crustal elements. The clusters in this study appear to correspond to distinct crustal elements within 2 of the broad basement domains, Pb domain 2 and 3 (Fig. 5c & 5d).

3. Results

3.1 Petrography and MLA

The sampled sandstones are in general texturally immature and poorly sorted ranging from coarse- to fine-grained with grain shapes varying from angular to subangular. The majority, 9 of the 15 sub-samples selected for detailed analysis, plot within the subarkosic-arenite and arkosic fields on a QFL plot with the remaining 6 plotting in the lithic-sublithic arenite fields (Fig. 2d). Mean point-count values for the A sandstones are quartz (43.4%), K-feldspar (13.2%), plagioclase (1.7%), mica including chlorite (0.9%), cement (dominated by poikilotopic calcite and minor clays), lithics (1.7%, in order of abundance; metamorphic, volcanic and sedimentary lithic fragments), (6.7%), heavy minerals (0.08%), pyrite (5.2%), kaolinite (1.1%) with the remainder representing pore spaces (Fig. 4). The B sandstones consist of quartz (45.3%), K-feldspar (11.20%), plagioclase (2.4%), mica and chlorite (0.6%), cement (dominated by poikilotopic calcite and minor clays) (11.8%), lithics (8.0%, in order of abundance; volcanic, sedimentary and metamorphic lithic fragments), heavy minerals (0.1%), pyrite (1.2%) and kaolinite (4.8%) with the remainder representing pore spaces.

Mineral Liberation Analysis was also performed on six samples for the purposes of robust grain characterisation and for identifying and quantifying the heavy mineral fraction within the two sandbodies (Table 2). Detrital rutile is the predominant heavy mineral in the A sandstones with minor amounts of apatite, zircon, garnet and negligible amounts of other minerals. The results of the MLA indicate that the B sandstones are relatively plagioclase-rich (1.7 - 2.36%), and mica (0.9 – 0.6%) and K-feldspar poor. The B sandstones are lithic-rich (1 – 8%), and contain significantly more calcite cement (6.7 – 11.8%), more abundant heavy mineral fractions and significantly more kaolinite than the A sandstones (1.3 – 4.8%). The increased kaolinite in the B sandbody occurs predominantly in sand-sized patches and occasionally within partially dissolved K-feldspar grains. On a thin section scale the B sandstones are more garnet rich and rutile poor than the A sandstones. These distinctions support the overall hypotheses by Pugliese et al. (2009) that the A sandstones may have a different provenance to the B sands. In Figure 3 it can be seen that the conventional point count overestimated the total quartz abundance and underestimated the total feldspar content in comparison to the 3 corresponding MLA analyses. This may be a function of operator error.

There is a modest decrease in average K-feldspar content from the A (13.2%) to the B (11.18%) sandbodies. The K-feldspar was counted with three categories reflecting different degrees of alteration – heavily altered, mildly altered and fresh. The majority of the K-feldspar was counted in the mild alteration category in both the A and the B sandbodies. Optically visible microstructure shows no correlation with the Pb composition of the K-feldspar grains. The new Pb analyses confirm variations in the isotopic composition of K-feldspar are independent of grain size and shape.

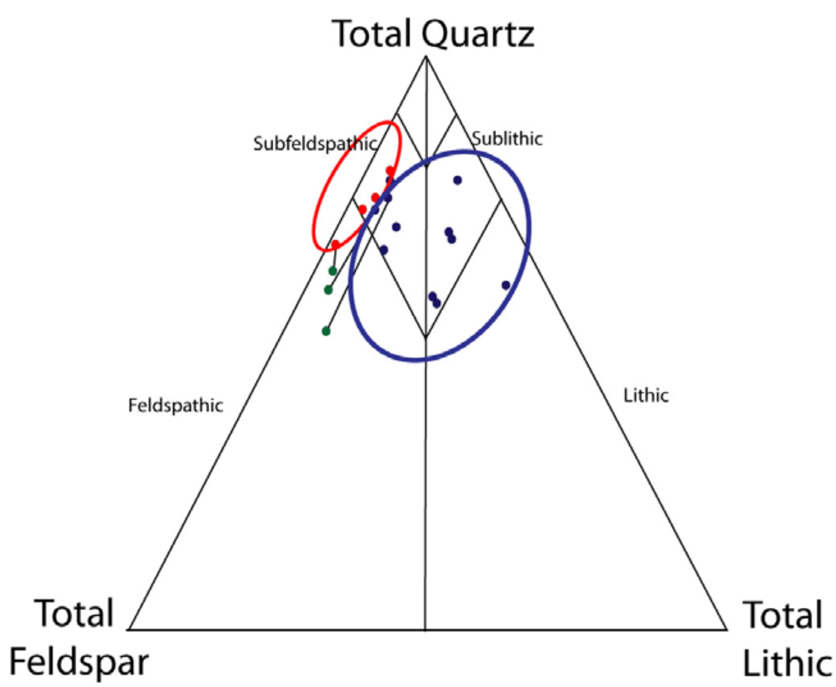

Figure 3: QFL diagram of 4 conventional point-counted samples from the A sandbody (red circles) and 11 point-counted samples from the B sandbody. Green circles represent the MLA composition for samples that were also point-counted and to which they are linked to by a black line.

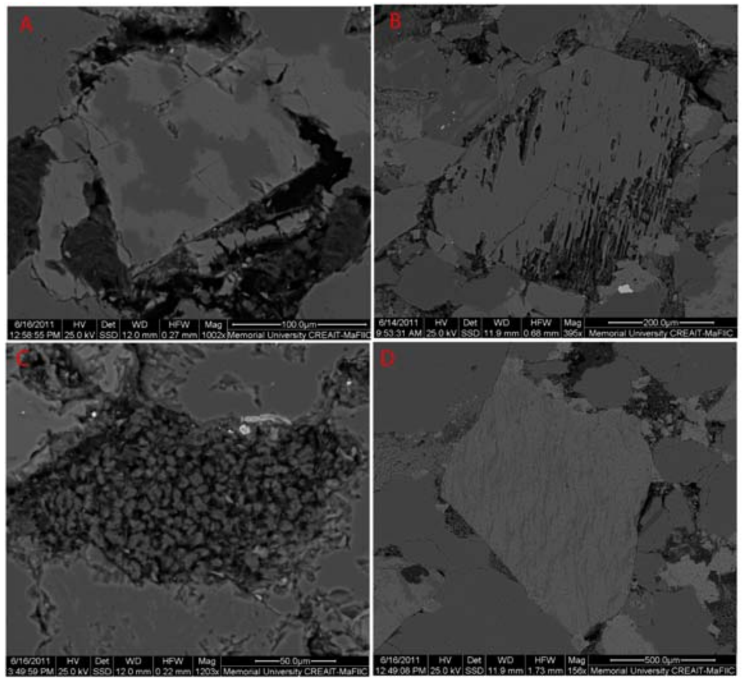

Figure 4: a) Patch perthite, sample 2-21, A sandstone, b) Fine film perthite with crystallographically controlled dissolution, sample 5-16, B sandstone, c) Kaolinite filling sand-sized patches, sample 5-16, B sandstone, and d) Fine film perthite. 5-16, B sandstone.

3.2 Common Pb isotopic analysis

New common Pb isotopic data for 334 K-feldspar grains from 15 samples have been acquired from Upper Jurassic sandstones in well 35/8-2 (Table 2). Obvious zones of alteration and inclusions identified by the SEM imaging were avoided during laser ablation. A total of 96 analysis were obtained from the A sandstone (cores 1 & 2) and 238 analysis from the B sandstones (cores 3, 4 and 5). Overall the K-feldspar composition is relatively radiogenic with $^{206}Pb/^{204}Pb$ values ranging from 15.76 – 18.80 (minus outliers; 3 K-feldspar grains with $^{206}Pb/^{204}Pb$ compositions in excess of 20). The radiogenic outliers may represent analyses that inadvertently sampled subsurface heterogeneities such as U, Th or Pb-rich inclusions that were not visible despite robust SEM characterization of the polished grain surfaces. K-means cluster analysis was applied to the Pb dataset, ignoring the outliers so as not to skew the clustering. Four clusters were optimally identified (Fig. 3b). The clusters are numbered 1-4 from the least radiogenic to the most radiogenic Pb composition and are considered to represent four distinct crustal sources. Cluster 1 comprises 107 K-feldspar analyses and is the dominant cluster in the dataset followed by Cluster 3 (95 analyses), Cluster 2 (89 analyses) and Cluster 4 (43 analyses).

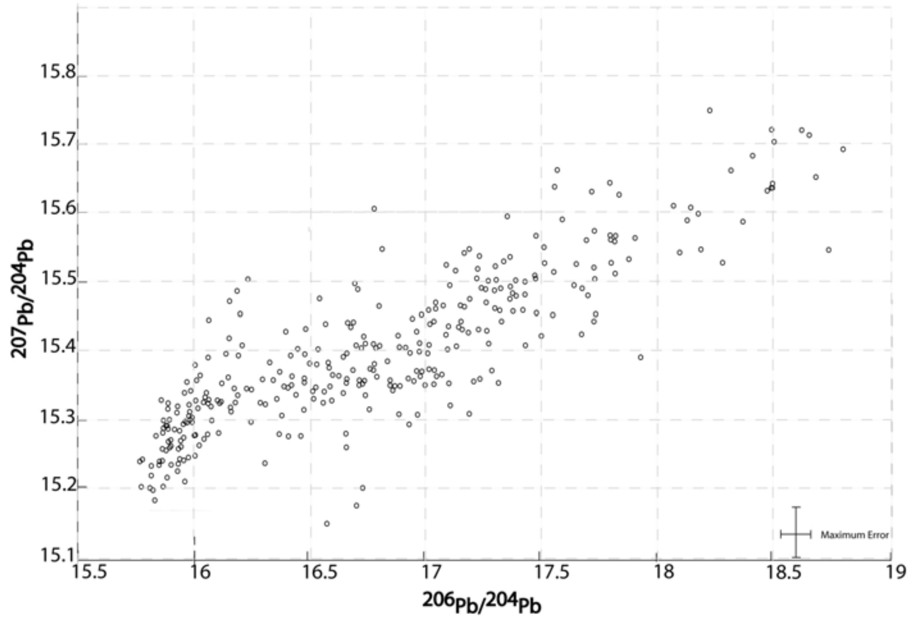

Figure 5: (a) 334 $^{206}Pb/^{204}Pb$ – $^{207}Pb/^{204}Pb$ isotopic analyses of fine and medium K-feldspar grains from well 35/8-2, northern Porcupine Basin.

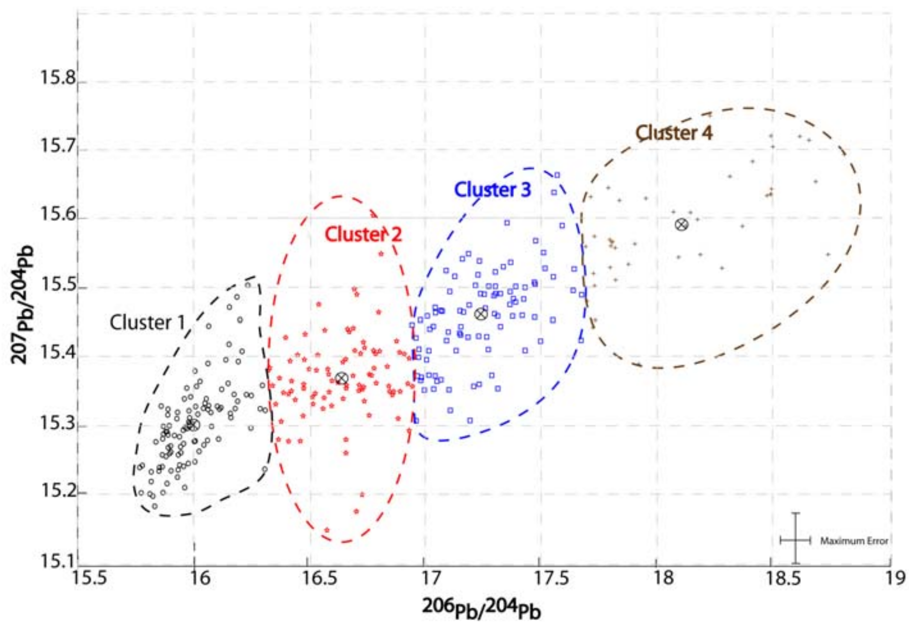

Figure 5: (b) K-means clustered $^{206}Pb/^{204}Pb$ – $^{207}Pb/^{204}Pb$ analysis from 334 detrital K-feldspar grains from well 35/8-2.

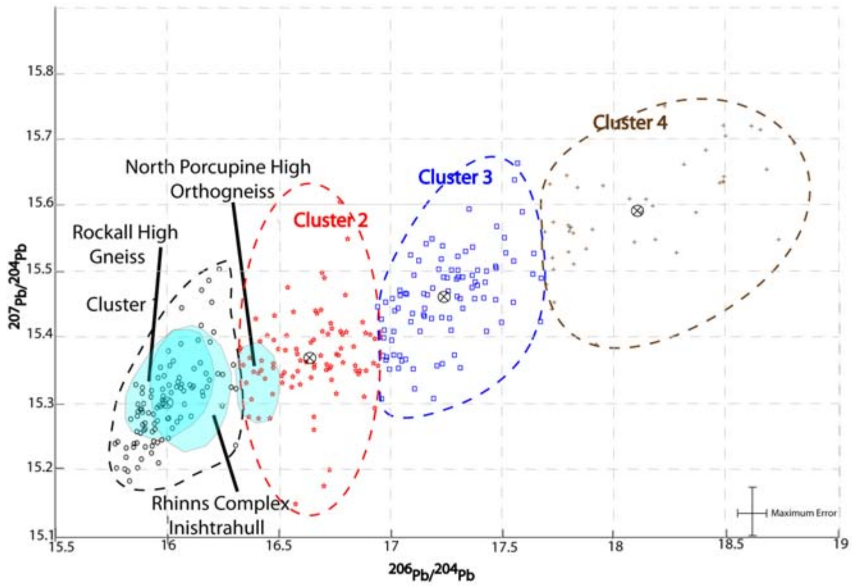

Figure 5: (c) K-means clustered $^{206}Pb/^{204}Pb$ – $^{207}Pb/^{204}Pb$ analysis from 334 detrital K-feldspar grains Pb data from well 35/8-2 plotted against offshore sources from Pb domain 2, Rockall High, North Porcupine High and the Rhinns Complex.

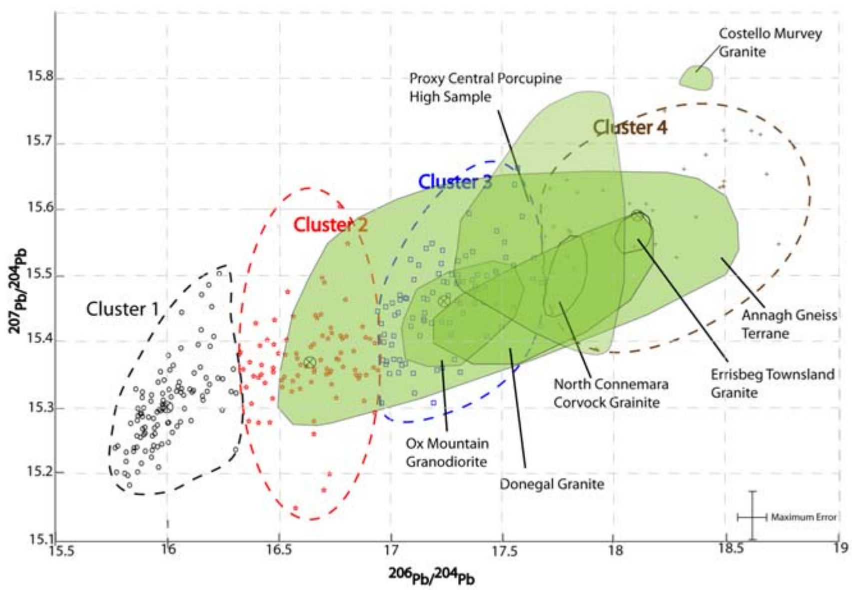

Figure 5: (d) K-means clustered $^{206}Pb/^{204}Pb$ – $^{207}Pb/^{204}Pb$ analysis from 334 detrital K-feldspar grains from well 35/8-2 plotted against offshore sources from Pb domain 3, north-western Ireland and a Cretaceous proxy sample for the Central Porcupine High, Tyrrell et al. (2007, Fig. 1b and references therein).

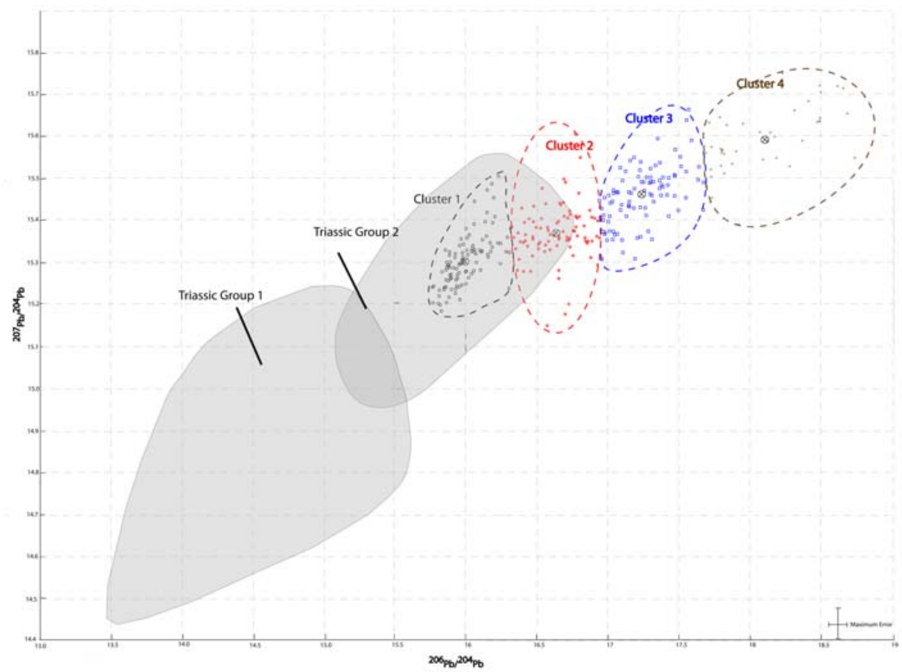

Figure 5: (e) K-means clustered ^{206}Pb/^{204}Pb – ^{207}Pb/^{204}Pb analysis from 334 detrital K-feldspar grains from well 35/8-2 plotted against Triassic data from the Slyne basin - Tyrrell et al. (2007, Fig. 1b and references therein).

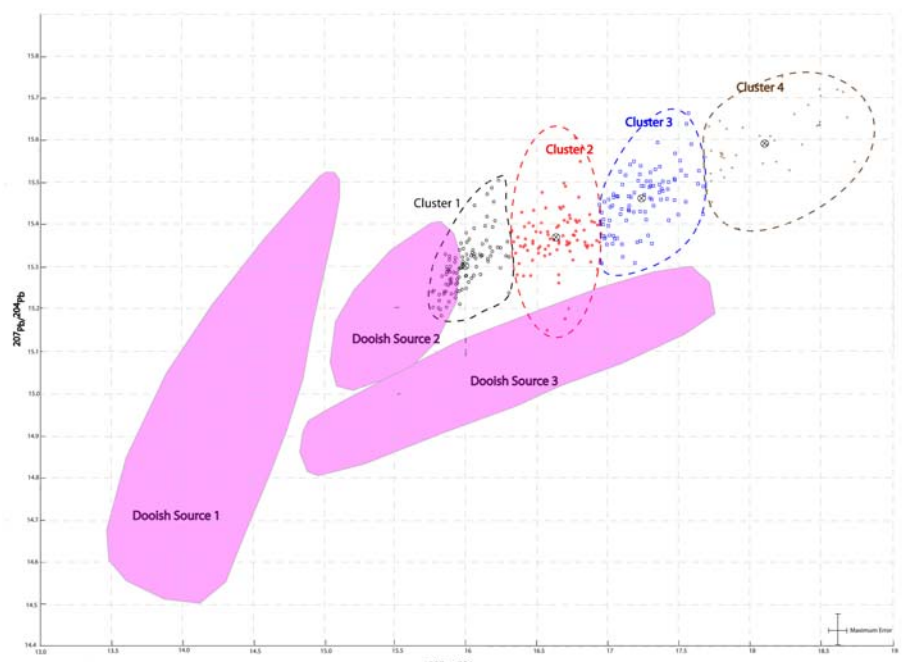

Figure 5: (f) K-means clustered ^{206}Pb/^{204}Pb – ^{207}Pb/^{204}Pb analysis from 334 detrital K-feldspar grains from well 35/8-2 plotted against data from presumed Permo/Triassic and Mid-Jurassic Dooish sandstones in well 12-2-1z on eastern margin of Rockall Basin (Tyrell et al. 2010).

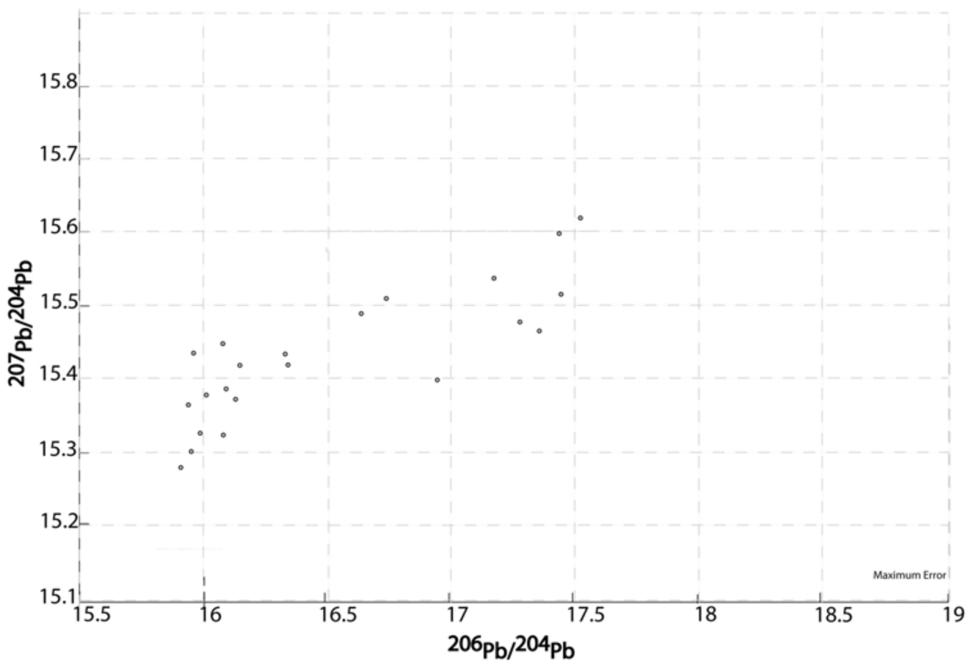

Figure 5: (g) Original pilot 25 $^{206}Pb/^{204}Pb$ – $^{207}Pb/^{204}Pb$ isotopic analyses of medium grained K-feldspar grains from well 35/8-2, northern Porcupine Basin, Tyrell et al. (2007).

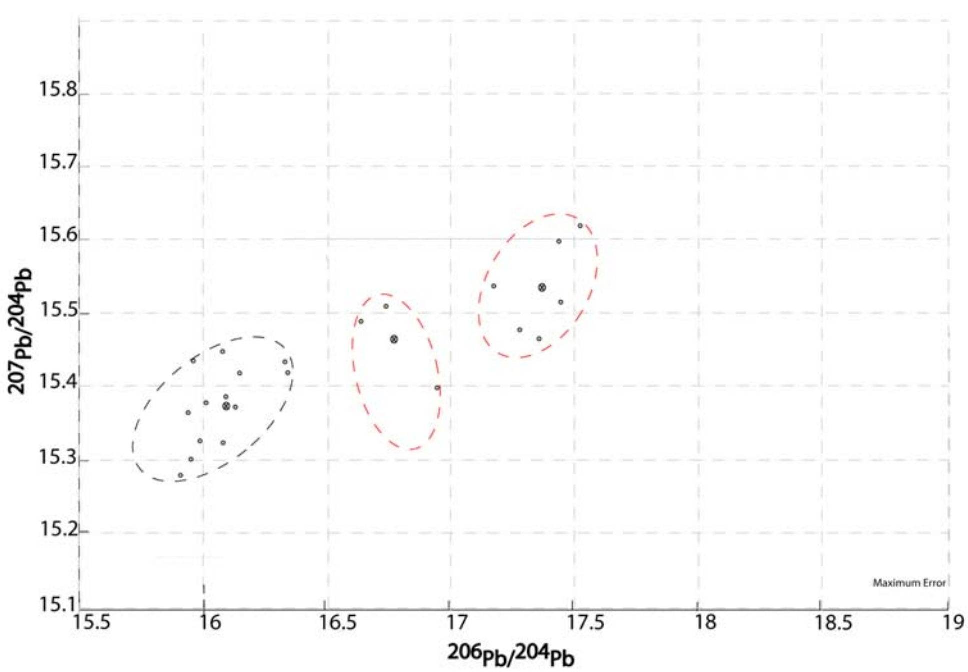

Figure 5: (h) K-means clustered $^{206}Pb/^{204}Pb$ – $^{207}Pb/^{204}Pb$ analysis from original pilot 25 detrital K-feldspar grains from well 35/8-2, northern Porcupine Basin, Tyrell et al. (2007).

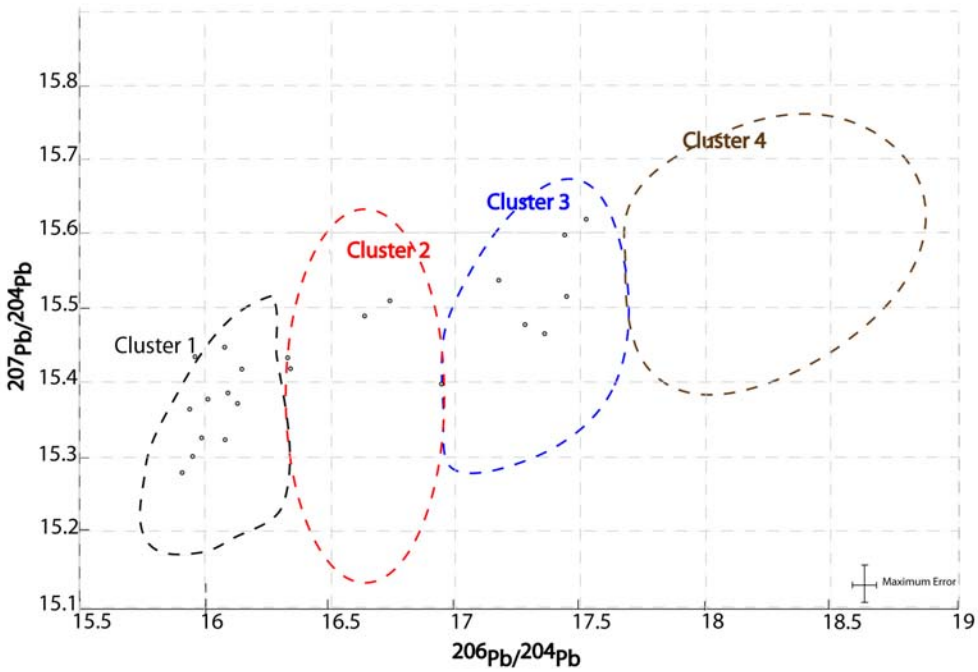

Figure 5: (i) K-means cluster outlines from the new Pb data arising from the present study overlain on analysis from original pilot work on 25 detrital K-feldspar grains from well 35/8-2, northern Porcupine Basin, Tyrrell et al. (2007).

In order to constrain potential source areas, the clusters have been compared to a database of Pb isotopic data from the broad North Atlantic region (Tyrrell et al. 2007). Basement sample locations are illustrated in Figure 1. In comparison to the pilot study, new groups have been identified by the higher resolution sampling (Fig. 5b). Clusters 2, 3 and 4 show an affinity with Pb domain 3 whereas Cluster 1 overlaps with Pb domain 2. Comparing each cluster with offshore sampled basement units from the database (Fig. 5c), Cluster 1 is shown to correspond well with the Palaeoproterozoic Rockall High (67 out of 107 analysis) and the Rhinns Complex exposed on Inishtrahull, NW Ireland (50 out of 107 analysis), although the sandstones may have been ultimately sourced from along strike equivalents of these units. Note that the field for the Rhinns Complex is based on just 4 analyses. It does not appear to correspond as well with Cluster 1 as the Rockall High data. The North Porcupine High analyses plot on the margin of Cluster 2 but the Pb composition of this block is only loosely constrained and may broaden with additional sampling. Cluster 4 shares an affinity with the basement rocks on the Central Porcupine

High as defined by a proxy sample on the eastern Rockall Basin margin in borehole 16/28-sb01 (Fig. 1, Haughton et al. 2005). The sedimentology of the sands and the Pb isotopic composition of the K-feldspar component in this borehole suggest they are locally derived directly from the Central Porcupine High. Clusters 2, 3 and 4 all share an affinity with potential northwest onshore Ireland Pb sources (Fig. 5d) highlighting, in addition to the north-south drainage axis identified in previous studies (Tyrrell et al. 2007), potential transverse input from the basin flanks. It should be noted that geographically different sources may have a shared basement history and thus have the same Pb composition. The poorly constrained offshore basement highs to the west of Ireland may share similar Pb compositions to the onshore NW Ireland Massif. Therefore sediment may have been delivered from hinterland drainage basins lying to the N, NE or NW of the basin.

Five stratigraphic intervals have been selected and the Pb data from all the samples in each interval have been summed and illustrated as pie-charts in Figure 6. These summary charts illustrate the provenance evolution throughout the stratigraphic interval cored in 35/8-2. At the base of the core in the B sandstones (Fig. 6), Cluster 1 (inferred Rockall High/Rhinns Complex-type source area) is the principal signal. Upward through the succession, Cluster 1 becomes progressively less dominant such that in the A sandstones, it no longer represents the principal signal. There is an overall concomitant increase in the contribution delivered from Clusters 2, 3 and 4 (North Porcupine High and northwest onshore Ireland type source areas) to the point that the latter represents the principal signal in the A sandstones. In all but one of the samples (5-13), all source groupings are represented suggesting that the sands were generally very well mixed at small scale.

Tyrrell et al. (2007) demonstrated that ~25 Upper Jurassic K-feldspar grains from well 35/8-2 cannot have been recycled from lower Triassic sandstones from the nearby Slyne basin. The new much larger dataset from this study have been compared with the Triassic data (Fig. 5e) and again these display very poor correspondence. There is some overlap with the Group 2 Triassic data suggesting that the Rockall High or Rhinns Complex source areas, or their respective along strike equivalents; may have contributed to both the Jurassic and the Triassic strata. There is, however, no evidence that the Triassic K-feldspar was recycled into the Upper Jurassic as it would not be possible to selectively sample Group 2 K-feldspar grains and exclude Group 1 grains. In an investigation into presumed Permo/Triassic and Mid-Late Jurassic sandstones (Dooish sandstones) on the eastern margin of the Rockall Basin, Tyrrell et al. (2010) identified three sources (Fig. 5f). There is also no correspondence between these Dooish source signatures and the detrital Pb data from the northern Porcupine Basin.

The original pilot Pb dataset can be seen in Figure 5(g). K-means cluster analysis defines 3 clusters within this dataset (Fig. 5h). In Figure 5(i) the outlines for the clusters defined in the present study are overlain on the pilot data and the clusters correspond very well. Cluster 4 is not represented in the original pilot dataset. This may be expected as Cluster 4 contains the smallest number of samples.

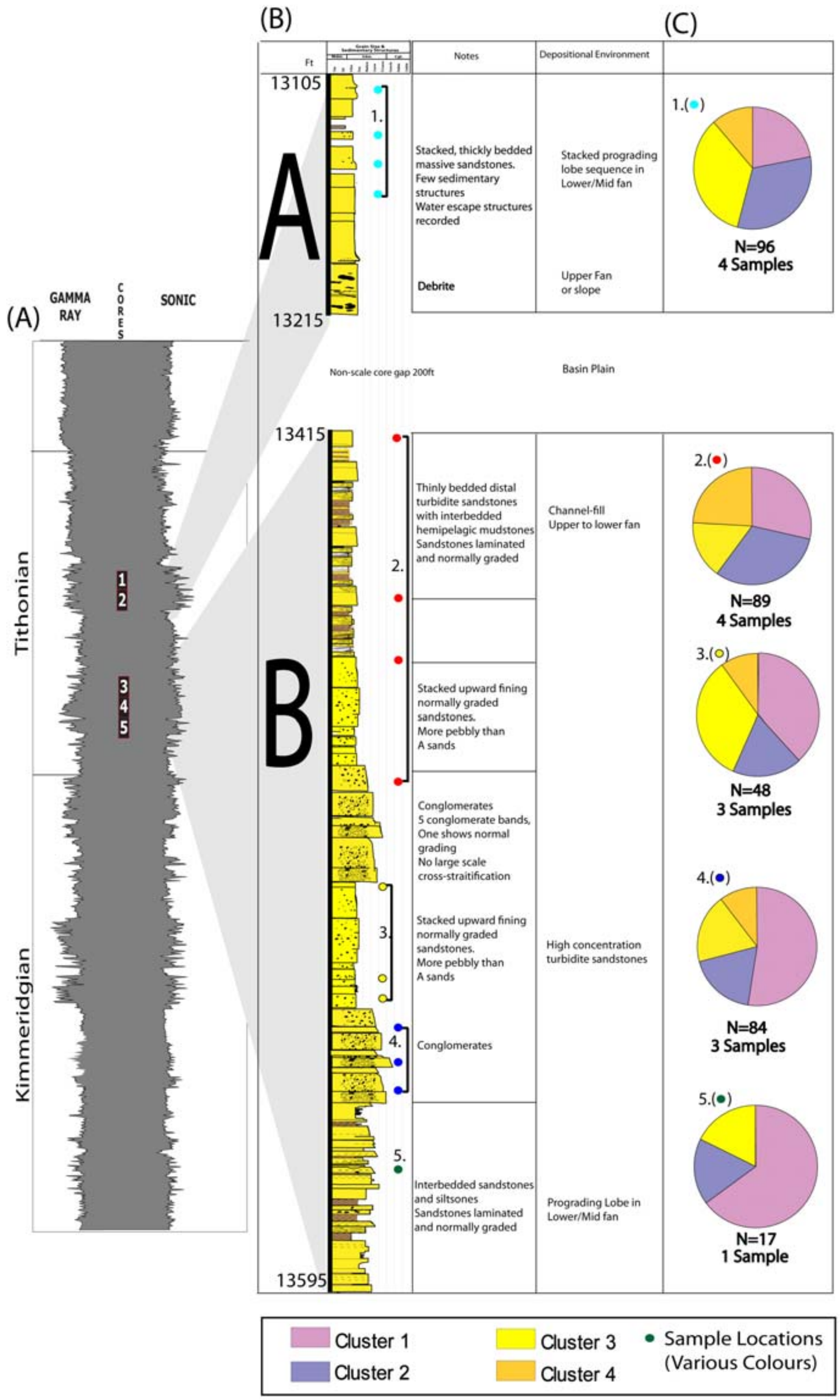

Figure 6: Illustration showing from left to right (a) wireline logs and simplified log of well 35/8-2 with (b) summary sedimentological log with stratigraphic intervals and sample positions highlighted and (c) summary pie-charts of proportions of grains belonging to different clusters for successive stratigraphic intervals.

4. Discussion

The new Pb isotopic data indicate that detrital K-feldspar in Upper Jurassic sandstones in well 35/8-2 in the northern Porcupine Basin were likely derived from a drainage system with three main catchment areas: (a) the Rockall High or Rhinns Complex (or their along strike equivalents = Cluster 1), (b) Central Porcupine High (or its along strike equivalent = Clusters 3 & 4) to and (c) the North Porcupine High (or its along strike equivalent = Cluster 2) to the N and rock types similar to (but possibly the offshore equivalent of) those found onshore in NW Ireland (Clusters 2, 3 & 4) to the NE from Pb domain 3 affinity. All of these sources could have been derived with transport distances of up to ~250 km implying small to modest scale hinterland drainage basins. The evidence for well mixed sand compositions at the scale of a thin section implies either efficient tributary mixing or homogenisation of sand in shelf settings. The limited Pb data from fluvial sands in the Connemara Prospect imply the mixing may have taken place within the hinterland drainage system. Significantly, the larger Pb dataset demonstrates that there is no far-traveled sand from the Archaean to the north or sand from the Variscides to the south in the 35/8-2 sandstones confirming the source areas were relatively proximal to the basin. This is consistent with the petrographical investigation with the samples commonly displaying textural immaturity with poor sorting ranging in size from fine-gravel-coarse sand and relatively angular grains. The provenance signal varies with depth through the cored sandstones over a vertical interval of 138 m. The different provenance signal in the A and B sandstones may be a controlling factor in the contrasting reservoir quality of these sands. The increased kaolinite in the B sandstones may negatively influence reservoir quality by reducing permeability.

Cluster 1 dominates the lower B sands suggesting possible input of Rockall High or Rhinns Complex type source areas (Fig. 5c). A Rockall High type source would imply relatively long transport across the nascent Rockall Basin into the Porcupine Basin. This would require that the Rockall Basin was not a significant bathymetric feature or sediment sink at the time. The nature of Jurassic deposition within the Rockall Basin is speculative although it has been suggested that Jurassic rocks may be widespread in the basin (Naylor & Shannon, 2005). Middle and Upper Jurassic strata have been interpreted from seismic data within the small perched basins along both margins of the Rockall Basin (Naylor et al. 1999) and Haughton et al. (2005) also confirmed the presence of Upper Jurassic strata in the North Bróna Basin and possibly in the South Bróna Basin, on the western flank of the Porcupine High. It is therefore easier to relate Cluster 1 to a Rhinns Complex-type source area that extended westwards towards the Porcupine area from where it has been characterised on Inishtrahull (Fig. 1). The overall textural immaturity of the sandstones in well 35/8-2 supports local sourcing.

In contrast, the Irish Massif and North Porcupine High signals dominate the younger A sandstones. This suggests that over time, less sand was delivered from Cluster 1 sources, suggesting a changing palaeodrainage pattern/source contributions. For a Rhinns Complex-type source area for Cluster 1, this reduction in sediment supply may represent a shortening of the drainage axis or increasing contributions from more proximal uplifts of the Cluster 2, 3 and 4 sources. In both cases sand was still delivered from the Cluster 1 source, as there is still an, albeit much reduced, signal from Cluster 1 in the A sandstone. Rifting activity in the hinterland may have led to rearrangement of the drainage system.

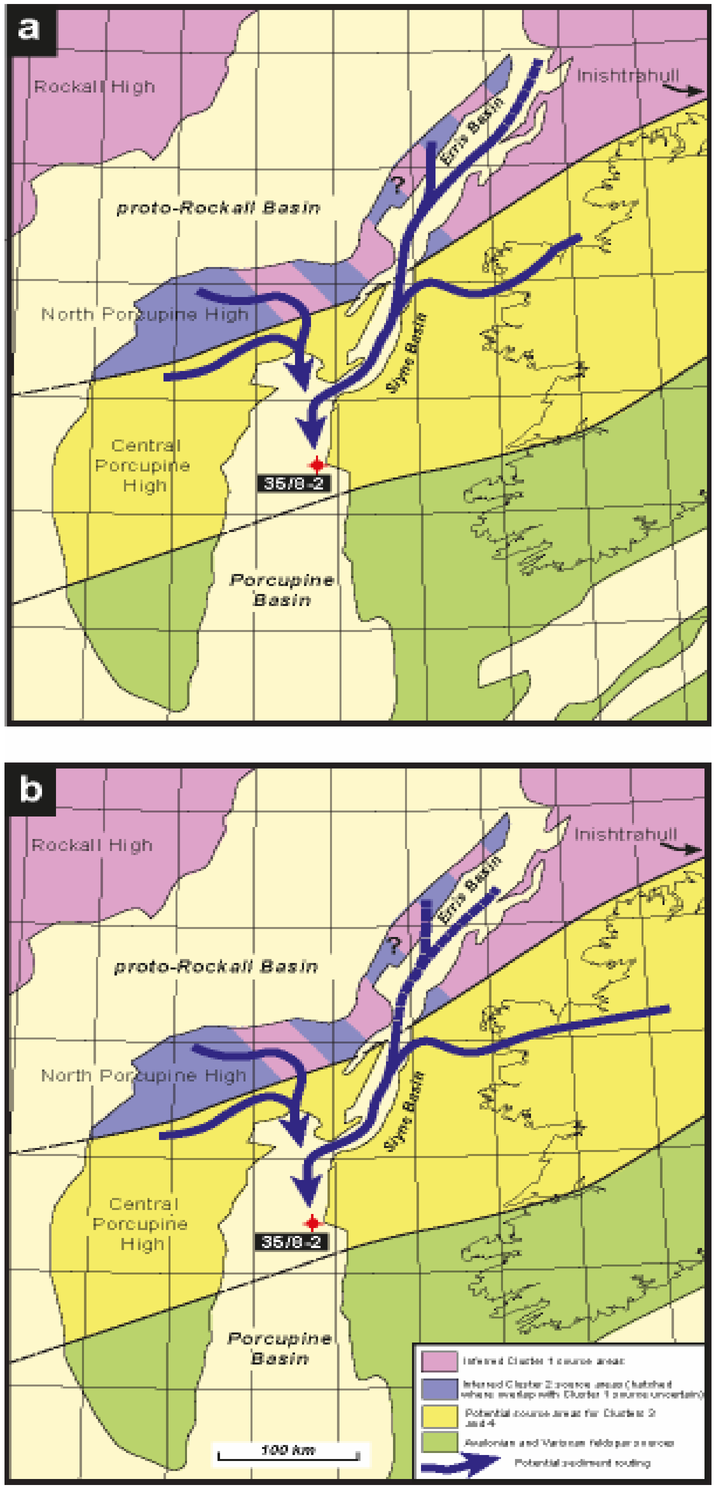

Figure 7: Preliminary palaeogeographic reconstruction and sediment transport paths (arrows) during deposition of (a) the B sandstones and (b) the A sandstones in well 35/8-2. The land masses are colour coded to reflect their bulk Pb signatures (in terms of cluster assignation). Palaeoposition of Rockall High nominally adjusted.

Hinterland palaeogeographic reconstructions for A and B sandstone deposition for well 35/8-2 and the position of likely source areas and drainage routing are shown in Fig. 7.

The B sandstones were likely derived from either the Rhinns Complex and Central Porcupine High source areas, with input from the NW-Irish Massif and from the North Porcupine High with maximum drainage lengths of ~250 km. More local sourcing is suggested for the upper A sandstones. In the Upper Jurassic it appears that relatively local sand sourcing dominated in the northern Porcupine basin.

5. Fulmar Formation

Project IS06/19 is also investigating extensively cored reservoir sandstones in the Upper Jurassic Fulmar Formation in the Central North Sea in order to (1) further develop the Pb-in-K-feldspar tool, (2) better understand potential limitations of the technique and (3) inform parallel Pb studies in the Irish offshore basins. The Fulmar Formation contains significant K-feldspar which some consider to have been recycled from local Triassic sedimentary rocks (Johnson et al., 1986, Wilkinson et al., 2001) but this remains unproven. In contrast to reservoir sandstones in the Porcupine Basin, the Fulmar can be sampled across a wide range of burial depths and it has thus undergone variable degrees of diagenetic modification. The Fulmar Formation comprises a thick succession of highly bioturbated shallow marine arkosic sandstones buried to current depths of 3.2 to 5.4 km. K-feldspar abundance has been shown to systematically decrease with increasing depth (Wilkinson et al., 1996) and more extensive burial diagenesis (principally feldspar dissolution) is thought to be the controlling factor (Wilkinson et al., 1996), although others have suggested that the evidence presented is ambiguous (Oxtoby & Gluyas, 1996).

The IS06/19 study is utilising the Pb-in-K-feldspar tool in sandstones drawn from a range of depths across the Central Graben area in order to investigate whether: 1) feldspar abundance is a function of changing provenance in this system; 2) the Pb isotopic composition of the detrital grains is compromised by burial diagenesis effects and if so to what extent this is predictable; and 3) whether the K-feldspar has been recycled from older sedimentary rocks as opposed to being first cycle. This research will have significant implications for applying the Pb tool to basins along the North Atlantic margin offshore Ireland, allowing for a detailed understanding of the effects of burial diagenesis on Pb signatures and the potential for grain recycling. It is possible that burial diagenesis may completely purge one or more populations of grains due preferential dissolution of chemically unstable K-feldspar grains with abundant microstructural defects. Parsons et al. (2003) have suggested that dissolution in the Fulmar Formation is strongly sensitive to mineral texture, implying that provenance exerts a strong control on the rate of development of secondary porosity and hence on reservoir quality. This study will investigate possible links between Pb composition and the microstructure in K-feldspar.

6. Interim Conclusions and Future Work

- New densely sampled Pb data (334 grains from 15 samples) from Upper Jurassic sandstones in well 35/8-2 in the Porcupine Basin have identified four Pb isotopic groupings which have been defined with the help of k-means cluster analysis. The four groupings are mixed on a thin section scale and occur independently of stratigraphic position although the proportions of grains derived from each of the groups do vary. The new data identifying contributions from sources at a higher resolution to the pilot work on this well which involved data from only 25 grains.
- The data implicate a small- to modest-scale hinterland drainage system (up to a maximum of 250 km long) in delivering sand to deep-water depocentres in the northern Porcupine Basin. There were three main sediment catchment areas: (a) the Rockall High (less likely) or Rhinns Complex (or possible along strike equivalents = Cluster 1), (b) the North Porcupine High (and/or its along strike equivalent = Cluster 2) and (c) the Central Porcupine High (and/or its along strike equivalent found onshore in NW Ireland = clusters 3 and 4).
- The proportion of K-feldspar grains from different source areas changed through time although all sources persisted through at least two phases of deep-water fan activity. Although the sand-input was pulsed, the change in sand composition appears to be more gradual. Cluster 1 dominates the lower B sandbody suggesting important early input from Rockall High or Rhinns Complex type source areas but probably not the Rockall High itself (on the grounds that the intervening Rockall Basin was probably already a sink at this time). In contrast, Clusters 2, 3 and 4

- The greatly enlarged Pb dataset appears to rule out recycling of K-feldspar (and by implication other framework components) from Triassic sandstones in the Slyne Basin. Areas that subsided in the Triassic must have remained low lying in the Upper Jurassic. The contrasting Pb isotopic populations in Triassic and Upper Jurassic sandstones may be useful in distinguishing barren sandstones of uncertain affinity in other wells.

Future Work Program:

Next 12 months.

- In depth investigation into the MLA technique in respect to comparison with traditional point counting, identification of heavy mineral suites and comparison between provenance signal and K-feldspar microtextures.
- Analysis of additional mid-level and deeply buried samples from the Fulmar Formation to build on initial data from this system. Integration of MLA analyses and conventional petrographical constraints on grain composition and diagenetic overprinting for a subset of the Fulmar samples.
- Interpretation of Fulmar Pb isotopic data, focussing on the role of diagenesis, the likelihood of first-cycle vs. recycled sources and possible spatial and stratigraphic provenance variations. The results of this will be used to inform parallel studies in the offshore Ireland basins.
- Preparation of manuscripts describing the results of both the Fulmar Formation and Porcupine studies and their integration with the MLA investigation in a PhD thesis.

Table 1 - Point count Data from A and B sandstones from well 35/8-2

	A Sand					B Sand										
	1-15	1.9	1-1	2-21	Average	3-22	3-11	3-5	4-16	4-11	4-2	5-18	5-16	5-13	5-21	Average
Depth (m)	3996.39	4001.27	4008.13	4009.55		4089.33	4099.21	4103.98	4111.07	4115.87	4124.99	4129.15	4130.85	4133.62	4126.92	
1. Quartz	**37.60%**	**45.60%**	**49.00%**	**53.30%**	**46.38%**	**53.60%**	**43.00%**	**57.00%**	**32.30%**	**45.00%**	**50.00%**	**37.30%**	**49.30%**	**49.30%**	**36.60%**	**45.34%**
Monocrystalline Unstrained	2.60%	88.00%	2.00%	43.00%	33.90%	7.50%	1.50%	11.00%	69.00%	7.00%	2.00%	14.00%	17.00%	5.00%	16.00%	15.00%
Monocrystalline Strained	87.60%	4.00%	83.00%	52.00%	56.65%	87.00%	79.00%	84.00%	8.50%	85.00%	72.00%	63.00%	59.00%	51.00%	38.00%	62.65%
Polycrystalline	9.70%	8.00%	15.00%	5.00%	9.43%	5.00%	19.00%	5.00%	22.00%	8.00%	26.00%	22.00%	23.00%	44.00%	45.00%	21.90%
2. Plagioclase	**1.00%**	**2.00%**	**0.60%**	**3.30%**	**1.73%**	**2.00%**	**3.60%**	**5.60%**	**2.00%**	**1.00%**	**0.60%**	**2.60%**	**2.30%**	**3.30%**	**0.60%**	**2.36%**
Heavy Alteration				10.00%	10.00%	34.00%	18.00%	24.00%	17.00%		100.00%	50.00%	17.00%	70.00%		**41.25%**
Mild Alteration	33.30%	100.00%	50.00%	60.00%	60.83%	50.00%	45.00%	30.00%	17.00%	100.00%		50.00%	60.00%	20.00%	100.00%	**52.44%**
Fresh	66.60%		50.00%	30.00%	48.87%	16.00%	37.00%	23.00%	66.00%				23.00%	10.00%		**29.17%**
Perthite								23.00%								
3. Orthoclase	**10.30%**	**11.00%**	**8.30%**	**21.00%**	**12.65%**	**11.00%**	**19.30%**	**6.00%**	**9.30%**	**7.00%**	**13.30%**	**10.00%**	**12.60%**	**7.00%**	**13.30%**	**10.88%**
Heavy Alteration				11.00%	11.00%	12.00%	5.00%	56.00%			25.00%	23.00%	19.00%	19.00%	7.50%	**20.81%**
Mild Alteration	84.00%	85.00%	72.00%	59.00%	75.00%	54.00%	83.00%	33.00%	86.00%	62.00%	55.00%	57.00%	68.00%	43.00%	57.50%	**59.85%**
Fresh	13.00%	15.00%	28.00%	25.00%	20.25%	12.00%	3.00%		11.00%	5.00%	17.50%	7.00%	0.00%	10.00%	25.00%	**10.06%**
Perthite	3.00%			5.00%	4.00%	22.00%	8.00%	11.00%	3.00%	33.00%	2.50%	13.00%	13.00%	28.00%	10.00%	**14.35%**
4. Microcline	**0.30%**	**0.30%**	**1.00%**	**0.60%**	**0.55%**	**0.60%**	**0.30%**	**0.30%**	**0.00%**	**0.60%**	**0.30%**	**0.00%**	**0.00%**	**0.30%**	**0.60%**	**0.30%**
Heavy Alteration	100.00%				100.00%						100.00%					100.00%
Mild Alteration		100.00%	33.30%	50.00%	61.10%		100.00%							100.00%		100.00%
Fresh			66.60%	50.00%	58.30%	100.00%		100.00%		100.00%					100.00%	100.00%
Perthite																
Total Feldpsar	**11.60%**	**13.30%**	**9.90%**	**24.90%**	**14.93%**	**13.60%**	**23.20%**	**11.90%**	**11.30%**	**8.60%**	**14.20%**	**12.60%**	**14.90%**	**10.60%**	**14.50%**	**13.54%**
5. Mica	**1.60%**	**0.00%**	**0.60%**	**1.60%**	**0.95%**	**1.60%**	**1.60%**	**1.00%**	**0.60%**	**0.00%**	**0.60%**	**0.60%**	**0.00%**	**0.00%**	**0.00%**	**0.60%**
Muscovite	100.00%		100.00%	60.00%	86.67%	40.00%	75.00%	67.00%	100.00%		50.00%		50.00%			63.67%
Chlorite				40.00%	40.00%	60.00%	25.00%	33.00%			50.00%		50.00%			43.60%
6. Calcite	**0.00%**	**18.30%**	**8.60%**	**0.00%**	**6.73%**	**12.60%**	**8.30%**	**3.30%**	**0.00%**	**22.30%**	**6.30%**	**3.30%**	**12.30%**	**21.30%**	**28.60%**	**11.83%**
Poik		82.00%	96.00%		89.00%	71.00%					95.00%	90.00%	95.00%		95.00%	89.20%
Non-Poik		18.00%	4.00%		11.00%	29.00%	100.00%	100.00%		100.00%	5.00%	10.00%	5.00%	100.00%	5.00%	50.44%
Dolomit																
7. Heavy Minerals	**0.00%**	**0.00%**	**0.00%**	**0.30%**	**0.08%**	**0.30%**	**0.00%**	**0.00%**	**0.30%**	**0.60%**	**0.00%**	**0.00%**	**0.00%**	**0.30%**	**0.00%**	**0.15%**
Zircon				100.00%					100.00%	50.00%				100.00%		83.33%
Apatite						100.00%				50.00%						75.00%
8. Kaolinite	**2.00%**	**0.00%**	**1.30%**	**1.30%**	**1.15%**	**6.00%**	**10.30%**	**6.00%**	**2.30%**	**6.60%**	**10.00%**	**0.00%**	**1.30%**	**3.60%**	**1.60%**	**4.77%**
Vermicular Booklets	100.00%		100.00%	100.00%	100.00%	100.00%	100.00%	89.00%	100.00%	100.00%	95.00%		100.00%	100.00%	100.00%	98.22%
After Mica								11.00%			5.00%					8.00%
9. Detrital Clay	**11.30%**	**0.00%**	**0.00%**	**3.60%**	**3.73%**	**3.30%**	**0.30%**	**10.00%**	**40.60%**	**0.60%**	**1.60%**	**25.30%**	**0.00%**	**0.00%**	**0.00%**	**8.17%**
Non-illitised	100.00%			42.00%	71.00%	100.00%	100.00%	93.00%	1.00%	100.00%	80.00%	100.00%				82.00%
Illitised				58.00%	58.00%			7.00%	99.00%		20.00%					42.00%
10. Pyrite	**14.00%**	**0.60%**	**0.60%**	**5.60%**	**5.20%**	**3.30%**	**1.30%**	**2.60%**	**3.60%**	**1.30%**	**1.00%**	**3.60%**	**1.30%**	**1.00%**	**0.00%**	**1.90%**
11. Porosity	**20.30%**	**19.60%**	**27.30%**	**8.00%**	**18.80%**	**1.00%**	**6.60%**	**3.60%**	**3.60%**	**2.30%**	**8.30%**	**2.00%**	**17.30%**	**4.60%**	**3.60%**	**5.29%**
12. Lithics	**1.30%**	**2.30%**	**2.30%**	**1.00%**	**1.73%**	**4.30%**	**5.00%**	**4.30%**	**5.00%**	**12.30%**	**7.60%**	**15.00%**	**3.30%**	**9.00%**	**14.60%**	**8.04%**
Volcanic			57.00%		57.00%	77.00%	40.00%	31.00%	40.00%	56.00%	30.00%	23.00%	50.00%	52.00%	41.00%	44.00%
Sedimentary	25.00%	85.00%	28.00%		46.00%		40.00%	15.00%	47.00%		26.00%	22.00%	30.00%	41.00%	43.00%	33.00%
Metamorphic	75.00%	15.00%		100.00%	63.33%	23.00%	20.00%	54.00%	13.00%	44.00%	44.00%	55.00%	20.00%	7.00%	16.00%	29.60%

Table 2 – Average Heavy Mineral % in A and B sandstones

Heavy Mineral	A Sandstones average % (3 samples)	B sandstones average % (3 samples)
Ilmenite	0.08	0.02
Rutile	0.39	0.22
Magnetite	0.01	0.01
Sphalerite	0.01	0.00
Apatite	0.04	0.07
Zircon	0.05	0.04
Barite	0.05	0.04
Gt-Almandine	0.02	0.07
Gt-Almandine (Mg)	0.04	0.10

Table 3 – Sample IDs and depths.

Sample ID	Core	Sandbody	Depth (ft) LD
1-1	1	A	13150.67
1-9	1	A	13128.17
1-15	1	A	13112.17
2-21	2	A	13155.33
3-5	3	B	13465.17
3-11	3	B	13449.50
3-22	3	B	13417.08
4-1	4	B	13534.08
4-2	4	B	13530.08
4-11	4	B	13504.17
4-16	4	B	13488.42
5-13	5	B	13562.42
5-16	5	B	13553.33
5-18	5	B	13547.75
5-21	5	B	13540.42

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8. Presentation Abstracts

Oral Abstract - Atlantic Ireland 2010 Conference

Pb isotopic composition of feldspars from Upper Jurassic sandstones in the northern Porcupine and North Sea basins

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Provenance studies help in constraining palaeogeography and sediment dispersal to ancient basins and can have important implications for the distribution and quality of potential hydrocarbon reservoirs. The Pb isotopic composition of detrital K-feldspar has proved to be an important indicator of provenance, particularly when reconstructing regional palaeodrainage. There are significant issues in Jurassic-Cretaceous basins west of Ireland in relation to sand-entry points, routing within and between the basins, sand-source areas and palaeogeography. The Mesozoic plate configuration, links between the conjugate Atlantic margins and the regional tectonostratigraphy are also key to future exploration in the Irish offshore.

A pilot Pb isotopic study (conducted in 2006) of Porcupine detrital K-feldspar grains highlighted a bimodal distribution and suggested that the Upper Jurassic reservoir sandstones were sourced from the north from the uplifted North Porcupine High (mainly Proterozoic basement rocks). This implied hinterland drainage extending a maximum of 200 km northwards and that the non-marine and deep-marine sandstones in the northern Porcupine may have lain on the same north-south dispersal path. A more detailed provenance analysis at a greatly increased resolution (including the analysis of the fine grain fraction for the first time) is currently being undertaken, initially focussing on well 35/8-2. The aim is to investigate how robust the bimodal signal is across a wider stratigraphic interval and in different facies. A parallel study of Jurassic sandstones (Fulmar Formation) in the North Sea is also underway in order to better constrain whether burial depth and progressive loss of K-feldspar can compromise the provenance signal. Feldspar abundance is known to decrease with depth in the Fulmar Formation.

Preliminary Pb results from 35/8-2 confirm the overall bimodal feldspar composition, but with larger numbers of analyses sub-populations can be defined within the main groups that may correspond to discrete basement sources. Early results from the well-drilled Fulmar Formation across a range of core depths (3-5 km) appear to show that there is no variation in Pb composition despite the loss of K-feldspar in deeper samples. This bodes well for the application of the technique in the Atlantic margin basins.

Oral Abstract - Irish Geological Research Meeting 2011

Pb isotopic composition of feldspars from Upper Jurassic sandstones in the northern Porcupine Basin, offshore Ireland: Implications for sediment routing.

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Sediment provenance studies provide key insights into palaeogeography, sediment routing and the distribution and quality of potential hydrocarbon reservoirs. There are significant issues in Jurassic basins west of Ireland in relation to sand-entry points, sediment routing within and between basins, the location of sand-source areas and palaeogeography. The Pb isotopic composition of detrital K-feldspar is proving to be a useful provenance indicator, and is particularly applicable to reconstructing regional palaeodrainage. A previous study of Pb in K-feldspar from Upper Jurassic sandstones in the northern Porcupine Basin suggested derivation from the North Porcupine High to the north, but was based on few (<50) analyses.

A more detailed provenance study at greatly increased resolution (~150 analyses) is currently being undertaken, initially focussing on well 35/8-2 (Spanish Point). The aim is to investigate whether the Pb signal is consistent across a wider stratigraphic interval and between different facies. Initial results indicate the presence of previously unrecognised grain populations, suggesting that although northern-derivation is significant, lateral input from the basin flanks may also be important. A parallel study of well-characterised Jurassic sandstones (Fulmar Formation) in the North Sea is also underway in order to investigate if burial depth and diagenesis can compromise the provenance signal in K-feldspar.

Oral Abstract – North Atlantic Petroleum Systems Assessment Conference 2011

Pb isotopic composition of feldspars from Upper Jurassic sandstones in the northern Porcupine Basin: Implications for sediment routing.

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There are significant issues in Jurassic basins west of Ireland in relation to sand-entry points, sediment routing within and between basins and the location of sand-source areas. In addition, the Mesozoic plate configuration, palaeogeography, links between the conjugate Atlantic margins and the regional tectonostratigraphy are particularly important for future exploration in the Irish offshore. Determining sand provenance can provide useful constraints and help resolve many of these issues.

Pb isotopic composition of detrital K-feldspar represents a powerful provenance tool. A previous study of feldspar from Upper Jurassic sandstones in the northern Porcupine Basin suggested derivation from the North Porcupine High to the north, but was based on few (<50) analyses. A detailed provenance study at a greatly increased resolution (~400 analyses) is underway, focusing on well 35/8-2 where three hydrocarbon-bearing sandstone intervals are recognized (A, B and C sandstones). The aim is to investigate whether the Pb signal is consistent across a wider stratigraphic interval and between different depositional elements - this is important for inferring continuity of supply during several cycles of deposition, the potential for multiple sand supply points to the basin, and hinterland evolution during extension.

Results indicate the presence of four Pb clusters, each attributed to a discrete basement source and include previously unrecognised grain populations. The relative proportion of different populations varies with stratigraphy, suggesting lower B sandstones have a different provenance to A sandstones. A parallel study of depth trends in North Sea Jurassic sandstones (Fulmar) suggests the change cannot be diagenetic. Axial derivation from the north appears to play a significant role, but either lateral input from the basin margins or a change to more proximal axial source may have become increasingly dominant over time.

Oral Abstract - Atlantic Ireland 2011 Conference

Sediment sources, transport paths and supply evolution in the Upper Jurassic of the northern Porcupine Basin; new evidence from the Pb isotopic composition of detrital K-feldspar.

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Provenance studies help in constraining palaeogeography and sediment dispersal to ancient basins and can have important implications for the distribution and quality of potential hydrocarbon reservoirs. Sources, sand-entry points, palaeodrainage and routing within and between Jurassic basins west of Ireland are poorly constrained. Pb isotopic composition of detrital K-feldspar can provide useful constraints and help resolve many of these issues.

This study investigates the provenance, palaeogeography and palaeodrainage of the Upper Jurassic reservoir sandstones in well 35/8-2 in the northern Porcupine Basin. The Pb composition of detrital K-feldspar is determined using LA-MC-ICPMS (laser ablation multi-collector inductively coupled-plasma mass-spectrometry). A previous study of K-feldspar from Upper Jurassic sandstones in the northern Porcupine Basin suggested derivation from the North Porcupine High to the north, but was based on few (<40) analyses. The new Pb isotopic data (334 analyses) have also been integrated with MLA (Mineral Liberation Analysis) tallies of the grain types to provide a more robust interpretation. The aim is to investigate whether the Pb signal is consistent across a wider stratigraphic interval and between different depositional elements.

These new data indicate the presence of four Pb clusters, each attributed to a discrete basement source and include previously unrecognised grain populations. The vertical distribution of Pb data show the relative contribution from the main sources varied through time recording the evolution of sediment supply to the deep-water northern Porcupine Basin. This gradual change in provenance may reflect increased lateral input, perhaps linked to local rifting associated with the early formation of the Rockall Basin.

<u>Oral Abstract - Provenance Studies in Hydrocarbon Exploration and Production Conference</u>

Evolving sand supply and dispersal in the Upper Jurassic of the northern Porcupine Basin: constraints from the Pb isotopic composition of detrital K-feldspar.

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The Pb isotopic composition of detrital K-feldspar has proved to be a useful tool in provenance characterization. Analyses are carried out *in-situ* using laser ablation multi-collector inductively coupled mass spectrometry (LA-MC-ICPMS). The approach can help overcome some of the inherent limitations with single grain studies using other techniques. As sediment is transferred from source to sink the provenance signal(s) may be masked by mixing of sediment contributed from multiple sources, merging of dispersal systems and incorporation of polycyclic grains recycled from older sedimentary rocks. Improved source discrimination can be achieved by interrogating the provenance signal in more labile mineral grains (e.g. K-feldspar) that are more likely to be first cycle components and derived directly from their source.

There are significant issues in Jurassic basins west of Ireland in relation to sand-entry points, the sediment routing within and between basins and the location of sand-source areas. In addition, the Mesozoic plate configuration, palaeogeography, links between the conjugate Atlantic margins and the regional tectonostratigraphy are particularly important for future hydrocarbon exploration in the Irish offshore. Sand provenance can help constrain many of these issues. The *in-situ* Pb isotopic study of K-feldspar grains reported here focuses on a thick sand-prone interval in well 35/8-2 in the northern Porcupine Basin. The basin lies approximately 100 km west of Ireland (Figure 1) and includes a thick Jurassic syn-rift sequence (Croker & Shannon 1987, Naylor, 2005). The studied succession comprises a series of stacked submarine fan units. Four sandstone intervals are recognised (A, B, C and D from top to bottom), each representing a phase of deep-sea fan activity. Pilot Pb data from <40 K-feldspar analyses identified two distinct Pb isotopic populations (Tyrrell et al. 2007). The small sample number prevented robust statistical analysis of the data or any assessment of temporal changes in sand supply. Tyrrell et al. (2007) interpreted these data to represent hinterland drainage

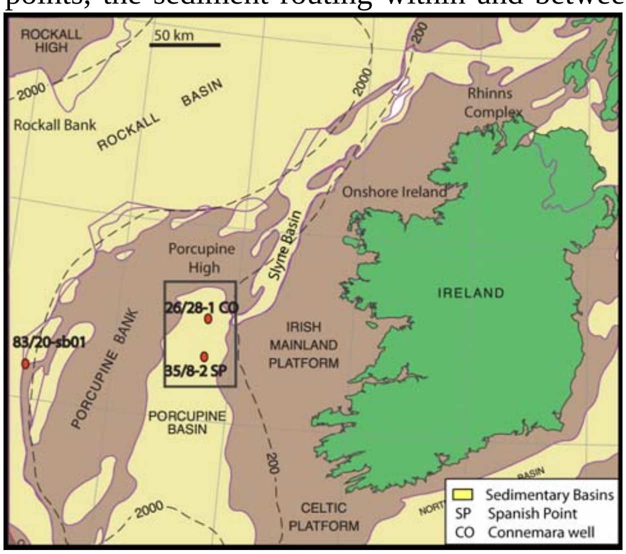

Figure 1 : Location map showing the study area – well 35/8-2 in the northern Porcupine Basin.

from a northern source, probably from an uplifted Porcupine High with a dispersal distance of c.100 km.

The detailed provenance study presented here focuses on the source of the A and B sandstones. The Pb isotope and conventional petrographic data have also been integrated with MLA (Mineral Liberation Analysis) tallies of the grain types to provide a more robust interpretation. The aim of this study is to investigate whether the Pb signal is consistent between different depositional elements recognised in the cores (channels, sheets) and across a wider stratigraphic interval. The latter is important for inferring the continuity of supply during several cycles of deposition, for assessing the potential for multiple sand supply points to the basin, and for constraining hinterland evolution during syn-rift extension. The new data comprise results from 334 K-feldspar grains analysed from 15 samples of fine to medium-grained sandstones. K-means cluster analysis was applied to the Pb dataset to highlight different grain populations and hence source contributions. In order to constrain the potential sources, the clusters are compared to Pb isotopic data from the wider North Atlantic region. Four clusters were identified, each attributed to a discrete basement source and the new data reveal grain populations unrecognised in the previous pilot study.

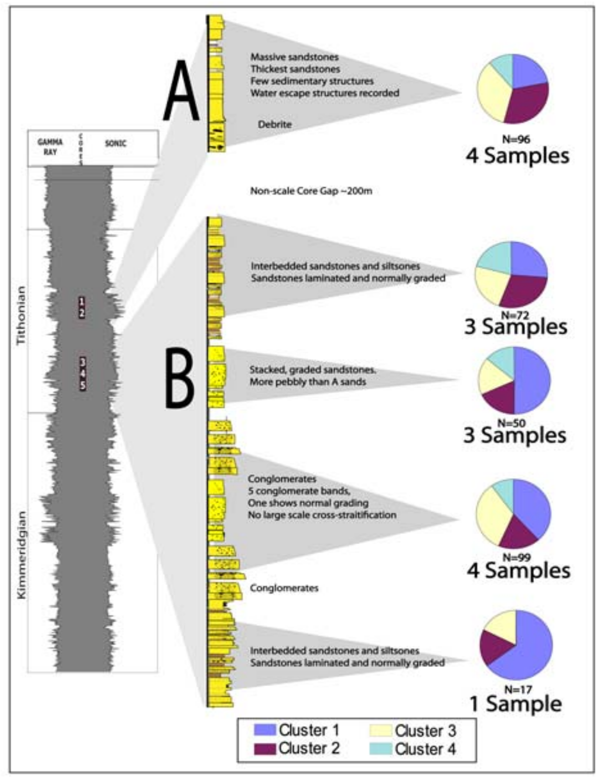

Figure 2 : Illustration showing from left to right - gamma ray and sonic log of well 35/8-2, simplified log of well 35/8-2 and summary pie-charts of proportions of clusters in each dominant facies.

These data suggest that four isotopically distinct sources supplied the K-feldspar in the A and B sandstones. The Rockall Bank, Porcupine Bank, Porcupine High and the Irish Massif, or its along strike extension, are identified as likely sources. All of these sources suggest transport distances less than 250 km. There are no far-traveled sand grains from Archaean – Palaeoproterozoic domains to the north or from the Variscides to the south. The vertical distribution of Pb data show the relative contribution from the main sources varied through time (Figure 2) recording the evolution of sediment supply to the deep-water northern Porcupine Basin. Axial derivation, from the north and northwest, seems likely to supply cluster 1 and 2 grains, while lateral input from the basin margins could account for cluster 3 and 4 grains. Cluster 4 is the dominant source in the lower B sands, with clusters 2 and 3 increasing higher in the stratigraphy. This gradual change in provenance may reflect increased lateral input, perhaps linked to local rifting associated with the early formation of the Rockall Basin. This study underscores the potential of the Pb in K-feldspar provenance approach as a useful tool in constraining sediment supply and evolution.