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Drainage re-organization during break-up of Pangea revealed by *in-situ* Pb isotopic analysis of detrital K-feldspar

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ABSTRACT

Pb isotopes in detrital K-feldspar grains provide a powerful provenance tracer for feldspathic sandstones. Common Pb isotopic compositions show broad (100s km scale) regional variation and this signature can survive weathering, transport and diagenesis. The feldspar Pb signature can be measured rapidly using laser ablation MC-ICPMS and careful targeting avoids inclusions and altered regions within grains. Here we combine a new Pb domain map for the circum-North Atlantic with detrital K-feldspar Pb isotopic data for Triassic and Jurassic sandstones from basins on the Irish Atlantic margin. The Pb isotopic compositions reveal otherwise cryptic feldspar populations that constrain the evolving drainage pattern. Triassic sandstones were sourced from distant Archean and Paleoproterozoic rocks, probably in Greenland, Labrador and Rockall Bank to the NW, implying long (>500 km) transport across a nascent rift system. Later Jurassic sandstones had a composite Paleo- and Mesoproterozoic source in more proximal sources to the north (<150 km away). No recognizable feldspar was recycled from Triassic into Jurassic sandstones, and the change in provenance is consistent with distributed, low relief Triassic extension in a wide rift, followed by narrower Jurassic rifting with more localized fault-controlled sediment sources and sinks.

Keywords: K-feldspar, Pb isotopes, provenance, paleodrainage, Pangea.

INTRODUCTION

Sandstone provenance helps constrain the scale and pattern of ancient drainage, and is a key tool in facies prediction and paleogeographic reconstructions. A wide range of techniques can be used to assess the source of sand grains, but not all yield definitive results. It can be difficult to see through recycling and mixing, particularly where the grains are robust and make-up a tiny fraction of the sand, as in the case of zircon. In addition, the use of a trace mineral requires detailed characterization of the sourcelands against which to compare the detritus. Denudation may have completely removed the source rocks and contemporaneity of magmatic events in unrelated terranes can lead to ambiguity as grains of a given age may come from more than one source area.

A new method, based on in situ Pb isotopic analysis of single K-feldspar grains by laser ablation MC-ICPMS (Tyrrell et al., 2006) offers some advantages over other techniques. K-feldspar is a relatively common, generally first-cycle, framework mineral in sandstones. Importantly, K-feldspar contains negligible U and Th, hence its Pb isotopic composition does not change significantly over time. Furthermore, Pb in basement rocks shows broad regional variations (due to different ages and variations in U-Pb-Th fractionation) and is likely to be consistent between the upper and middle crust and thus insensitive to erosion level. Hence Pb isotopic mapping is used to identify important crustal boundaries (Connelly and Thrane, 2005. Potential source areas can therefore be characterised by a relatively small number of K-feldspar or galena analyses. Two orientation studies have shown that the Pb isotopic composition of feldspar sand grains is relatively robust, as it can survive weathering, transport and diagenesis (Tyrrell et al., 2006). Targeted laser sampling within individual sand grains avoids internal heterogeneities (e.g., inclusions, altered regions within grains), avoiding some of the uncertainties inherent in multi-grain or the single-grain leaching techniques previously employed to determine Pb isotopes in detrital K-feldspar (e.g., Hemming et al., 1996) and MC-ICPMS offers better precision that ion microprobe techniques (Clift et al., 2001).

The Pb provenance method is used here to explore drainage evolution prior to and during the break-up of Pangea, when opening of the North Atlantic stranded remnants of early rift basins on the conjugate passive margins. Here we focus on basins offshore western Ireland, combining a new circum-Atlantic Pb domain map (Fig. 1) with Pb isotopic data from K-feldspar in Triassic and Jurassic sandstones. Together, these data (1) constrain the scale of the drainage, with implications for the depositional setting and hinterland geology; (2) shed new light on the drainage orientation and source location; (3) demonstrate major drainage reorganisation driven by a change in rift style, and (4) suggest minimal recycling of Triassic sand into Jurassic depocenters.

MESOZOIC BASINS WEST OF IRELAND

Pangean break-up west of Ireland involved polyphase rifting associated with collapse of the Variscan orogenic belt and protracted crustal extension along the Atlantic margin (Naylor and Shannon, 2005). The Slyne, Erris and Donegal basins originally formed as part of a distributed network of Permo-Triassic depocenters (Dancer et al., 1999) as a consequence of wide extensional rifting (Praeg, 2004). Some of these basins were internally drained, while others were fed by large rivers, such as those flowing northwards from the trans-Pangean Variscan uplands (Audley-Charles, 1970). Sand-rich Triassic successions have been drilled in the basins west of Ireland, and have been identified seismically in the Porcupine and Rockall basins (Walsh et al., 1999, Naylor and Shannon, 2005). In the Slyne Basin, Triassic sandstones, thought to be equivalent to the Sherwood Sandstone of NW Europe, host the Corrib gas field and comprise fine- to medium-grained arkosic fluvial and alluvial sandstones with sub-ordinate sand-flat and playa mudstone deposits (Dancer et al., 2005). Previous interpretations based on dipmeter logs, petrography and whole-rock geochemistry suggested sand derivation from the Variscan uplands to the south with additional input from the Irish Mainland (Dancer et al., 2005).

The Porcupine Basin, southwest of the Slyne Basin (Fig. 1), includes a Jurassic sequence deposited during a phase of “narrow” extensional rifting (Croker and Shannon, 1987, Naylor and Shannon, 2005). In the northern part of the basin, an Upper Jurassic (Kimmeridgian-Tithonian) sequence of north-derived low-energy fluvial (meandering river) and marginal marine facies is replaced southwards by shallow marine sandstones and deep-water turbiditic fans (Butterworth et al., 1999, Williams et al., 1999). Petrography suggests a source including granites, basic intrusives and metasedimentary rocks (Geraghty, 1999) of uncertain location.

SAMPLING AND METHODOLOGY

Medium-grained sandstones were sampled from cored Triassic intervals in two Slyne Basin wells (18/25–1 and 18–20–2z; Fig. 1) and from Upper Jurassic intervals in two wells from the northern Porcupine Basin (26/28–1 and 35/8–2; Fig. 1).

The Pb isotopic composition of sand-sized K-feldspar grains was analyzed using LA-MC-ICPMS at the Geological Institute, Copenhagen, following Tyrrell et al. (2006). Prior to analysis, grains were imaged using backscattered electron microscopy (BSE) and cold cathodoluminescence (CL) to avoid intra-grain heterogeneities, which might compromise the Pb signal. Polished K-feldspar surfaces were ablated along pre-determined 300μm - 700μm tracks, guided by the BSE and CL imaging. Typical 2σ errors on $^{206}Pb/^{204}Pb$ were <0.1%.

To constrain the composition of potential sourcelands, a database of basement Pb isotopic analyses of K-feldspar and galena from the circum-North Atlantic was compiled, drawing on literature data and new K-feldspar Pb analyses from Ireland, Britain and Rockall Bank. These data were combined with basement terrane maps (Roberts et al., 1999, Karlstrom et al., 2001) and general structural trends (Naylor and Shannon, 2005) to produce a Pb domain map (Fig. 1), described below. In addition, presumed locally-derived (Haughton et al., 2005) Cretaceous sands and sandstones on the margins of the Porcupine Bank (Fig. 1) were analyzed to provide a proxy for the basement beneath the bank which currently is uncored.

RESULTS

Pb isotopic results are provided in the GSA data repository[1]. Analyses were obtained from 45 K-feldspar grains from seven Lower Triassic sandstone samples in the Slyne Basin, 32 K-feldspar grains from 11 Upper Jurassic sandstone samples in the northern Porcupine Basin and 10 K-feldspar grains from Cretaceous sand and sandstone samples from Porcupine Bank (Fig. 1).

Pb analyses of K-feldspar grains from Triassic sandstones form two distinct groups which are independent of stratigraphic position, grain size and K-feldspar petrography (see supplementary plots in GSA data repository[1]). Both populations are present in single thin-sections. Triassic Group 1 (n = 10) grains show a broad spread of relatively unradiogenic Pb isotopic compositions (^{206}Pb/^{204}Pb from 13.75 to 15.20). Triassic Group 2 (n = 31) shows a more restricted range of ^{206}Pb/^{204}Pb values (15.41–16.70; Fig. 2a). Three grains have outlying Pb compositions.

K-feldspar grains from Jurassic sandstones form two main populations with one outlier (Fig. 2b). Jurassic Group 1 (n = 20) comprises a relatively unradiogenic population (^{206}Pb/^{204}Pb from 15.80 to 16.74) whereas Group 2 (n = 12) is more radiogenic (^{206}Pb/^{204}Pb from 16.93 to 17.83). As with the Triassic populations, both these populations occur within individual thin sections and are independent of facies, stratigraphic position and K-feldspar petrography (see supplementary data plots). Significantly, K-feldspars in sandstones in the alluvial/fluvial successions have identical compositions to those in broadly age-equivalent turbidite sandstones farther south.

CIRCUM-ATLANTIC BASEMENT Pb DOMAINS

Five principle Pb basement domains are identified in the circum Atlantic region (Fig. 1, Fig. 2). These zones strike NE-SW and correspond to the basement terranes involved in the assembly of Laurentia and Rodinia (Karlstrom et al., 2001), the Caledonian collision of Laurentia with Avalonia, and the Variscan Orogen. Although there are variations within each of these zones, there is a broad shift toward more radiogenic Pb values toward the SE reflecting the history of crustal growth. The five zones are 1) Archean characterised by the least radiogenic Pb; 2) Proterozoic I, corresponding mainly to basement formed during the late Paleoproterozoic; 3) Proterozoic II, a zone comprising mainly Paleoproterozoic to Mesoproterozoic basement, Neoproterozoic metasedimentary rocks and Caledonian granites; 4) a zone comprising Avalonian basement; and 5) the Variscan with Pb remobilised from Avalonian basement during end-Palaeozoic closure of the Rheic Ocean.

The new Pb data from the Irish Mainland and from the Paleoproterozoic Rhinns Complex of Inishtrahull (Fig. 1, GSA data repository[1]) help constrain the boundary between Proterozoic I and II basement. New data from the crystalline rocks of the Rockall Bank indicate it shares an affinity with Proterozoic I basement. Pb analysis of detrital K-feldspar from condensed and coarse grained Cretaceous sediments and sedimentary rocks draping highs on the Porcupine Bank help constrain the position of boundaries west of Ireland (Fig. 1); locally-derived grains (Haughton et al. 2005) from 16/28-sb01 have a Proterozoic I affinity, whereas those from 83/20-sb01 in the south dominantly show Proterozoic II and Avalonian affinities (Figure 2a and b, GSA data repository[1]).

SAND PROVENANCE AND IMPLICATIONS FOR PALEODRAINAGE

The two isotopically distinct K-feldspar groups in Triassic sandstones from the Slyne Basin correspond to a combined Archean (Triassic Group 1; Fig. 2a) and Proterozoic I source (Triassic Groups 2; Fig. 2a). There is no significant K-feldspar component originating from the Irish Mainland (Proterozoic II) or from a more southerly (Avalonian or Variscan) source. This would appear to exclude derivation of sand from the south and east, as previously suggested (Dancer et al., 2005). Derivation of sand from the north and west is consistent with the K-feldspar Pb populations, with Archean grains derived from Labrador or Greenland and Proterozoic I grains derived from south Greenland, south Labrador, and/or from Rockall Bank (Fig. 3a). These data imply grain transport in excess of 500 km. The NW-SE orientation of the palaeodrainage corresponds well with the orientation of the proto-Labrador Sea on Triassic paleogeographic reconstructions (Eide, 2002; Fig. 3a). The sand delivery system is on similar scale to that envisaged to have operated elsewhere during the Triassic, such as the 'Budleighensis' river system which drained northwards from the uplifted Variscides to feed basins in the East Irish Sea and farther north (Audley-Charles, 1970, Warrington and Ivimey-Cooke, 1992). The subdued physiography of Pangea during the onset of "wide" extensional rifting was probably important in allowing the operation of large-scale drainage systems.

The two groups of isotopically distinct K-feldspar from Upper Jurassic sandstones in the northern Porcupine Basin correspond to a combined Proterozoic I (Jurassic Group 1) and Proterozoic II source (Jurassic Group 2). There are no significant Archean, Avalonian or Variscan contributions, ruling out a far-northerly source or any input from the south. Significantly, there are no indications that K-feldspar grains have been recycled from inverted Triassic sandstones. These data are consistent with existing palaeogeographic models (Butterworth et al., 1999) that envisage drainage from north to south with grain transport distances <150 km. The proto-Rockall Basin may have acted as a sediment trap at this time, preventing the delivery of Archean grains across the rift, with sand dispersed from footwall uplifts southwards into the Porcupine, and possibly northwestwards into Rockall Basin (Fig. 3b). The narrow rifting style and significant topography may have limited the scale of drainage, with local highs supplying sediment and controlling drainage to a greater extent than during the Triassic.

CONCLUSIONS

Pb isotopic data for detrital K-feldspar in Mesozoic sandstones west of Ireland demonstrate the utility and insight offered by the Pb provenance tool. Targeted laser ablation sampling avoids heterogeneities within grains and is rapid, allowing adequate numbers of medium to coarse sand grains to be analyzed. Prospective source areas are relatively easily characterised. The data (1) reveal unsuspected sub-populations in one of the main framework grain components in both groups of sandstones, (2) highlight a major change in sand provenance tied to different rift phases, (3) rule out certain source areas, (4) constrain the direction of sand transport, (5) limit the dispersal distance, (6) provide evidence for links between continental and offshore depositional systems and (7) suggest a lack of recycling of Triassic sandstones into the Jurassic. The sandstones analyzed in this studied are all from offshore cores, and such data are important to predicting the scale, distribution and orientation of reservoir sandstones. Ultimately, higher resolution Pb domain mapping and sediment typing on the conjugate Atlantic margins will help place the rifted basins, intervening blocks and sediment source areas back in their pre-rift positions.

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FIGURE CAPTIONS

Figure 1. Map of the North Atlantic region (after Roberts et al., 1999, Karlstrom et al., 2001 and Lundin and Doré, 2005), showing the Pb domains constrained by published and new Pb isotopic analyses of K-feldspar grains from crystalline basement (data from Zartman and Wasserburg, 1969; Blaxland et al., 1979; Vitrac et al., 1981; Ashwal et al., 1986; Ayuso and Bevier, 1991; Kalsbeek et al., 1993; DeWolf and Mezger, 1994; Dickin,

1998; Yamashita et al., 1999; Ayer and Dostal, 2000; Loewy et al., 2003; Connelly and Thrane, 2005; Tyrrell, 2005; Tyrrell et al., 2006. Also shown are the main Mesozoic basins offshore western Ireland and the numbered locations of sampled wells; 1: Triassic sandstones from wells 18/25–1 and 18/20–2z in the Slyne Basin; 2: Upper Jurassic sandstones from wells 26/28–1 and 35/8–2 in the Porcupine Basin; 3: Cretaceous sandstones from shallow borehole 83/20-sb01; 4: Cretaceous sandstones from shallow borehole 16/28-sb01. FC = Flemish Cap, FSB = Faeroe-Shetland Basin, GB = Galicia Bank, HB = Hatton Bank, IT = Inishtrahull, JB = Jeanne D’Arc Basin, OB = Orphan Basin, OCCB = Oceanic/Continental Crust Boundary, P = Porcupine Bank, PBs = Porcupine Basin, RB = Rockall Bank, RT = Rockall Trough, SB = Slyne Basin.

Figure 2. Plot of $^{206}Pb/^{204}Pb$ versus $^{207}Pb/^{204}Pb$ of individual detrital K-feldspar grains from a) Triassic sandstones from the Slyne Basin and b) Jurassic sandstones from the north Porcupine Basin. Also shown are Pb analyses of K-feldspar grains from Cretaceous sands and sandstones from the margins of the Rockall Bank. Pb isotopic ranges for the five basement domains described in the text and illustrated on Figure 1 (for color legend and Pb data sources, see Fig. 1).

Figure 3. Schematic paleogeographic reconstructions of the North Atlantic region during a) the Lower Triassic (after Audley-Charles, 1970; Zeigler, 1990; Warrington and Ivimey-Cook, 1992; Torsvik et al., 2001; Scotese, 2002; Eide, 2002; Dancer et al., 2005) and b) the Upper Jurassic (after Ziegler, 1990; Scotese, 2002; Williams et al., 1999; Butterworth et al., 1999 and Eide, 2002) showing potential drainage paths as indicated by

the Pb isotopic composition of detrital K-feldspar grains. NPB = Northern Porcupine Basin, WHP = West Hebridean Platform, for additional abbreviations, see figure caption 1.

[1] GSA Data Repository item 2007xxx, comprising lead isotopic data from detrital/basement K-feldspar and supplementary data plots, is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.


70ºN
40ºW
30ºW
60ºN
Norwegian - Greenland Sea
Torngvist Line
70ºW
FSB
?
HB
?
RB
RT
IT
SB
4
1
2
3
P
PBs
Labrador Sea
North Atlantic Ocean
OCCB
50ºN
0º
Celtic Sea Basins
Bay of Biscay
?
60ºW
OB
FC
JB
?
GB
50ºW
20ºW
40ºN
10ºW
Basement affinity of continental crust
Archaen
Proterozoic I
Proterozoic II
Avalonian
Variscan
Basins with bathymetric expression
Crustal sutures
Sampled well(s)


A
B
16.2
16.0
15.8
15.6
15.4
15.2
15.0
14.8
14.6
14.4
14.2
$^{207}Pb/^{204}Pb$
13
14
15
16
17
18
19
20
13
14
15
16
17
18
19
20
$^{206}Pb/^{204}Pb$
Cretaceous 83/20-sb01
Cretaceous 16/28-sb01
Triassic Group 2
Triassic Group 1
Other Triassic
Cretaceous 83/20-sb01
Cretaceous 16/28-sb01
Jurassic Group 2
Jurassic Group 1
Other Jurassic


A) Lower Triassic
?
?
? RB
WHP
SB
Irish Massif
Celtic Sea Basins
Welsh Massif
Cornubia Massif
?
?
300 km
B) Upper Jurassic
?
Labrador Sea Basins
Proto-Rockall Basin
?
RB
?
?
NPB
Porcupine Bank
Irish Massif
Welsh Massif
Celtic Sea Basins
?
Porcupine Basin
Orphan Basin
?
Flemish Cap
Cornubia Massif
Basement affinity of massifs
Archaen
Proterozoic I
Proterozoic II
Avalonian
Variscan
Depocenters
Likely deposits
Crustal sutures
Paleodrainage routes
Position of sampled wells