Supplemental Material

Raman Spectroscopy of Carbonaceous Material Maturation Thermometry

The degree of graphitization depends both upon the magnitude and duration of heating. Because graphitization of carbonaceous material is irreversible, the structural modification recorded by Raman spectrometry is insensitive to retrogression and can therefore be used to constrain maximum temperature with confidence of ± 50 °C in the temperature range 330-650 °C (Beyssac et al., 2002). Relative differences in temperature between individual samples are smaller, in the 10-15 °C range (Beyssac et al., 2004). Accordingly, we have also provided a standard deviation for each sample ($\sigma/\sqrt{n-1}$), which gives an insight into within-sample heterogeneity. For more discussion on the procedures of Raman graphite thermometry, readers are directed to Beyssac et al. (2002). Around 600 spectra were collected from 25 samples. Following the suggestion of Aoya et al. (2010), we attempted to measure 25 spot analyses per sample. We monitored a frequency range between 1100-1800 cm^{-1} with a 240 s acquisition time. Background correction and calculation of peak areas were performed following standard procedures.

Si-in-phengite geobarometry

Chemical compositions of phengite were analyzed using a JEOL JXA-8900 Superprobe at the U.S. Geological Survey in Menlo Park (California, USA). Nine elements were analyzed at 15 kV accelerating voltage and 15 nA using a 5 um spot for 30 s (peak)/10 s (background) each, except for Na which was analyzed at 10 s (peak)/5 s (background). Approximately 40 spot analyses from individual grains were determined from each sample to account for analytical errors, and produce a statistically

representative sample set. Averages and errors (2 sigma) of Si concentrations are reported in Supplemental Table 2. In addition to Si concentration in phengite, temperatures are required to determine pressures (Massonne and Schreyer, 1987). For samples that lacked measurable amounts of carbonaceous material, temperatures were estimated from the regional trend in Raman graphite thermometry. Results from the electron microprobe analyses are reported in Supplemental Table 2.

Since none of the samples contain the limiting assemblage (K-feldspar + phlogopite + quartz) for the Si-in-phengite barometer developed by Massonne and Schreyer (1987), we utilized calculated Si isopleths and pseudosections generated in THERMOCALC for metapelites with similar compositions and mineralogy's as rocks sampled from the southern Brooks Range. Due to the presence of albite ± paragonite in almost all samples, calculated pseudosections using the NKFMASH system (e.g., Wei and Powell, 2004; Zhu and Wei, 2007; Escuder-Viruete et al., 2011) were applied to determine pressures. We are confident in the measured pressure due to (1) the presence of other Mg- or Fe-silicates, which allows the Si content in phengite within the KFMASH assemblage to be used to derive *minimum* pressures for the formation of the host rock (Massonne and Schreyer, 1987) and (2) the addition of Na_2O (i.e. glaucophane, crosstie, or paragonite) which lead to similar (one Na-phase) or elevated pressures (two or more Na-phases) (Zhu and Wei, 2006).

Diode Laser $^{40}Ar/^{39}Ar$ Incremental Step-Heating Measurements

$^{40}Ar/^{39}Ar$ measurements of multi-grain aggregate, Diode laser incremental step-heating analyses were performed with a Nu Instruments Noblesse multicollector mass

spectrometer fitted with a high mass Faraday cup and two low mass ion-counting detectors (Coble et al., 2011). Process control software developed in LabVIEW® by Dr. Jeremy Hourigan (Santa Cruz Laser Microfurnace) manages the laser output, vision, and stage motion as well as gas purification and the vacuum system. The Noblesse mass spectrometer is digitally interfaced with the extraction line control system for unattended analysis over several days. The Noblesse acquires $^{40}Ar/^{39}Ar$ analyses by dynamically selecting between one of two procedures at the time gas is inlet into the mass spectrometer. Signal size is continuously monitored on the Faraday detector as gas is inlet into the mass spectrometer over the 15 seconds required for equilibration with the extraction line to occur. Most gas aliquots are sufficiently large (e.g. $1x10^{-15}$ mol ^{39}Ar) to use a multi-collecting procedure that involves a peak hop between the mass station used to measure ^{40}Ar-^{38}Ar-^{36}Ar and that used to measure ^{39}Ar-^{37}Ar (method 3 in Coble et al., 2011). Smaller gas aliquots are dynamically selected to be measured in mono-collection mode using the axial ion counter. In either procedure, the first measurement are acquired within 20 seconds of inletting the sample gas. Both procedures collect 300 seconds of data per $^{40}Ar/^{39}Ar$ incremental step-heat analysis.

The overall approach for standardizing the $^{40}Ar/^{39}Ar$ measurement is described in Coble et al., (2011). The measurement procedures employed in this study were standardized using a newly synthesized reference gas prepared in collaboration with Dr. Andrew Calvert at the U.S. Geological Survey (Menlo Park) that was put into service in June, 2015. In calculating $^{40}Ar/^{39}Ar$ ages, we used a decay constant of $\lambda = 5.543x10^{-10}/a$ (Steiger and Jäger, 1977). In this study, we used Fish Canyon sanidine with a K-Ar age of 28.02 Ma (Renne et al., 1998). J-factor data calculated as outlined in McDougall and

Harrison (1999).

A near-infrared (λ = 908 nm), 75 watt Jenoptik® fiber optic diode laser with beam delivery optics focused to a spot of ca. 2 mm supplied the radiation used to heat the sample. To heat the samples, approximately 0.5-2 mg of sample were wrapped in Ta foil, placed on a stainless steel substrate tray with the diode laser chamber and is incrementally step-heated via a laser through a sapphire window. Non-contact temperature measurements were acquired with a 1.6 μm spectral range optical pyrometer (Omega® OS1562 sensor) whose fiber optic focusing lenses (*f* = 125 mm) sampled a 0.8 nm diameter region that was manually centered upon a heated blank Ta disk target. Procedures for temperature calibration of the optical pyrometer are outlined in Oze et al., (2017).

$^{40}Ar/^{39}Ar$ analyses from this study are characterized by staircase or gradient release patterns, suggestive of multiple mica populations or a loss of radiogenic ^{40}Ar. Even for samples that yield nearly flat $^{40}Ar/^{39}Ar$ gradient patterns, Due to this loss of ^{40}Ar, the measured $^{40}Ar/^{39}Ar$ ratio will never yield the maximum age in which radiogenic ^{40}Ar was retained (Huneke, 1979). Even if a sample records a flat release pattern, or plateau, at the higher gas-release steps this likely reflects the minimum age for radiogenic ^{40}Ar retention in the mineral phase. Therefore, we reported the total gas ages for all samples.

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