Supplementary Material A

**ANALYTICAL METHODS**

*In situ Rb–Sr dating and trace element laser ablation analysis*

Laser analyses on samples and standards were carried out at Adelaide Microscopy, University of Adelaide using a laser ablation (RESOlution-LR ArF 193nm excimer laser) inductively couple-mass spectrometer (Agilent 8900x ICP-MS/MS) with the analytical parameters and tuning conditions following Redaa et al. (2021). One spot analysis consisted of 20 seconds of gas background collected while the laser was not firing followed by 40 seconds of ablated signal. Strontium isotopes were measured in the oxidised molecule SrO. Strontium is oxidised with N2O gas in the reaction chamber (e.g. 87Sr16O formed from 87Sr at 103 amu) whilst the unreactive 85Rb was measured on-mass. Dwell times for each Sr isotope were 50ms, 10ms for Rb and 5ms for all other masses totalling to 0.31 seconds. The mass spectrometer and laser analytical parameters as well as tuning conditions used in this study are summarised in Table 1.

*In situ* Rb**‒**Sr dating of CRPG reference material Mica-MG (Govindaraju et al., 1994) prepared as a nano-powder pellet and a phlogopite mineral sample MDC sourced from the same quarry in Bekily, Madagascar were assumed to be of the same age (Armistead et al., 2020; Hogmalm et al., 2017; Li et al., 2020; Redaa et al., 2021; Tamblyn et al., 2020) were used as primary and secondary standards respectively (Supplementary Figure 1). A glauconite grain mount sample GL-O of known Cretaceous age from Bagnols-sur-Cèze, France was also analysed (Supplementary Figure 1) as an independent secondary standard (Rousset et al., 2004). Glass standards NIST-610 and BCR-2G (Jochum et al., 2016; Wilson, 1997) were also analysed for element quantification. Isochron ages were calculated using IsoplotR software (Vermeesch, 2018). The mineral standard MDC was anchored to 87Rb/86Sr = 0.00001 ± 0.000001 and 87Sr/86Sr = 0.72607 ± 0.00363 initial ratios as reported by Hogmalm et al. (2017) yielding an age of 529 ± 6 Ma (Supplementary Figure 1). This is within error of the Mica-MG age from the same analysis of 523 ± 4 Ma (Supplementary Figure 1) as well as the mean age of the standard (519.4 ± 6.5 Ma) published by Hogmalm et al. (2017). Furthermore, the glauconite grain GL-O (Supplementary Figure 1) also gave an age (94 ± 3 Ma) within the error of its published value (98 ± 4 Ma) published by Rousset et al. (2004). Elemental analyses of standards and their subsequent QAQC are reported in and cross-referenced with their respective published values (Supplementary Figure 2). Average values of major and rare earth element in BCR2-G are within error and positively covaries with their published data (Jochum et al., 2016).

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| **Laser Parameters** | ***Value*** | ***Unit*** |
| Ar carrier gas | 1050 | ml/min |
| Fluence | 3.5 | J/cm2 |
| He carrier gas | 350 | ml/min |
| N2 addition | 3.5 | ml/min |
| Repetition rate | 10 | Hz |
| Spot size | 74 | µm |
| **ICP-MS/MS Plasma Parameters** | ***Value*** | ***Unit*** |
| RF plasma power | 1350 | W |
| **ICP-MS/MS Lens Parameters** | ***Value*** | ***Unit*** |
| Lens extract 1 | -2.0 | V |
| Lens extract 2 | -150 | V |
| Omega bias | 75 | V |
| Omega lens | 7.0 | V |
| Q1 entrance | 2.0 | V |
| Q1 exit | -1.0 | V |
| Cell focus | -2.0 | V |
| Cell entrance | -100 | V |
| Cell exit | -150 | V |
| Deflect | -10 | V |
| Plate bias | -80 | V |
| **ICP-MS/MS Q1 Parameters** | ***Value*** | ***Unit*** |
| Q1 bias | -2.0 | V |
| Q1 prefilter bias | -9.0 | V |
| Q1 postfilter bias | -10 | V |
| **ICP-MS/MS Cell Parameters** | ***Value*** | ***Unit*** |
| N2O flow rate | 0.37 | mL/min |
| OctP bias | -23 | V |
| Axial acceleration | 2.0 | V |
| OctP RF | 180 | V |
| Energy discrimination | -10 | V |
| **ICP-MS/MS Q2 Parameters** | ***Value*** | ***Unit*** |
| Q2 bias | -33 | V |

Table 1: Summary of LA-ICP-MS/MS instrumental parameters.

*Carbonate Elemental Analysis*

Carbonate samples were leached to ensure minimum incorporation of non-carbonate phases (Cao et al., 2020; Halverson et al., 2010; Tostevin et al., 2016). Rock chips were micro-drilled along laminae to target the carbonate matrix, making sure to avoid veining, clasts and weathered surface. The rock powder were then reacted with 1M ammonium acetate to remove any loose cations on the surface. This was then followed by a second and third leach with 0.2 M acetic acid to extract the carbonate phase. Between each step, the solution was sonicated and centrifuged for 20 and 10 minutes respectively. The final supernatant was set aside for solution inductively coupled plasma mass spectrometer (ICP-MS) analysis at Adelaide Microscopy using an Agilent 8900x mass spectrometer instrument. This was then digested with 2% nitric acid and split into aliquots of 1:10000 and 1:1000 dilutions for major and trace element analysis. Calibration solutions were prepared from a multi-element stock standard solution and diluted with 2% nitric acid as well. Primary standard JDo-1 was used for all analytical runs (IMAI et al., 1996).

For sample introduction, the ICP-MS was equipped with a Miramist nebuliser and a quartz spray chamber, into which samples were introduced by a peristaltic pump at a flow rate of 1.0mL/min. An internal standard, Indium, was mixed online with the samples to compensate for matrix effects. All element concentrations were determined against certified multi-element calibration standards (Choice Analytical, Australia) and blanks were interspersed throughout the analysis session, as well as measurement of the 200ppb calibration solution to check the instrument stability. The instrument was operated with an RF power of 1500W, a carrier gas flow of 0.89 L/min and a make-up gas flow of 0.19 L/min. Sample uptake rate was 1.0 mL/min and the dwell times ranged between 10ms to 1s. Three replicates were obtained for each sample. The data was processed using Agilent Mass-Hunter Data Analysis.

*Carbonate Isotopic Analysis*

A fraction of the solution prepared for elemental geochemistry in carbonates were measured for isotopic analyses. Coupled 87Sr/86Sr and δ88/86Sr analyses were undertaken using a Phoenix Isotopx thermal ionisation mass spectrometry (TIMS) following the extensive methodology described by (Shao et al., 2018; Shao et al., 2021). Two aliquots each containing around 500 ng of Sr were taken from the sample solution, with one being spiked with a 87Sr-84Sr double spike solution and consequently giving a spike to sample ratio 84Srsp/84Srsa between 10-50. The 87Sr-84Sr double spike solution was prepared at GEOMAR (Kiel, Germany) with a total Sr concentration of 0.0090mg/g, and its respective Sr isotope composition as determined by TIMS at University of Adelaide is provided in Shao et al. (2021) .

Procedural Sr blanks prepared for analyses consisted of a drop of deionized water, a drop of 0.1 M phosphoric acid and an additional drop of 84Sr-enriched single spike in a Teflon vial. Next, the Sr fraction of all samples and standers along with the blanks used were purified using a 600 μL Micro Bio-Spin separation columns filled with Sr-specific resin (Eichrom Sr-SPS). They were then loaded onto single degassed Re filaments to be prepared for 87Sr/86Sr and δ88/86Sr data collected.

87Sr/86Sr isotopic ratios of carbonate samples were analysed through the conventional ‘dynamic’ analytical method for better accuracy (Shao et al., 2018). On the other hand δ88/86Sr data were collected using a ‘static’ analytical method and corrected for instrumental and procedural fractionation effects via the double spike technique (Krabbenhöft et al., 2010). To apply this method, a separate analyses with an ‘un-spiked’ aliquot for each sample also needed to be analysed concurrently (Krabbenhöft et al., 2010). As such, each analytical session contained both spiked and un-spiked samples ran parallel with NIST SRM 987 (Krabbenhöft et al., 2009) and JCP-1 (Inoue et al., 2004) standards. Both spiked and unspiked samples were analysed by TIMS using a static multicollection routine. During analysis, an 88Sr beam with a magnitude of about 5–6 V was attained, and 84Sr, 85Rb, 86Sr, 87Sr, and 88Sr isotope beams were collected over 200 cycles (10 cycles for 20 blocks, with 30 s baseline and 8 s peak integrations). From these collected data, the following isotope ratios were calculated: 88Sr/84Sr, 86Sr/84Sr, 87Sr/84Sr and 88Sr/86Sr. This is then used to determine the ‘double-spike corrected’ 88Sr/86Sr ratios. Isotopic fractionation effects due to the procedure or instrument applied were corrected using a modified 87Sr-84Sr double spike correction algorithm (Shao et al., 2021) modified from Heuser et al. (2002) and Samanta et al. (2016).

Stable Sr isotopic data of all samples is normalised relative to SRM 987 standard following the equation:

δ88/86Sr values of unknown samples as well as the JCP-1 standards were normalised to the average of the SRM987 standards analysed in the same analytical session. This approach was used to correct any session-to-session drifts, which were quantified by monitoring SRM 987 like previously done in other high-precision Sr isotope studies (Andrews and Jacobson, 2017; Andrews et al., 2016; Krabbenhöft et al., 2010; Ohno et al., 2008; Shalev et al., 2017; Shao et al., 2021; Vollstaedt et al., 2014).

High precision 87Sr/86Sr isotopic results were collected by re-running the TIMS on unspiked samples using the ‘dynamic’ method. With this analysis, a typical 88Sr beam of 5–6 V was attained, and the following isotope ratios were collected: 87Sr/86Sr, 86Sr/88Sr and 84Sr/86Sr, using a method consisting of 100 cycles (20 cycles for 5 blocks). Mass dependent fractionation due to the instrument or procedural effects were corrected using an internal normalisation assuming the 86Sr/88Sr ratio of 0.1194 (Nier, 1938). Sr isotopic results from secondary standard JCP-1 and NIST SRM 987 are summarised in Supplementary Figure 3 and compared with their published values (Balcaen et al., 2005; Inoue et al., 2004; Krabbenhöft et al., 2009).

Approximately 100 mg of carbonate powder were micro-drilled for each sample to prepare for analysis of δ13Ccarb and δ18O values. Analysis were undertaken using a duel inlet Isotope Ratio Mass Spectrometry (IRMS) Fision Optima with combined Isocarb Carbonate Preparation System at the University of Adelaide following Falster et al. (2018). Powders were purged with 1M phosphoric acid to dissolve the carbonate and injected with helium. The resultant fumes were then measured to produce δ13Ccarb and δ18O values. An in-house standard ANU-P3 (Australian National University- carbonate), UAC-1 and IAEA CO-8 was used during analysis which all have been calibrated against international standards. The analytical errors (2SD) for δ13Ccarb and δ18O values are on the order of 0.05 per mil (‰) or better. Carbonate and Oxygen isotopic ratios were recorded in conventional delta notation with respect to values of Pee Dee Belemnite (VPDB) as follows:

*Shale Geochemical Analysis*

Black, organic-rich shale intervals were crushed into a fine powder using a tungsten carbide mill for their elemental and pyrolysis analysis. Major and trace element concentrations were done using an Agilent 8900 quadrapole ICP-MS with Octopole Reaction System from a multi-acid dissolution of individual shale powdered samples following Cox et al. (2016) and Yang et al. (2020) at Adelaide Microscopy. Integrated sample introduction was tuned daily to optimise plasma conditions and sensitivity. Calibration was carried out using standards prepared from two multi-element stock standard solutions in the range 0.3 µg/L to 300 µg/L. A single solution prepared from an independent set of stock standards was analysed as an ‘unknown’ to determine the accuracy of the calibration standards. The data was processed using Agilent Mass-Hunter Data Analysis. An internal standard solution containing 61Ni, 115In, 147Sm, 169Tm and 205Tl was mixed in-line with the sample stream ahead of aspiration.

Organic geochemical pyrolysis measurements were done using a Weatherfords Source Rock Analyser and Rock-Eval 6 Turbo at the University of Adelaide. Shale powders were loaded onto the carousel and heated under inert helium in the pyrolysis and oxidation modes to obtain S1-4 peaks as well as Tmax. The pyrolysis oven was first held at 300°C for 5 minutes and ramped at 25°C per minute from 300°C to 650°C. Subsequently the oven was reduced to 220°C and held for 5 minutes with the carrier gas converted to inert air (CO & CO2 free) and purged, ramped at maximum heating to 580°C and held for 20 minutes. The flame ionisation detector (FID) was calibrated by running Weatherford Laboratories Instruments Division Standard 533. The IR Analysers were calibrated against standard gas with known concentration of CO2 and CO. An analysis blank was run as ‘blank’ mode with the sample batch and the blank data was automatically subtracted from all analyses. An external check standard was also run first with each batch to ensure the instrument status with additional check standards every 10 samples. The results were processed where peak areas and geochemical indices including Total organic carbon (TOC), Oxygen Index (OI), Hydrogen Index (HI) and Production Index (PI) are automatically calculated. Rock-Eval pyrolysis data was screened using quality control criteria defined by Hall et al. (2016).

*High resolution Scanning Electron Microscope mapping of shale samples*

Shale samples investigated for *in situ* Rb*–*Sr dating and trace element analysis were also mapped to determine their petrographic textures and elemental compositions. This is done to avoid the non-authigenic component of each sample, which can negatively impact the precision and accuracy of the geochronological results and potentially yield mixed ages (Field and Råheim, 1979). Back scatter electron (BSE) and elemental maps of shale samples were obtained using an FEI Quanta 450 Scanning Electron Microscope (SEM) with attached Oxford Ultima Max Large Area SDD EDS detector at Adelaide Microscopy following Subarkah et al. (2021).

Images of samples in this study show that they have not experienced any extensive, late-stage alteration event (Supplementary Figures 4 a-d). Samples selected for this study do not look crystalline or fissile. Furthermore, they also do not show evidence of veining or foliation (Supplementary Figures 4 a-d). In addition, large, sub-rounded or sheet-like detrital grains are still preserved, along with primary sedimentary structures. These detrital grains largely consisted of quartz (Si-bearing, shown in black), micas or clays (K and Fe-bearing, shown in orange) and were circumvented during analysis. Authigenic K-bearing minerals are shown in green and look mottled and mossy, lacking distinct grain boundaries (Supplementary Figure 4 a-d). They can also be seen wrapping around resistant sedimentary grains, recording the compaction process as these rocks were deposited (Deepak et al., 2022; Rafiei and Kennedy, 2019; Rafiei et al., 2020; Subarkah et al., 2022). Another authigenic phase found in the samples bears Fe and S and are interpreted as sulphides. These microcrystalline, framboidal crystals were interpreted to have formed syngenetically in the water column or possibly during early diagenesis in the top few centimetres of seafloor muds (Raiswell and Plant, 1980; Wilkin et al., 1996). They are consistently smaller than 100 μm in nature, which further supports their early origin as opposed to forming during late diagenesis or metamorphism (Large et al., 2007; Large et al., 2017). As such, the petrographic evidence found in these samples indicate that they have not been affected by a secondary event after they were deposited. Consequently, the authigenic K-bearing (and therefore Rb-bearing) phases were targeted for *in situ* Rb*–*Sr dating, as they would have the best potential for recording the primary burial history of these samples.

**FIGURE CAPTIONS**

Supplementary Figure 1: Results for primary and secondary standards for in situ *Rb–Sr* dating shows that they overlap with previously published data (Hogmalm et al., 2017; Rousset et al., 2004).

Supplementary Figure 2: Major and rare earth element values of BCR-2G from *in situ* analyses in comparison with certified data (Jochum et al., 2016).

Supplementary Figure 3: Sr isotopic values of standard JCP-1 and NIST SRM 987 in relation to published data (Balcaen et al., 2005; Inoue et al., 2004; Krabbenhöft et al., 2009).

Supplementary Figure 4 a-d: BSE images overlain with elemental maps of the shale samples selected for *in situ* laser ablation analysis in this study. Samples a) and b) are from LV09001 at depths 463.60 m and 469.50 m. The Manbulloo S1 well was sampled at depths 785.24 m and 868.75 m, denoted as c) and d). White line = 100 μm. Black = Si component, Green = K component, Red = Fe and S components, Orange = Fe and K components.

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