**Supplementary Material**

Please note that all Supplementary Figures can be found in Subarkah et al. (2022).

1. **Analytical Methods**

Samples were comprehensively characterized by scanning electron microscope (SEM) energy dispersive X-ray spectroscopy (EDS) for mineral liberation analysis (MLA) in conjunction with bulk XRD data to confirm phase identifications. Backscatter electron (BSE) images and MLA maps were obtained with a Hitachi SU3800 Automated Mineralogy Scanning Electron Microscope at Adelaide Microscopy. Classification of individual spectra was done using the Advanced Mineral Identification and Characterization System (AMICS) software. AMICS deconvolves mixed spectra and assigns up minerals per analysed in a single spot. Mineral concentrations (reported as wt. %) in the mapped areas are determined by converting the mineral area % to wt. % using published densities for all identified sample constituents, with accuracy and precision comparable to quantitative XRD analysis (Table 1). Bulk XRD analyses (Cox et al., 2016; NTGS, 2012) were used as an independent crystallography based mineral identification of samples to confirm the phases characterized by AMICS micro-imaging.

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) and summarised in Table S1. 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.

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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 S1. LA-ICP-MS/MS instrumental parameters following Redaa et al. (2021)

1. **Petrography And Mineralogy**

High resolution SEM-EDS MLA mapping and bulk XRD analysis showed that quartz was the most abundant mineral phase in all samples selected for in situ laser ablation investigation in this study. They are the main detrital component, with grain sizes ranging from < 10 μm and up to 50 μm. They are commonly sub-angular in coarser layers and more sub-rounded in finer interbeds. Quartz has negligible Rb and Sr, so does not influence our results.

All Upper and Middle Velkerri Formation had similar mineral assemblages based on bulk XRD and SEM-EDS mineral mapping. The sample derived from 415 m and 520 m depth were matrix-supported siltstones (Figure S2A-B), with illite being the second most dominant mineral phase (ca. 35 wt. %). These samples still preserve its primary sedimentary structures, with well-defined interbedded siltstones and very fine sands. Illite here is mottled and commonly intergrown with authigenic quartz. Some phases can be seen forming thing elongated interconnected slivers. Furthermore, illite in these samples are dispersed throughout the matrix, filling in pore spaces. These illite domains are commonly randomly oriented with respect to bedding. Some matrices are so fine that individual flakes could not be distinguished. This can be similarly found in the Velkerri Formation shale from 696 m (Figure S2C). However, Velkerri Formation shale from 696 m was more dominated by detrital quartz and had less illite phases within the sample. Some larger flakes of illite can be found are likely physical weathering products of biotite. Another less common occurrence of illite morphology is the alteration of feldspar. Nevertheless, the matrix supported nature of samples and the presence of illite compacted concretions are found in other Roper Group shales and suggest that they originate through reverse weathering processes (Rafiei and Kennedy, 2019; Subarkah et al., 2021). These are the dominant mineralogy in each sample. Therefore, we conclude that the Rb‒Sr data collected from each spot analysis are derived predominantly from cogentic K-hosting (and therefore Rb-bearing) illites.

The Lower Velkerri Formation shales consisted of similar mineral assemblages compared to samples from the Upper and Middle Velkerri Formation. However, these samples did not preserve primary sedimentary textures as the previous subset. The sample sourced from 938 m depth had illite matrices which looked fissile, with a prominent foliated fabric (Figure S2D). This is not commonly found in clay morphologies originating from authigenic or early diagenetic processes and is instead likely induced by a later-stage secondary reaction. Pyrite present in this sample filled cavities and overprint earlier illite and chlorite phases. In addition, apatite in this sample has two main morphologies. This included phosphates that either grew in framboidal structures or as alteration products of clay minerals. On the other hand, the Lower Velkerri Formation shale from 1220 m depth is comparatively more crystalline (Figure S2E). Only a minor amount of detrital quartz has evident, and they are consistently up to 100 µm in size. However, illite grain morphologies in this sample do not look detrital. Instead, they form interlocking grain fabrics and seemed to be products from recrystallisation of a finer-grained clay matrix. Moreover, fine-grained clays can also be seen replaced by large chlorite domains larger than 100 µm in size. Overall, the petrography of the Lower Velkerri Formation shales suggest that they have experienced post-depositional secondary fluid-rock interactions. The full MLA maps overlain by BSE images of all samples in this study can be found in the Supplementary Information.

1. **One-Dimensional Thermal Modelling**

One-dimensional thermal modelling of the Altree 2 well was conducted using the MATLAB code SILLi 1.0, as produced by Iyer et al. (2018). As the simulation aims to model thermal conditions following emplacement of a Derim Derim Dolerite sill at ca. 1300 Ma, the modelled sedimentary column is different to that preserved currently in the Altree 2 well. Post-Mesoproterozoic sedimentary rocks have been removed for this simulation, and an additional 1.5 km of upper Roper Group sedimentary rocks have been added to satisfy the maximum Palaeotemperatures predicted by Tmax values preserved in the upper and middle Velkerri Formation. Physical properties for lithologies are from the global geochemical dataset of Gard et al. (2019), apart from average density and TOC values, which are taken from Altree 2 well logs. A typical geothermal gradient of 25 °C/km has been used for the simulation, with a surface temperature of 25 °C. Input model formation top ages are not true representations of the Mesoproterozoic strata but are instead designed to deposit required sedimentary rocks over a reasonable time period and allow the geothermal gradient to achieve equilibrium prior to sill emplacement at a model time of 10 Ma. Full sedimentary rock physical properties and model deposition times are provided in Table S2, and sill physical properties and emplacement characteristics are provided in Table S3.

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| ***Lithology*** | ***Top Depth (m)*** | ***Top Age (Ma)*** | ***Density (kg m-3)*** | ***Heat Capacity (J kg-1 C-1)*** | ***Thermal Conductivity (W m- 1K-1)*** | ***TOC***  ***(wt. %)*** |
| Upper Roper Group | 0 | 20 | 2550 | 731 | 2.79 | 0 |
| Moroak Sandstone | 1500 | 40 | 2450 | 780 | 3.76 | 0 |
| Upper Velkerri Formation | 1572 | 60 | 2625 | 731 | 2.79 | 0.55 |
| Upper Velkerri Formation | 1800 | 63 | 2550 | 731 | 2.79 | 2.74 |
| Middle Velkerri Formation | 1852 | 65 | 2550 | 731 | 2.79 | 5.41 |
| Middle Velkerri Formation | 1980 | 67 | 2450 | 731 | 2.79 | 3.51 |
| Lower Velkerri Formation | 2128 | 69 | 2550 | 731 | 2.79 | 0.12 |
| Lower Velkerri Formation | 2135 | 70 | 2100 | 731 | 2.79 | 0.07 |
| Lower Velkerri Formation | 2140 | 71 | 2550 | 731 | 2.79 | 0.58 |
| Lower Velkerri Formation | 2307 | 73 | 2450 | 734 | 3.77 | 3.12 |
| Lower Velkerri Formation | 2310 | 74 | 2650 | 731 | 2.79 | 0.78 |
| Bessie Creek Sandstone | 2410 | 106 | 2750 | 780 | 3.76 | 0 |
| Bessie Creek Sandstone | 2415 | 108 | 2500 | 780 | 3.76 | 0 |
| Corcoran Formation | 2827 | 120 | 2625 | 780 | 3.76 | 0 |
| Corcoran Formation | 2980 | 122 | 2625 | 731 | 2.79 | 0 |

Table S2. Lithospheric and stratigraphic parameters used for one-dimensional modelling with SILLi 1.0.

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| *Top Depth (m)* | 2868 |
| *Thickness (m)* | 75 |
| *Emplacement Time (Ma)* | 10 |
| *Emplacement Temp (°C)* | 1150 |
| *Density melt (kg m-3)* | 2550 |
| *Heat Capacity melt (J kg-1 K-1)* | 850 |
| *Density solid (kg m-3)* | 3000 |
| *Heat Capacity solid (J kg-1 K-1)* | 820 |
| *Thermal Conductivity (W m-1 K-1)* | 2.1 |
| *Solidus T (°C)* | 950 |
| *Liquidus T (°C)* | 1150 |
| *Latent Heat of Crystallization (kJ kg-1)* | 320 |

Table S3. Thermal properties and emplacement conditions for Derim Derim Dolerite sill used in one-dimensional modelling with SILLi 1.0.

1. **Figure Captions**

**Figure S1. Summary of geochronological data from standards GL-O glauconite (Charbit et al., 1998; Derkowski et al., 2009) and MDC phlogopite (Hogmalm et al., 2017) used in this study agrees with published values.**

**Figure S2A-E. BSE images overlain with MLA maps of the Velkerri Formation shale samples selected for *in situ* laser ablation analysis in this study (legend in Figure 5). Supp. Figure 2A – sample at 415 m depth. Figure 2B – sample at 520 m depth. Figure 2C – sample at 696 m depth. Figure 2D – sample at 938 m depth. Figure 2E – sample at 1220 m depth.**

**Figure S3. Compiled bulk XRD diffractograms for this study showing their respective 001-reflection of illite spectra.**

1. **References**

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