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Supplemental Material

Forming and preserving aragonite in shear zones: first report of blueschist facies metamorphism in the Jabal Akhdar Dome, Oman Mountains

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1. Analytical details

1.1 U-Pb LA-ICP-MS Analysis

Calcite U-Pb dating was performed by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) on polished thick sections. The analyses were conducted at the ETH Zürich, Switzerland, by using a RESOlution laser ablation system with a 193 nm excimer (ArF) laser source and a two-volume Laurin Technic S-155 ablation cell coupled to a Thermo Element XR sector-field ICP-MS equipped with a high-capacity interface pump. The analytical and data reduction protocols follow Roberts et al. (2017) using NIST 614 and WC-1 primary reference materials and Guillong et al. (2020) using spot sizes of 110 and 163 μm with a matched ablation crater aspect ratio for the reference materials and unknowns. U-Pb ages were calculated from Tera-Wasserburg concordia lower intercepts using the IsoplotR software package (Vermeesch, 2018). All uncertainties are reported at the 95% confidence level. A long-term excess variance of 2% relative was propagated

by quadratic addition to the uncertainty of the individual lower intercept dates (Guillong et al., 2020). In addition to the samples, the two secondary reference materials ASH15D (Nuriel et al., 2021) and JT (Guillong et al., 2020) were analyzed in all sessions for validation. Correction for matrix effects with WC-1 was done with anchoring to 0.85 common-lead while samples and secondary reference materials were not anchored. No disequilibrium correction was applied.

1.2 Raman spectroscopy on carbonaceous material

Micro-Raman spectra on graphite (Fig. 3A) were obtained using a ThermoScientific DXR Raman microscope installed at the Department of Chemistry Sciences, University of Padova, Italy. We used a 50× objective and a 532 nm excitation source. Laser power was 1 mW (to avoid graphite damage) and Raman spectra were collected for about 900 s. The spatial resolution was about 1.1 μm, whereas the spectral resolution was about 2.5 cm^{-1}.

The Omnic software (Thermo Fisher Scientific) was used for Raman spectrum decomposition by using the software Lorentian/Gaussian function, following the procedure described in Kouketsu et al. (2014). Peaks with centre in position at~ 1580 cm^{-1}, 1350 cm^{-1} and 1620 cm^{-1} were identified respectively as G, D1 and D2. The R2 parameter, defined as the ratio between the peaks area D1/(D1+D2+G), was calculated for each measurement.

A linear relationship between temperature and the Raman parameter R2 forms the basis of the CM geothermometer (Beyssac et al., 2002). The temperature can be estimated to ± 50° C in the range 330–650° C. Deformation can affect the internal disorder and underestimate the temperature obtained from the spectra analysis (Kirilova et al., 2018). Care was thus taken to avoid measuring CM within cracks, and to prevent altered measurement from CM damaged during the thin section polishing; we performed measurements by focusing the laser beam on CM beneath the surface of a transparent adjacent grain as suggested in Beyssac et al. (2002). CM in the host rock was analysed with λ=473 nm, while CM in the mylonite was analysed with λ=532 nm. To avoid errors in the temperature estimation we applied two different geothermometers calibrated for the different laser wavelength used to collect the data: Beyssac et al. (2002) for the λ=475 nm analysis and Aoya et al. (2010) for the λ=532 nm analysis. Although both yield similar results, the equation given in Beyssac et al. (2002) for the Raman CM geothermometer is linear whereas that in Aoya et al. (2010) is quadratic.

1.3 High-resolution Micro-Raman Spectroscopy maps

High-resolution micro-Raman spectra of calcite-aragonite crystals and fibres were produced with a Witec Alpha 300 R Raman microscope installed at the Department of Geosciences, University of Padova, Italy. In particular, 2D maps were collected on samples CZ2004B and CZ2018 by using a 50X objective and a 532 nm excitation wavelength. At the conditions employed during the analyses, the spectral resolution was ~3 μm while the spatial resolution is <1 μm.

The analyses employed a nominal laser power of 40 mW and integration time of 0.5 s. The high power and low integration time were selected to collect a large number of spectra in a reduced amount of time, while maintaining a high intensity of the signal. In fact, the maps for samples CZ2004B and CZ2004B covered a 300x300 and 400x400 μm^2 area, respectively, where single spot analyses were collected at 1 μm steps.

CAPTIONS TO FIGURES AND TABLES

Fig. S1. Microphotograph of the protolith undeformed Hajir Fm outside of the mylonitic shear zones. A) Plain polarized view of the Hajir Fm organic matter-rich carbonate containing abundant dispersed graphite. B) Crossed polarized view of (A) highlighting twinned calcite grains. C) Plain polarized view microphotograph of the typical mylonitic fabric. The mylonitic foliation is outlined by highly transposed and aligned relic carbonate grains. Samples used for RSCM are from these mylonitic shear zones, where graphite-rich layers outline and define the foliation. D-E) Plain polarized and crossed polarized view of twinned calcite porphyroclast mantled by recrystallised new grains.

Fig. S2. Microphotographic evidence of brittle – ductile deformation cyclicity. A-B) Plain and crossed polarized view of calcmylonitic fabric cut across by mode-I veins infilled by stretched aragonite and quartz fibres. Fibres do not exhibit evidence of plastic deformation. C-D) Plain and crossed polarized view of stretched, segmented and transposed veins and fibres composed of quartz and aragonite-calcite. Veins and fibres, related to an earlier transient brittle phase, are transposed within and along the mylonitic foliation of the calcmylonitic shear zones.

Fig. S3. Cathodoluminescence imaging of brittle and ductile fabrics. A-B) Cross polarized and cathodoluminescence images of detail in Fig. S2A-B, where stretched vein of quartz is represented by the dark brown/black. C-D) Cross polarized and cathodoluminescence images of Fig. 2C, showing the difference in chromatic response of rod-shaped aragonite grains (dark orange) and of multiple late fractures (bright orange). E-F) Cross polarized and cathodoluminescence images of structural relationships of rod-shaped aragonite grains with strong SPO (dark orange) and late veins cutting across and along the main foliation (bright orange). G-H) Cross polarized and cathodoluminescence images showing the constant dark brown sign of rod-shaped aragonite grains. Note that no evidence of reaction between fluids infilling fractures and the calcmylonitic fabric is present.

Fig. S4. Location of points for trace element analysis within quartz and aragonite veins filling mode-I fracture within the mylonitic shear zone. Refer to Table S1 for numerical data. Is not possible to discriminate which phase is investigated (aragonite or calcite) due to the size difference between LA-ICP-MS spot (hundreds of microns) and preserved aragonite (2 to ~ 20 micron^2).

Fig. S5. Trace element pattern of aragonite and calcite pseudomorphs over aragonite reported in Table S1. Spot location is shown in Fig. S4. Points from the rod-shaped crystals of the mylonitic shear zone are reported in the grey field.

Fig S6. U-Pb radiometric constraints and overview of spot points. A) Hand specimen of calcmylonite. Spots analysed for dating are shown. B) Example of dated elongated fibres. C) Example of dated mode-I fibres. D) Example of dated rod-shaped grains. E) U-Pb Tera-Wasserburg (Tera and Wasserburg, 1972) plot of calcite-aragonite fibres. F) U-Pb Tera-Wasserburg plot of calcite-aragonite crystals of mylonitic fabric, yielding Upper Cretaceous (above) and upper Ediacaran (bottom) ages. G) Summary plot of existing radiometric constraints on the principal tectonic events dated for the Jabal Akhdar and Saih Hatat Domes (data from Garber et al., 2021; Gray et al., 2004; Grobe et al., 2019; Lippard, 1983; Ninkabou et al., 2021; Tavani et al., 2020; Warren et al., 2003). For all Tera-Wasserburg plots, the grey area is 2 σ error envelopes of the regression line.

Table S1. Trace elements within aragonite and calcite pseudomorphs over aragonite crystals and fibres. Analysed spots are shown in Fig. S4.

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