Supplementary Material A

**ANALYTICAL METHODS**

*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:

$$δ$$

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 1 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:

$$δ$$

$$δ$$

*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).

**FIGURE CAPTIONS**

Supplementary Figure 1: 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).

**REFERENCES**

Andrews, M. G., and Jacobson, A. D., 2017, The radiogenic and stable Sr isotope geochemistry of basalt weathering in Iceland: role of hydrothermal calcite and implications for long-term climate regulation: Geochimica et Cosmochimica Acta, v. 215, p. 247-262.

Andrews, M. G., Jacobson, A. D., Lehn, G. O., Horton, T. W., and Craw, D., 2016, Radiogenic and stable Sr isotope ratios (87Sr/86Sr, δ88/86Sr) as tracers of riverine cation sources and biogeochemical cycling in the Milford Sound region of Fiordland, New Zealand: Geochimica et Cosmochimica Acta, v. 173, p. 284-303.

Balcaen, L., Schrijver, I. D., Moens, L., and Vanhaecke, F., 2005, Determination of the 87Sr/86Sr isotope ratio in USGS silicate reference materials by multi-collector ICP–mass spectrometry: International Journal of Mass Spectrometry, v. 242, no. 2, p. 251-255.

Cao, C., Liu, X.-M., Bataille, C. P., and Liu, C., 2020, What do Ce anomalies in marine carbonates really mean? A perspective from leaching experiments: Chemical Geology, v. 532, p. 119413.

Cox, G. M., Jarrett, A., Edwards, D., Crockford, P. W., Halverson, G. P., Collins, A. S., Poirier, A., and Li, Z.-X., 2016, Basin redox and primary productivity within the Mesoproterozoic Roper Seaway: Chemical Geology, v. 440, p. 101-114.

Falster, G., Delean, S., and Tyler, J., 2018, Hydrogen Peroxide Treatment of Natural Lake Sediment Prior to Carbon and Oxygen Stable Isotope Analysis of Calcium Carbonate: Geochemistry, Geophysics, Geosystems, v. 19, no. 9, p. 3583-3595.

Hall, L., Boreham, C. J., Edwards, D. S., Palu, T., Buckler, T., Troup, A., and Hill, A., 2016, Cooper Basin Source Rock Geochemistry, Geoscience Australia.

Halverson, G. P., Wade, B. P., Hurtgen, M. T., and Barovich, K. M., 2010, Neoproterozoic chemostratigraphy: Precambrian Research, v. 182, no. 4, p. 337-350.

Heuser, A., Eisenhauer, A., Gussone, N., Bock, B., Hansen, B., and Nägler, T. F., 2002, Measurement of calcium isotopes (δ44Ca) using a multicollector TIMS technique: International Journal of Mass Spectrometry, v. 220, no. 3, p. 385-397.

IMAI, N., TERASHIMA, S., ITOH, S., and ANDO, A., 1996, 1996 COMPILATION OF ANALYTICAL DATA ON NINE GSJ GEOCHEMICAL REFERENCE SAMPLES, “SEDIMENTARY ROCK SERIES”: Geostandards Newsletter, v. 20, no. 2, p. 165-216.

Inoue, M., Nohara, M., Okai, T., Suzuki, A., and Kawahata, H., 2004, Concentrations of Trace Elements in Carbonate Reference Materials Coral JCp-1 and Giant Clam JCt-1 by Inductively Coupled Plasma-Mass Spectrometry: Geostandards and Geoanalytical Research, v. 28, no. 3, p. 411-416.

Krabbenhöft, A., Eisenhauer, A., Böhm, F., Vollstaedt, H., Fietzke, J., Liebetrau, V., Augustin, N., Peucker-Ehrenbrink, B., Müller, M. N., Horn, C., Hansen, B. T., Nolte, N., and Wallmann, K., 2010, Constraining the marine strontium budget with natural strontium isotope fractionations (87Sr/86Sr∗, δ88/86Sr) of carbonates, hydrothermal solutions and river waters: Geochimica et Cosmochimica Acta, v. 74, no. 14, p. 4097-4109.

Krabbenhöft, A., Fietzke, J., Eisenhauer, A., Liebetrau, V., Böhm, F., and Vollstaedt, H., 2009, Determination of radiogenic and stable strontium isotope ratios (87Sr/86Sr; δ88/86Sr) by thermal ionization mass spectrometry applying an 87Sr/84Sr double spike: Journal of Analytical Atomic Spectrometry, v. 24, no. 9, p. 1267-1271.

Nier, A. O., 1938, The isotopic constitution of strontium, barium, bismuth, thallium and mercury: Physical Review, v. 54, no. 4, p. 275.

Ohno, T., Komiya, T., Ueno, Y., Hirata, T., and Maruyama, S., 2008, Determination of 88Sr/86Sr mass-dependent isotopic fractionation and radiogenic isotope variation of 87Sr/86Sr in the Neoproterozoic Doushantuo Formation: Gondwana Research, v. 14, no. 1, p. 126-133.

Samanta, M., Ellwood, M. J., and Mortimer, G. E., 2016, A method for determining the isotopic composition of dissolved zinc in seawater by MC-ICP-MS with a 67Zn–68Zn double spike: Microchemical Journal, v. 126, p. 530-537.

Shalev, N., Gavrieli, I., Halicz, L., Sandler, A., Stein, M., and Lazar, B., 2017, Enrichment of 88Sr in continental waters due to calcium carbonate precipitation: Earth and Planetary Science Letters, v. 459, p. 381-393.

Shao, Y., Farkaš, J., Holmden, C., Mosley, L., Kell-Duivestein, I., Izzo, C., Reis-Santos, P., Tyler, J., Törber, P., Frýda, J., Taylor, H., Haynes, D., Tibby, J., and Gillanders, B. M., 2018, Calcium and strontium isotope systematics in the lagoon-estuarine environments of South Australia: Implications for water source mixing, carbonate fluxes and fish migration: Geochimica et Cosmochimica Acta, v. 239, p. 90-108.

Shao, Y., Farkaš, J., Mosley, L., Tyler, J., Wong, H., Chamberlayne, B., Raven, M., Samanta, M., Holmden, C., Gillanders, B. M., Kolevica, A., and Eisenhauer, A., 2021, Impact of salinity and carbonate saturation on stable Sr isotopes (δ88/86Sr) in a lagoon-estuarine system: Geochimica et Cosmochimica Acta, v. 293, p. 461-476.

Tostevin, R., Shields, G. A., Tarbuck, G. M., He, T., Clarkson, M. O., and Wood, R. A., 2016, Effective use of cerium anomalies as a redox proxy in carbonate-dominated marine settings: Chemical Geology, v. 438, p. 146-162.

Vollstaedt, H., Eisenhauer, A., Wallmann, K., Böhm, F., Fietzke, J., Liebetrau, V., Krabbenhöft, A., Farkaš, J., Tomašových, A., Raddatz, J., and Veizer, J., 2014, The Phanerozoic δ88/86Sr record of seawater: New constraints on past changes in oceanic carbonate fluxes: Geochimica et Cosmochimica Acta, v. 128, p. 249-265.

Yang, B., Collins, A. S., Cox, G. M., Jarrett, A. J. M., Denyszyn, S., Blades, M. L., Farkaš, J., and Glorie, S., 2020, Using Mesoproterozoic Sedimentary Geochemistry to Reconstruct Basin Tectonic Geography and Link Organic Carbon Productivity to Nutrient Flux from a Northern Australian Large Igneous Province: Basin Research, v. n/a, no. n/a.