ISPSG Project Number IS06/19

Interim report

Provenance of Jurassic-Cretaceous sandstones in Mesozoic basins on the North Atlantic margin – new insights into palaeogeography, sediment dispersal and reservoir sandstone distribution.

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1.1 Project Aims

The primary aim of this project is to investigate and constrain Upper Jurassic and Lower Cretaceous palaeogeography, palaeodrainage and reservoir distribution in the Porcupine Basin and along the wider North Atlantic Margin using the Pb in detrital K-feldspar provenance tool. This is a relatively novel approach; hence an important aspect of the work is the refinement of the Pb isotopic technique. The robustness of the Pb signal during progressive burial and diagenesis will be explored using extensively cored Upper Jurassic Fulmar sandstones from the

Central North Sea. The North Sea data set will also address the significance of K-feldspar recycling. Until now, the presence of second cycle K-feldspar has been deemed unlikely, but this needs to be addressed systematically. Significant recycling of K-feldspar would make drainage reconstructions more difficult. Results from the Fulmar study will inform parallel work along the North Atlantic Margin.

1.2 Project staffing

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

1.3 Project Rationale

K-feldspar grains have been shown to retain the common Pb isotopic signature of their source (Tyrrell *et al.,* 2006). The Pb in K-feldspar tool thus provides a powerful indicator of provenance. The Pb isotopic signature of K-feldspar in potential basement source terranes shows broad regional patterns that are easily characterised on the basis of a small number of samples (Tyrrell *et al.,* 2006). The robustness of the Pb signature during weathering, sediment transport and burial diagenesis has been demonstrated (Tyrrell *et al.,* 2007) but requires further study. Reactions during burial diagenesis may systematically purge grains of a certain composition, modifying the original detrital population.

1.3.1 Porcupine Basin

A pilot study was conducted in 2006 (IS05/19) on Upper Jurassic arkosic sandstones (wells 35/8-2, 26/28-1 & 26/28-2) from the northern part of the Porcupine Basin. This study, albeit based on a small sample set, revealed two distinct Pb populations for the K-feldspars analysed indicating at least two sources. Mixed on a thin-section scale but otherwise petrographically indistinct, these strongly suggested derivation from the north of the basin. The sand was most likely delivered via a small scale sedimentary routing system (<200 km). However the significance of the results from the pilot study is unclear. Analysis for the pilot work was carried out using a Faraday collector configuration such that the sensitivity of the mass spectrometer was reduced and Pb data could only be obtained from K-feldspar of above lower medium (> 300 μm diameter) grain size. This limitation may have introduced a sample bias with the possibility that an isotopically distinct population of sub-300 μm K-feldspar grains could be present but remains unidentified. However, the use of new facilities at the National Centre for Isotope Geochemistry at UCD (a Neptune MC-ICPMS configured with a more sensitive ion counter collector array (see Tyrrell *et al.* 2009 for a description of the refined technique), paired with a New Wave Excimer 193nm laser ablation system) will allow the analysis of finer grain sizes, thus addressing any potential sampling bias. In addition, during previous analyses pristine K-feldspar grains were preferentially targeted. In the current study, K-feldspar grains displaying discrete heterogeneities will be analysed in a systematic way in order to determine if burial diagenesis or other alteration affects the Pb signature. A smaller laser spot size will allow intragrain measurements to be made on grains that are partly dissolved. This will further substantiate the application range of the tool. It is possible that burial diagenesis selectively removes feldspar grains depending on the defect inventory (microtexture) and this may remove some grain populations (Parsons *et al.,* 2003). This would have implications for accurate palaeodrainage and sediment routing reconstructions. Furthermore, the number of grains actually analysed in the pilot study may not be statistically significant. More data (both stratigraphically and for single samples) is required to both confirm and explore the initial results. Greater numbers of grains will also allow the significance of small numbers of outlier grains to be assessed.

Based on the results of the pilot study, Porcupine well 35/8-2 was chosen for initial detailed study in this PhD project. This well is significant as it cored deep water deposits hosting the Spanish Point gas condensate discovery. And the discovery is currently under re-appraisal by Providence Resources with a view to future development. Three hydrocarbon-bearing sandstone intervals were encountered in the well, and more than 120m of core were taken of different deep water sand bodies. Pugliese *et al.*, (2009) have identified an overlying fourth uncored thin sand c.200 ft above the A sand and refer to this unit as the “Z” sand. The provenance of this sand will be explored if cuttings be can accessed. Original sampling and logging was carried out on a poorly preserved quarter core slice stored at the PAD core store in Sandyford, Dublin. A newly uncovered half-slice core which is in much better condition has been located in Kent. New work on 35/8-2 will include a reappraisal of the core now in Kent focusing on the depositional setting of the main reservoir intervals and the detailed context of the samples for the provenance assessment. Additional sample material from recent fracture work at Providence Resources will be used for heavy mineral analysis to identify patterns in heavy mineral persistence and whether these match potential changes in the Pb signature of detrital K-feldspar. This combination of K-feldspar Pb isotopic analysis with other provenance tools will help to identify potentially recycled components and better constrain the provenance of feldspar-poor sandstones in the Atlantic margin basins, allowing a more complete evaluation of the palaeodrainage on a regional scale.

As noted above, the cored intervals of well 35/8-2 represent three continuous sandy successions: A (13101’0” – 13215’0”ft, cores 1 & 2), B (13415’0” – 13595’0”ft, cores 3, 4 & 5) and C (13763’0” – 13824’0”ft, core 6). The sandy intervals are separated by mud-prone intervals which were not cored. Mean grain size is generally fine sand although the sand texture is variable and ranges from very fine to coarse with poor to moderate sorting and a dominance of massive sandstones. Petrological assessment prior to Pb analysis have been completed and has shown the A sand appears more bioclastic rich and plagioclase poor than the B or C sands. The A sand is also lithic poor in comparison to the B or C sands which supports the suggestion based on petrological evidence by Pugliese *et al.,* (2009) that the A sand may have a different provenance to either the B or C sands.

Preliminary Pb Results and interpretation

Preliminary ICPMS work has been undertaken at UCD. Analyses have been obtained from 5 K-feldspar grains (Appendix B, Figure 2, b, c & d. Figure 3, a & b) in a single section from Core 5 in well 35/8-2. K-feldspar from Core 5 had not been previously investigated. The Faraday collector configuration was utilized as a data quality control measure on this preliminary run. Future analysis will utilize a more sensitive ion counter collector array. Informed by conventional optical petrography and backscattered-electron-microscopy imaging, laser ablation tracks were chosen along the K-feldspar surfaces avoiding any heterogeneities. Analyses was limited to grains with a long axis in excess of 300 µm. Tyrrell *et. al.,* 2007 identified contributions from at least two distinct basement source terranes (Figure 1) - Group 1 consisting of a relatively unradiogenic population ($^{206}Pb/^{204}Pb$ from 15.80 to 16.74), and group 2 which is more radiogenic ($^{206}Pb/^{204}Pb$ from 16.93 to 17.83).

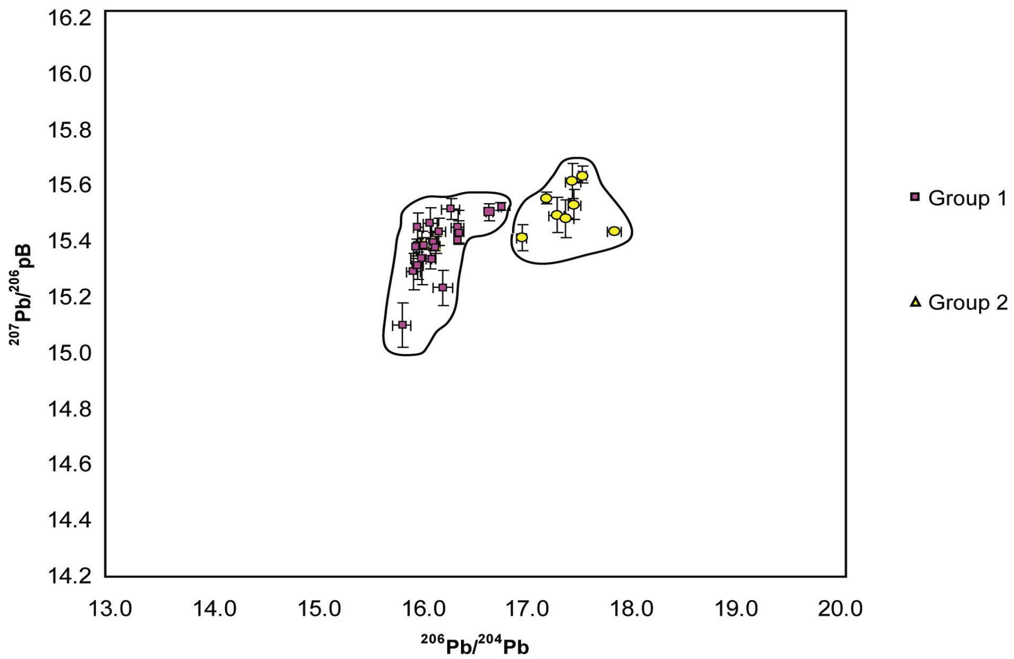

Figure 1 Plot of $^{206}Pb/^{204}Pb$ versus $^{207}Pb/^{204}Pb$ of individual detrital K-feldspar grains from Jurassic sandstones, well 35/8-2 North Porcupine Basin, cores 1,2,4 & 6 from Tyrrell *et al.,* 2007.

The results of the preliminary work (Figure 2) appear to correspond to Group 1 (n=4) along with 1 feldspar grain recording a more radiogenic signal. Analyses of a further 120 K-feldspar from cores 3, 4 & 5 is scheduled for July. The original pilot study comprised the analysis of only 32 K-feldspar grains.

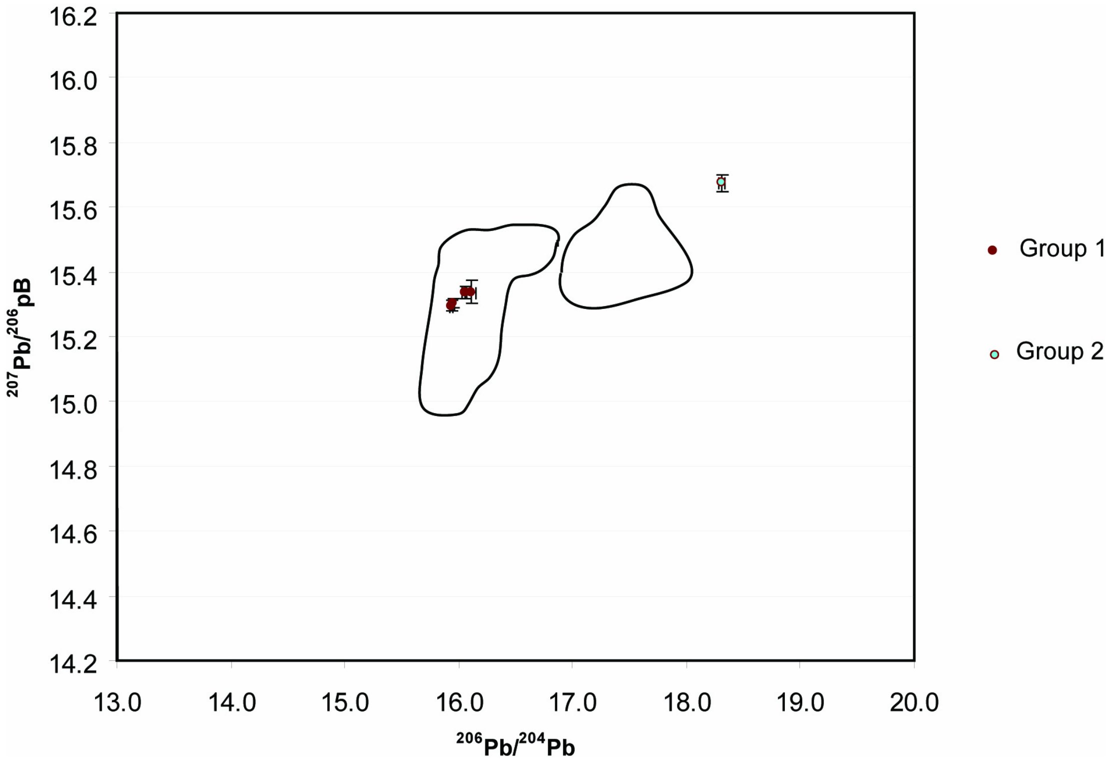

Figure 2 **Preliminary plot of $^{206}Pb/^{204}Pb$ versus $^{207}Pb/^{204}Pb$ for individual detrital K-feldspar grains from core 5, well 35/8-2, North Porcupine Basin.**

1.3.3 Fulmar Formation

This PhD project is also investigating reservoir sandstones in the Upper Jurassic Fulmar Formation in the Central North Sea to help constrain any potential limitations with the tool and to inform the studies in Irish offshore basins. The Fulmar Formation contains significant K-feldspar which is envisaged 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, this formation has been extensively cored. The Fulmar comprises a thick succession of highly bioturbated shallow marine arkosic sandstones and importantly is currently buried to a range of depths (3.2 - 4.7 km). K-feldspar abundance has been shown to systematically decrease with increasing depth in the formation (Wilkinson *et al.,* 1996). It is currently inferred that burial diagenesis (principally feldspar dissolution) is the controlling factor (Wilkinson et al., 1996), although others have suggested that the evidence presented is ambiguous (Oxtoby & Gluyas, 1996) and there may be provenance changes. Our study will utilise the Pb in K-feldspar tool at a range of depths in order to investigate 1) if feldspar abundance is a function of changing provenance; 2) whether the Pb isotopic composition of the detrital grains is compromised by burial diagenesis effects; and 3) to what, if any, extent the feldspar has been recycled from older sedimentary rocks. This research will have significant implications for applying the tool to basins along the North Atlantic margin offshore Ireland, allowing for a detailed investigation into the effects of burial diagenesis on Pb signatures. Is it possible that burial diagenesis may completely remove populations of grains with a certain Pb signature? Parsons *et al.,* 2003 have suggested that dissolution in the Fulmar Formation is strongly texture sensitive, 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.

1.4 Work to date

During the last 9 months, the following project-related works have been carried out:

Well 35/8-2 Porcupine Basin

- Review of work to date carried out by Andreas listed below:
  - Detailed sedimentological logging of core 1-5, well 35/8-2.
  - High-resolution sampling of core 1-5, well 35/8-2.
  - Selection and preparation of 105 thin sections from samples.
  - Preparation of thick sections for target samples.
- Imaging of potential K-feldspar target grains using a SEM (Appendix B).

- Further optical petrographical analysis based on thin sections (Appendix C).
- Pb analysis of K-feldspar grains from of sandstones in core 5.

Fulmar Formation

- Visit to Edinburgh University and the BGS Core Store - sampling of cores 29/2a-2, 30/16-6, 29/10-2, 30/17b-5, 29/5b-6, 30/17b-5 from the Fulmar Formation, Central North Sea. These wells were chosen as they provide suitable sandy intervals over a wide range of depths.
- Selection, preparation and screening of ~72 thin sections from samples from the Fulmar formation.
- Standard petrographic analysis and preliminary SEM assessment of feldspar component on the thin sections (Appendix A).
- Preparation of thick sections from target samples for the Fulmar Formation.
- Selection of 66 potential target samples for laser ablation analysis.

General project Work

- Introductory presentation at the UCD School Seminar.
- Attendance at the British Sedimentological Research Group Annual Meeting and Atlantic Ireland (PIP-ISPSG) conference.
- Extensive literature review.
- Project training i.e. SEM, core logging & petrography.

Future Work:

Next 6 to 12 months.

- Presentation at the Atlantic Ireland (PIP-ISPSG) conference at the Burlington Hotel Dublin, 2nd November 2010 .
- Presentation at BSRG Annual General Meeting Southampton, UK, 19th - 21st December 2010.

- A visit to Kent to inspect/complete detailed logging of new core slice from well 35/8-2 in the Porcupine Basin.
- Assess whether heavy minerals can be recovered from slices of the “Kent Core” used for fracture characterisation.
- Further standard optical petrographical analysis based on thin sections for the Fulmar and Porcupine samples.
- Interpretation of provenance based on Pb isotopic character with a view to inform palaeogeographic reconstruction and palaeodrainage modeling for both the Fulmar and Porcupine basins. Explore the possibility of facies variations and the detrital K-Feldspar populations, multiple source areas, input from the basin margins and the effect of diagenetic overprinting (i.e. alteration/dissolution of grains and cement precipitation).
- Continue to update and expand the database of Pb isotopic analyses for potential basement source areas from the circum- and sub-North Atlantic and to provide this as a GIS-enabled Pb-domain map to underpin future provenance studies and continental reconstructions in the North Atlantic.
- Acquire a statistically meaningful Pb isotopic dataset for detrital K-feldspar from Upper Jurassic and Middle Jurassic sandstones and in both fluvial (26/28) and turbidite sandstones in the northern Porcupine Basin to investigate whether routing systems vary in different areas of the basin. Expand the study to possible equivalent Jurassic successions in the southern Porcupine Basin (e.g. 62/7-1).
- Identification of possible future cores in the Porcupine to analyse (26/28 and 62/7-1).
- Investigate K-feldspar recycling primarily in the Fulmar Formation with a view to add to the understanding of how feldspar may be lost at depth and how important feldspar recycling may be in arkosic sands.

1.5 References

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Appendix A
Well 35/8-2 Porcupine Basin SEM images of K-feldspar

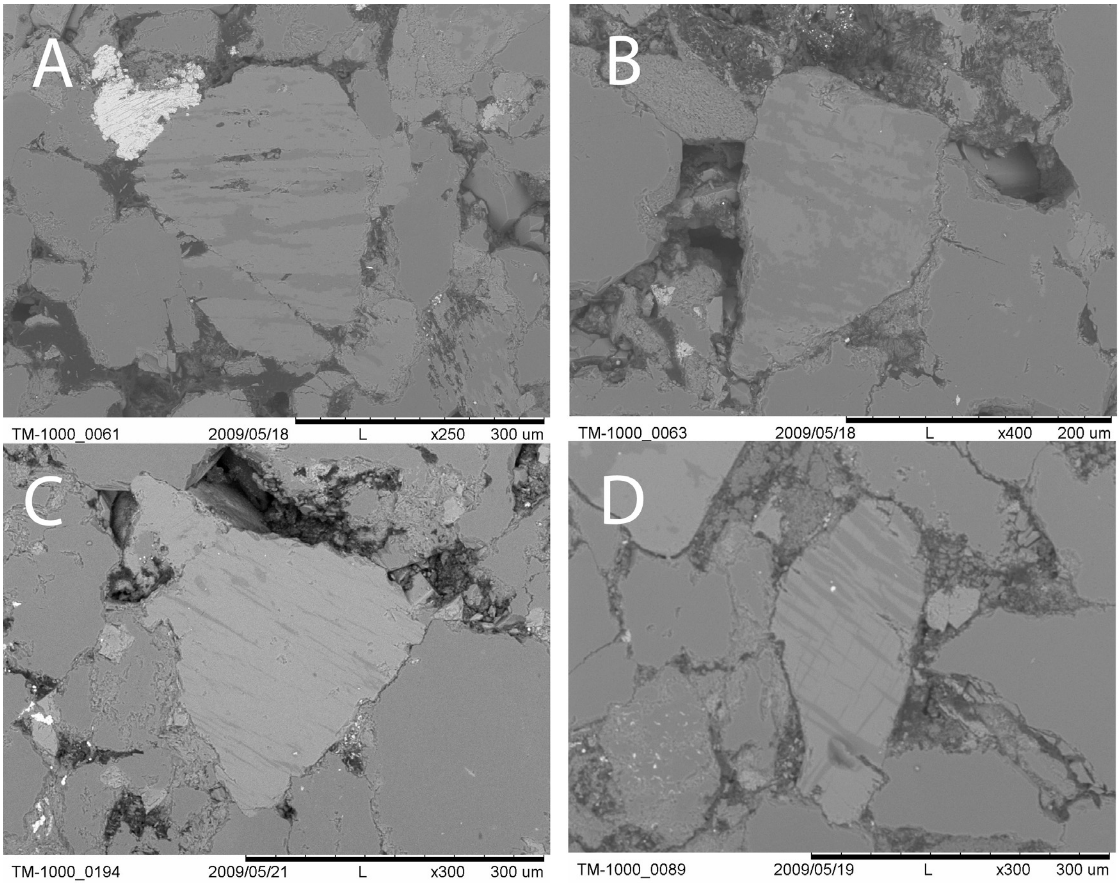

Figure A1. BSE images of K-feldspar from well 35/8-2 in Porcupine Basin. A) Deuterically coarsened perthite. Sample 1.1 - 13150'8". Deuteric coarsening is a result of a discontinuous process involving dissolution and reprecipitation in an aqueous fluid, while the crystal retains its external shape. B) Antiperthite (Or-rich feldspar is enclosed by plagioclase). Sample 1.1 - 13150'8". C) Fine film perthite. Sample 1.1 - 13150'8". A coherent intergrowth, the result of a continuous process in which Na and K ions diffuse through an unbroken Si–Al–O framework. D) Perthite, largely mesoperthitic (Or-rich phase and Ab-rich phases are present in approximately equal proportions) towards top of grain. Sample 1.9 - 13128'2"

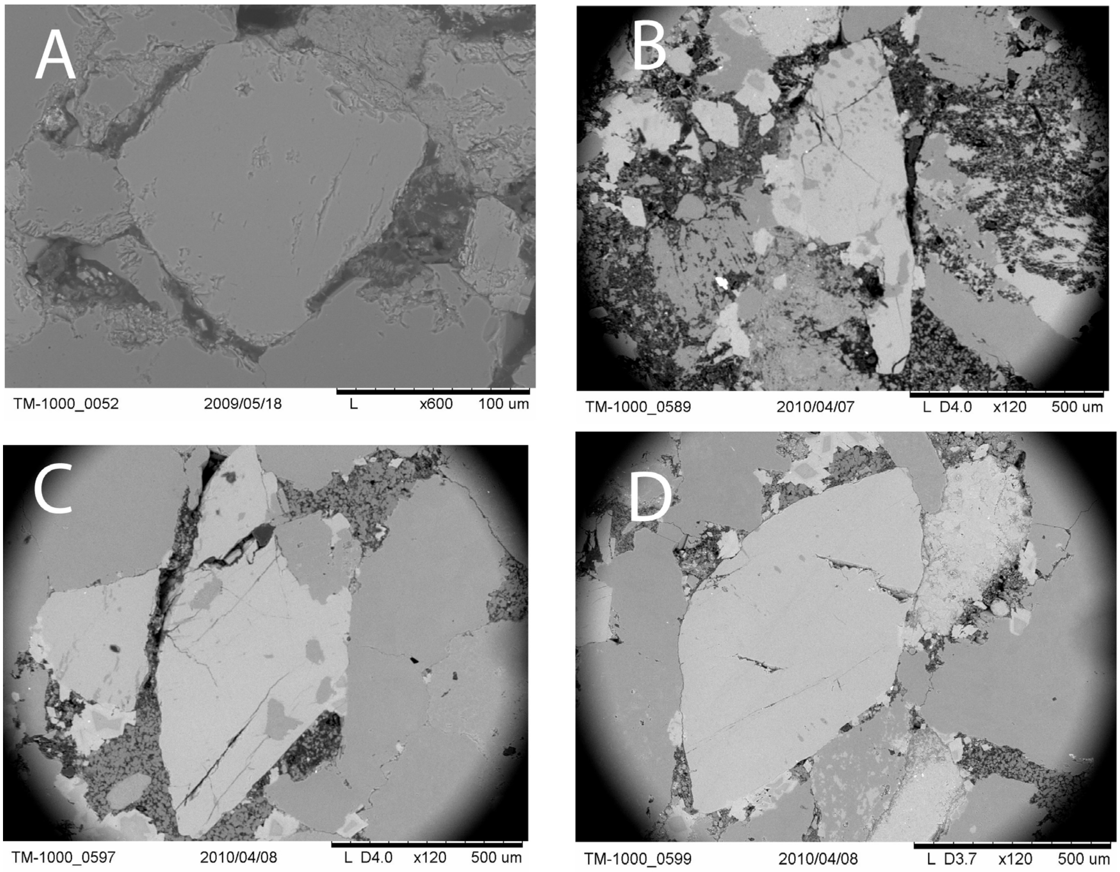

Figure A2. **BSE images of K-feldspar from well 35/8-2 in Porcupine Basin. A) Optically featureless orthoclase, possibly cryptoperthite. Sample 1.1 - 13150'8". B) Patch perthite. Sample 5-16 (1) - 13553'4". C) Film perthite that has been albitised. Sample 5-16 (3) - 13553'4". D) Largely optically featureless orthoclase with some albite blebs, possibly cryptoperthitic. Sample 5-16 (5) - 13553'4".**

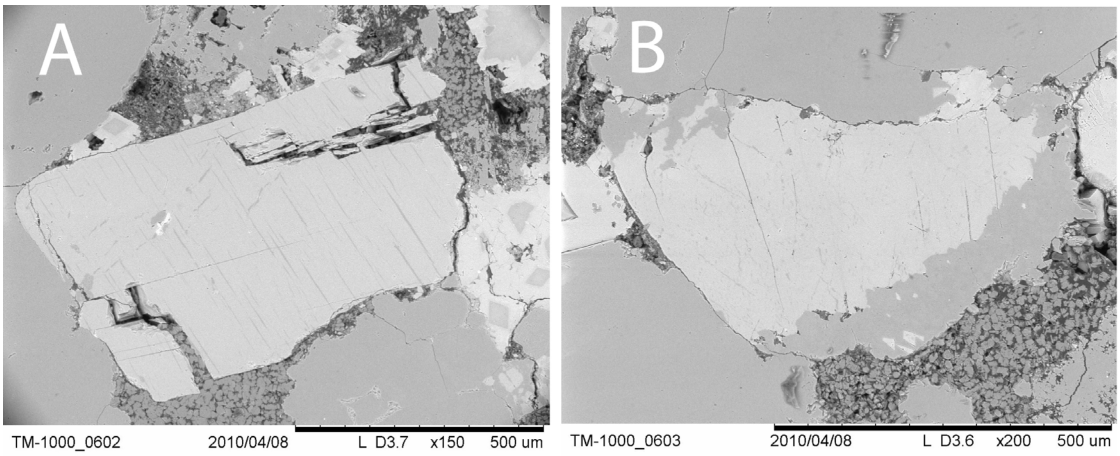

Figure A3. **BSE images of K-feldspar from the well 35/8-2 in Porcupine Basin. A) Fine film perthite. Sample 5-16 (6) - 13553'4". B) Albitised fine film perthite. Sample 5-16(7) - 13553'4"**

Table 1 – Sample numbers and depths – Well 35/8-2 Porcupine Basin

Ref. No.	Well	Core	Depth (Ft)	Ref. No.	Well	Core	Depth (Ft)
1	35/8-2	1	13150'8"	3-13	35/8-2	3	13443'3"
2	35/8-2	1	13147'3"	3-14	35/8-2	3	13440'8"
3	35/8-2	1	13144'8"	3-15	35/8-2	3	13438'4"
4	35/8-2	1	13140'9"	3-16	35/8-2	3	13434'
5	35/8-2	1	13140'	3-17	35/8-2	3	13433'2"
6	35/8-2	1	13137'8"	3-18	35/8-2	3	13427'11"
7	35/8-2	1	13136'	3-19	35/8-2	3	13425'3"
8	35/8-2	1	13132'10"	3-20	35/8-2	3	13422'1"
9	35/8-2	1	13128'2"	3-21	35/8-2	3	13419'9"
10	35/8-2	1	13125'4"	3-22	35/8-2	3	13417'1"
11	35/8-2	1	13123'3"	4-1	35/8-2	4	13534'1"
12	35/8-2	1	13119'8"	4-2	35/8-2	4	13530'1"
13	35/8-2	1	13116'5"	4-3	35/8-2	4	13525'9"
14	35/8-2	1	13114'	4-4	35/8-2	4	13523'8"
15	35/8-2	1	13112'2"	4-5	35/8-2	4	13520'9"
				4-6	35/8-2	4	13518'3"
16	35/8-2	2	13194'	4-7	35/8-2	4	13516'8"
17	35/8-2	2	13190'7"	4-8	35/8-2	4	13513'8"
18	35/8-2	2	13187'2"	4-9	35/8-2	4	13510'11"
2-1	35/8-2	2	13213'2"	4-10	35/8-2	4	13506'5"
2-2	35/8-2	2	13212'2"	4-11	35/8-2	4	13504'2"
2-3	35/8-2	2	13207'4"	4-12	35/8-2	4	13501'2"
2-4	35/8-2	2	13206'3"	4-13	35/8-2	4	13498'3"
2-5	35/8-2	2	13205'5"	4-14	35/8-2	4	13495'7"
2-6	35/8-2	2	13202'8"	4-15	35/8-2	4	13491'11"
2-7	35/8-2	2	13200'3"	4-16	35/8-2	4	13488'5"
2-8	35/8-2	2	13196'2"	4-17	35/8-2	4	13487'
2-9	35/8-2	2	13194'6"	4-18	35/8-2	4	13482'8"
2-10	35/8-2	2	13185'11"	4-19	35/8-2	4	13479'5"
2-11	35/8-2	2	13182'7"	4-20	35/8-2	4	13475'7"
2-12	35/8-2	2	13179'8"				
2-13	35/8-2	2	13177'1"	5-1	35/8-2	5	13594'4"
2-14	35/8-2	2	13174'6"	5-2	35/8-2	5	13589'11"
2-15	35/8-2	2	13171'2"	5-3	35/8-2	5	13588'5"
2-16	35/8-2	2	13170'7"	5-4	35/8-2	5	13586'9"
2-17	35/8-2	2	13166'7"	5-5	35/8-2	5	13583'4"
2-18	35/8-2	2	13163'6"	5-6	35/8-2	5	13580'11"
2-19	35/8-2	2	13161'	5-7	35/8-2	5	13578'6"
2-20	35/8-2	2	13158'7"	5-8	35/8-2	5	13576'1"
2-21	35/8-2	2	13155'4"	5-9	35/8-2	5	13571'11"
2-22	35/8-2	2	13172'9"	5-10	35/8-2	5	13569'2"
				5-11	35/8-2	5	13565'11"
3-1	35/8-2	3	13474'2"	5-12	35/8-2	5	13564'5"
3-2	35/8-2	3	13471'8"	5-13	35/8-2	5	13562'5"
3-3B	35/8-2	3	13469'4"	5-14	35/8-2	5	13559'7"
3-3A	35/8-2	3	13469'4"	5-15	35/8-2	5	13556'7"
3-4	35/8-2	3	13467'2"	5-16	35/8-2	5	13553'4"

3-5	35/8-2	3	13465'2"	5-17	35/8-2	5	13552'1"
3-6	35/8-2	3	13462'3"	5-18	35/8-2	5	13547'9"
3-7	35/8-2	3	13461'2"	5-19	35/8-2	5	13545'0"
3-8	35/8-2	3	13458'9"	5-20	35/8-2	5	13543'11"
3-9	35/8-2	3	13455'8"	5-21	35/8-2	5	13540'5"
3-10	35/8-2	3	13452'	5-22	35/8-2	5	13539'0"
3-11	35/8-2	3	13449'6"	5-23	35/8-2	5	13536'8"
3-12	35/8-2	3	13446'9"				

Appendix B
Fulmar Formation SEM images of K-feldspar

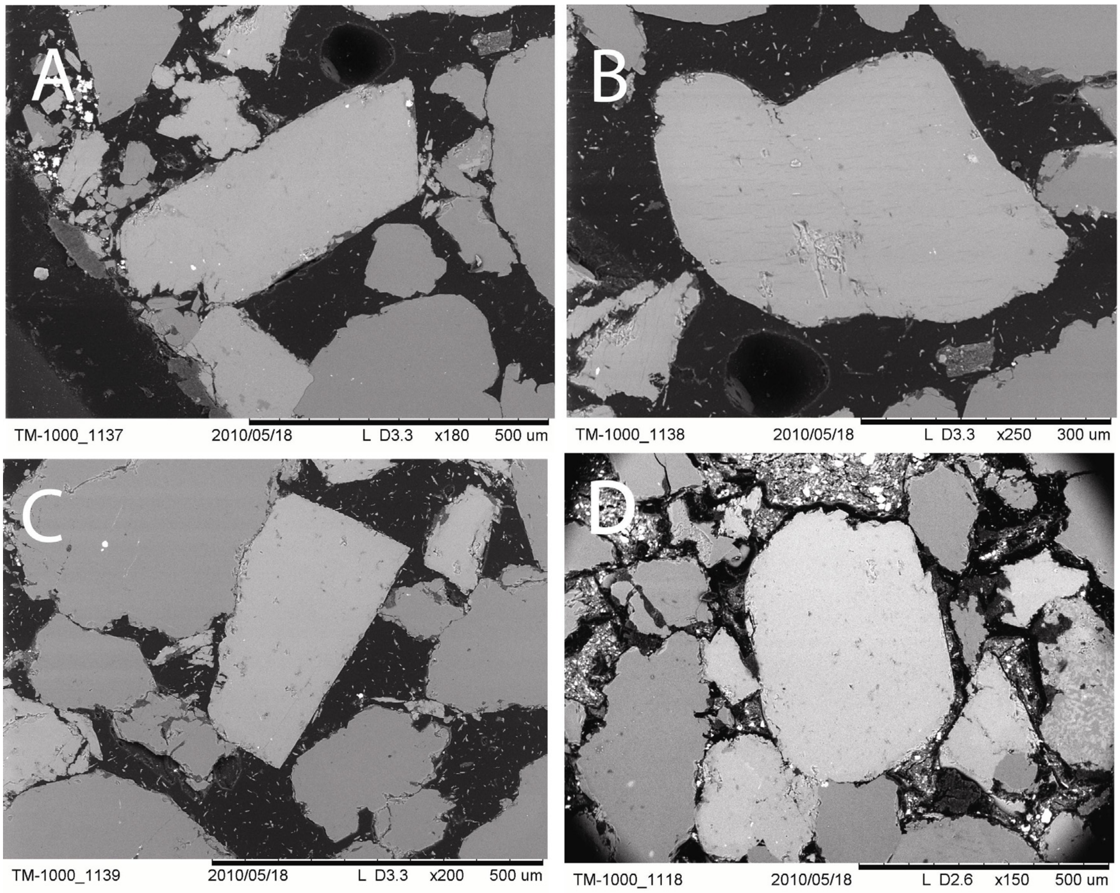

Figure B1. A) BSE images of K-feldspars from the Fulmar Formation. Optically featureless K-feldspar, possibly cryptoperthitic. F 43 – 18694'0''. B) Fine film perthite. Sample F 43 – 18694'0''. C) Optically featureless K-feldspar, possibly cryptoperthitic . F 43 – 18694'0''. D) Optically featureless K-feldspar – possibly cryptoperthitic. F 71 – 10367'4''

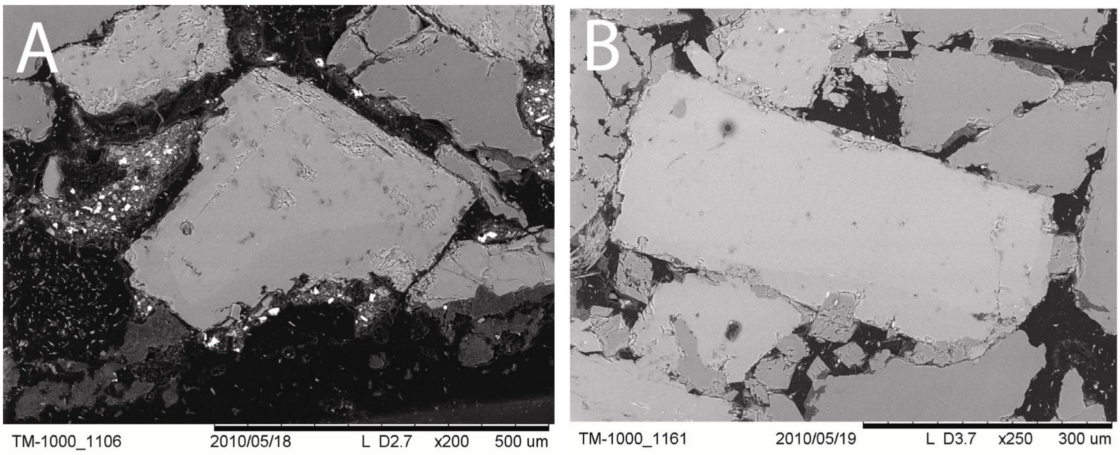

Figure B2. BSE of K-feldspars from the Fulmar Formation. A) Optically featureless K-feldspar – possibly cryptoperthitic. F 43 - 10367'4'' B) Optically featureless K-feldspar – possibly cryptoperthitic. F30 - 10552'5''

Appendix C

Well 35/8-2 Porcupine Basin Sample 5.4

Sample Petrography Description

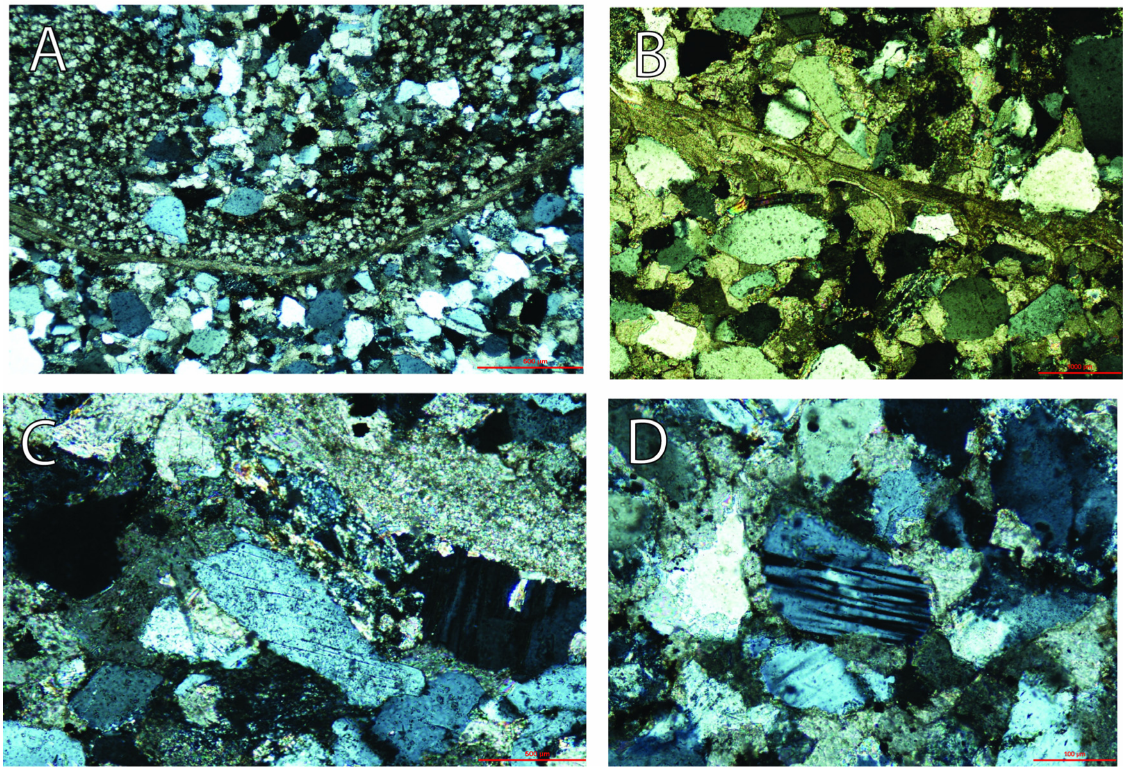

Figure C1 – Sample 5.4 PPL images A) Moderately sorted dolomitic feldspathic arenite B) Skeletal fragment displaying weak compaction C) Orthoclase D) Perthite

Depth:	13583.33ft
Sandbody:	B
Lithology:	Dolomitic feldspathic arenite
Grain size:	Fine to coarse sand
Structures:	Massive
Compaction:	Weak
Sorting:	Moderate

Summary:

Sample 5.4 comprises a moderately sorted dolomitic feldspathic arenite displaying weak compaction (Figure 1-A). Carbonate is the principal authigenic phase and includes both calcite and dolomite. Numerous skeletal fragments are present throughout the sample which, although disarticulated, have suffered limited fragmentation (Figure C1-B). Figure C1-A exhibits the two forms of dolomite present, the larger dolomite display cleaner crystal terminations than the smaller crystals within the large bioclast. There is a section of larger dolomite surrounded by the smaller crystals in the bioclast which suggests the smaller crystals might be a dolomitisation of lime mud. Alkali feldspar is slightly dominant over plagioclase being commonly untwinned orthoclase (Figure C1-C) with twinned microcline occasionally observed.