## Supplementary

##  Analytical techniques and result

### Major/trace elements

Bulk-rock shale chemistry data were collected by Bureau Veritas Ltd. Major/trace elements were analysed on an Agilent 7900 ICP-MS. Analysis was performed on ~0.15g of rock powder that have been digested and refluxed with a mixture of Acids, including: Hydrofluoric, Nitric, Hydrochloric and Perchloric Acids. Rh and Ir were used as an internal standard for drift correction. The generation of oxides and doubly charged species was monitored using the mass ratios Th/ThO with on-line interference correction and internal standard correction carried out. To assess accuracy of the digestion process and analysis, certified reference materials (CRMs) Rmad25, Rmad 500 (A set), Rref25, Rref500 (B set) were run. Analytical reproducibility was assessed by repeat analysis of random duplicates at the end of the run.

Table Bulk-shale major/trace element compositions of the analysed Kyalla samples from the core Balmain-1.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| IDENT | Al | Ca | Mg | P | FORMATION | CORE | DEPTH |
|  | ppm | ppm | ppm | ppm |  |  | m |
| B1 940 | 108000 | 900 | 8500 | 450 | KYALLA | BALMAIN-1 | 940 |
| B1 940 Rpt | 111000 | 900 | 8900 | 450 |  |  |  |
| B1 945 | 117000 | 800 | 8100 | 400 | KYALLA | BALMAIN-1 | 945 |
| B1 949 | 98200 | 1500 | 8800 | 600 | KYALLA | BALMAIN-1 | 949 |
| B1 958 | 111000 | 700 | 5600 | 350 | KYALLA | BALMAIN-1 | 958 |
| B1 962 | 91600 | 400 | 4900 | 100 | KYALLA | BALMAIN-1 | 962 |
| B1 962 Rpt | 95600 | 500 | 5000 | 100 |  |  |  |
| B1 967 | 104000 | 500 | 5700 | 350 | KYALLA | BALMAIN-1 | 967 |
| B1 971 | 96600 | 600 | 7000 | 150 | KYALLA | BALMAIN-1 | 971 |
| B1 976 | 99700 | 1100 | 7700 | 50 | KYALLA | BALMAIN-1 | 976 |
| B1 985 | 101000 | 500 | 6700 | 150 | KYALLA | BALMAIN-1 | 985 |
| B1 990 | 80600 | 300 | 5300 | 100 | KYALLA | BALMAIN-1 | 990 |
| B1 990 Rpt | 77300 | 400 | 5100 | 150 |  |  |  |
| B1 994 | 99700 | 500 | 5600 | 150 | KYALLA | BALMAIN-1 | 994 |
| B1 998 | 106000 | 400 | 5600 | 150 | KYALLA | BALMAIN-1 | 998 |
| B1 1003 | 71100 | 500 | 4100 | 50 | KYALLA | BALMAIN-1 | 1003 |
| B1 1007 | 92200 | 400 | 5200 | <50 | KYALLA | BALMAIN-1 | 1007 |
| B1 1012 | 106000 | 500 | 5600 | 150 | KYALLA | BALMAIN-1 | 1012 |
| B1 1012 Rpt | 107000 | 500 | 5600 | 100 |  |  |  |
| S9 1013.37 | 107436 | 357 | 5307 | 250 | KYALLA | BALMAIN-1 | 1013 |
| B1 1016 | 98400 | 600 | 4900 | 150 | KYALLA | BALMAIN-1 | 1016 |
| S8 1018.9 | 109553 | 500 | 5126 | 270 | KYALLA | BALMAIN-1 | 1019 |
| S7 1024.35 | 113787 | 572 | 6694 | 270 | KYALLA | BALMAIN-1 | 1024 |
| S7 1024.35 Rpt | 113257 | 572 | 6634 | 260 |  |  |  |
| S6 1026.95 | 123313 | 500 | 6573 | 370 | KYALLA | BALMAIN-1 | 1027 |
| S5 1030.53 | 114845 | 858 | 5970 | 480 | KYALLA | BALMAIN-1 | 1031 |
| S4 1036.3 | 116962 | 500 | 5970 | 350 | KYALLA | BALMAIN-1 | 1036 |
| S3 1040.1 | 113257 | 500 | 5608 | 320 | KYALLA | BALMAIN-1 | 1040 |
| S2 1043.8 | 118550 | 429 | 5669 | 340 | KYALLA | BALMAIN-1 | 1044 |
| B1 1050 | 109000 | 500 | 6000 | 150 | KYALLA | BALMAIN-1 | 1050 |
| S1 1050.71 | 112199 | 429 | 5910 | 320 | KYALLA | BALMAIN-1 | 1051 |
| BLANK 1 | <100 | <100 | <100 | <50 |  |  |  |

### Sm–Nd and Pb–Pb isotopes

A total of 15 shale samples, taken at approximately 30 metres intervals, covering the core length of the Balmain-1, were crushed for both Sm–Nd and Pb–Pb isotopic analysis. Approximately 80 mg rock powder of each sample was combined with a spike of 150Nd and 147Sm, was dissolved with a mixture solution of nitric acid (2 mL, 7 N) and hydrofluoric acid (4 mL, 48 wt.%). Samples were over-heated at a constant temperature (140 °C) in sealed Teflon cups for two days. The samples were then evaporated to dry, with nitric acid (6 N) reconcentration. The dried samples were redissolved with hydrochloric acid (6 N) and heated at 160°C for two days. Each sample was separated to two portions for Sm–Nd and Pb–Pb analysis, respectively.

For Sm–Nd analysis, the rare earth element concentration was obtained by passing samples through columns filled with 200-400 mesh AGW X8 anion exchange resin in Polyprep columns to removal free iron. Then the subsequent isolation of both Sm and Nd was carried out by using glass columns filled with 1 mL Eichrom Ln ion exchange resin. After the purification, samples were loaded onto outgassed rhenium filaments and the 143Nd/144Nd and 147Sm/144Nd ratios were measured on an Isotopx Pheonix TIMS at the University of Adelaide. Mass bias corrections were performed using 146Nd/144Nd=0.721903. Repeated measurement of JNdi-1 (n=4) and SCo-1 (n=2) standards returned 143Nd/144Nd values of 0.512107 ± 2 (2σ) and 0.512157 ± 2 (2σ). Nd and Sm corrections were corrected for 200 pg and 150 pg blanks.

Pb extraction was conducted by using standard miniaturised HBr–HCl chemistry on columns charged with AG1x8, 200–400 mesh resin after *Reuer et al. (2003)*. The samples were then eluted by with 1 N HBr, 2 N HCl and 6 N HCl to achieve the required purity for analysis. Samples were loaded onto outgassed rhenium filaments and Pb isotopic compositions were measured on an Isotopx Pheonix TIMS at the University of Adelaide. The reported uncertainties are better than ± 1.1% (2σ, 206Pb/204Pb), ± 1.3% (2σ, 207Pb/204Pb) and ± 0.5% (2σ, 208Pb/204Pb). The SRM-981 standard was analysed to correct the instrumental mass fractionation, using the values of 16.9412 (206Pb/204Pb), 15.4988 (207Pb/204Pb) and 36.7233 (208Pb/204Pb) after *Taylor et al. (2015)*. Two SCo-1 standard analyses returned 206Pb/204Pb = 19.240 ± 0.16, 207Pb/204Pb = 15.695 ± 0.018 and 208Pb/204Pb = 38.933 ± 0.38. The procedural blanks during the measurement were less than 100 pg.

### U–Pb TIMS dating

Baddeleyite crystals were separated using the Wilfley water-shaking table in a technique modified after *Söderlund and Johansson (2002)*. This method, using a pipette to remove a concentrate of small, dense, flat minerals off the Wilfley table, yielded several small baddeleyite grains. No pre-treatment methods were used beyond cleaning the grains with concentrated distilled HNO3 and HCl and, due to their small size, no chemical separation methods were required. For ID-TIMS analysis, the samples were spiked with an in-house 205Pb-235U tracer solution, which has been calibrated against SRM981, SRM 982 (for Pb), and CRM 115 (for U), as well as an externally-calibrated U–Pb solution (the JMM solution from the EarthTime consortium).

Dissolution and equilibration of spiked single crystals was by vapour transfer of HF, using Teflon microcapsules in a Parr pressure vessel placed in a 200°C oven for six days. The resulting residue was re-dissolved in HCl and H3PO4 and placed on an outgassed, zone-refined rhenium single filament with 5µL of silicic acid gel. U–Pb isotope analyses were carried out using a Thermo Triton T1 mass spectrometer at the John de Laeter Centre of Curtin University, in peak-jumping mode using a secondary electron multiplier. Uranium was measured as an oxide (UO2). Fractionation and deadtime were monitored using SRM981 and SRM 982. Mass fractionation was 0.03 ± 0.06 %/amu. Data were reduced and plotted using the software packages Tripoli (from CIRDLES.org) and Isoplot (*Ludwig, 2009*). All uncertainties are reported at 2σ. Sample weights are calculated from crystal dimensions and are associated with as much as 50% uncertainty (estimated). Blank composition is: 206Pb/204Pb = 18.55 ± 0.63, 207Pb/204Pb = 15.50 ± 0.55, 208Pb/204Pb = 38.07 ± 1.56 (all 2σ), and a 206Pb/204Pb – 207Pb/204Pb correlation of 0.9. Th/U calculated from radiogenic 208Pb/206Pb and age. Measured isotopic ratios corrected for tracer contribution and mass fractionation (0.03 ± 0.06 %/amu). Ratios involving 206Pb are corrected for initial disequilibrium in 230Th/238U using Th/U = 4 in the crystallization environment.

**References**

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