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

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Abstract:
We report the first occurrence of high-pressure metamorphic aragonite in Precambrian carbonates of the Jabal Akhdar Dome in the Oman Mountains. We offer a model for its formation at blueschist facies metamorphic conditions and its subsequent preservation to the surface within the tectonic framework of the late Cretaceous obduction of the Semail Ophiolite. Aragonite formed at T ~350{degree sign}C and P{greater than or equal to} 0.9 GPa and is preserved within mylonitic shear zones and in stretched fiber dilational veins where the necessary conditions for its formation and preservation, such as plastic strain accommodation, fluid-enhanced mineralogical reactions, and an anisotropic permeability structure, were preferentially met with respect to the surrounding rock. High-strain structural domains are thus documented to potentially be ideal sites where to look for- and study pro- and retrograde high-pressure metamorphic histories in deeply subducted and exhumed terrains.

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

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ABSTRACT

We report the first occurrence of high-pressure metamorphic aragonite in Precambrian carbonates of the Jabal Akhdar Dome in the Oman Mountains. We propose a model for both its formation at blueschist facies conditions and its subsequent preservation to the surface within the tectonic framework of the late Cretaceous obduction of the Semail Ophiolite. Aragonite formed at T~350°C and P≥ 0.9GPa and is preserved within mylonitic shear zones and in stretched fiber dilational veins where the necessary conditions for its formation and preservation, such as plastic strain accommodation, fluid-enhanced mineralogical reactions, and an anisotropic permeability structure were preferentially met with respect to the surrounding rock. High-strain structural domains are ideal sites where to look for and study pro- and retrograde high-pressure metamorphic histories in deeply subducted and exhumed terrains.

1. INTRODUCTION

The identification and characterization of relic high-pressure (HP) assemblages in exhumed rocks are key to constraining the thermobaric conditions and the deformation processes typical of otherwise inaccessible subduction zones (e.g., Agard et al., 2009; Rubatto et al., 2011). Even though exhumed terrains may be affected by retrograde metamorphism, relic assemblages may locally survive within favourable structural sites that act as sheltering capsules to specific HP phases. Formation and later preservation of such phases therein is favoured or inhibited by the interplay of numerous factors, such as the exhumation rate and geothermal gradient, which may inhibit retrograde mineralogical re-equilibrations, presence and composition of fluids, which can favour element transport and enhance mineralogical reactions during pro- and retrograde histories, amount of strain and type of involved mineralogical phases (e.g., Goffé and Velde, 1984; Bucher and Frey, 2002). The documentation of index minerals, such as lawsonite and carpholite, has facilitated the study of blueschist facies conditions within metabasite and metapelite (e.g., Evans and Brown, 1986). Aragonite, on the other hand, is a metastable polymorph of calcite that represents a reliable blueschist facies indicator for "pure" carbonates that otherwise lack other P-sensitive mineral phases (e.g., Hacker et al., 1992; Stöckhert et al., 1999; Giuntoli et al., 2020). Aragonite formation and preservation are mostly limited to <10°C/km thermal gradients and rapid exhumation in dry conditions (e.g., Carlson, 1980; Hacker et al., 1992).

We report the first record of HP aragonite in the Precambrian carbonates of the Jabal Akhdar Dome (Oman Mountains), universally acknowledged as a non-subducted portion of the Arabian Plate (e.g., Breton et al., 2004). We demonstrate that aragonite is therein selectively preserved within narrow mylonitic shear zones that formed due to cyclic brittle-ductile deformation under blueschist facies conditions during the Cretaceous obduction of the Semail Ophiolite. We propose a model wherein the identified mylonitic shear zones acted as sheltering structural capsules, within which aragonite initially formed at HP metamorphic conditions and through which it survived exhumation all the way to the surface.

2. GEOLOGICAL SETTING

The Jabal Akhdar Dome is the largest tectonic window in the NW-SE Oman Mountains (Fig. 1A-B). It is composed of a pre-mid Carboniferous series overlain by a 2.5km-thick Permian to Cretaceous carbonate succession (Autochthonous A and B, respectively). This stack was overthrusted by the Hawasina Nappe and the Semail Ophiolite during the Cretaceous (e.g., Searle, 2007; Fig. 1B). The autochthonous series is part of the Arabian passive margin, which is reported as having experienced subduction, exhumation and obduction only in its northeasternmost external portion (e.g., Lippard, 1983). Therefore, deformation in the Precambrian JAD has so far been predominantly related to a complex sequence of contractional and extensional phases from the late Ediacaran to the early Cambrian (e.g., Callegari et al., 2020; Scharf et al., 2021; Fig. 1C), with evidence of Cretaceous continental subduction exclusively confined to the Saih Hatat Dome (Fig. 1B), where rocks experienced up to eclogite facies conditions (e.g., Warren et al., 2003; Agard et al., 2010). The JAD in the inner part of the Arabian margin is thus considered to belong to the un-subducted portion of the Arabian passive margin, and to have experienced only anchizonal deformation conditions during the Semail Ophiolite obduction (e.g., Searle, 2007). Exhumation of the subducted Arabian margin through a still ill-defined mechanism started at the end of the Cretaceous (e.g., Hansman et al., 2021), leading to rapid cooling of the whole region (e.g., Grobe et al., 2019).

3. METHODS AND RESULTS

3.1 ARAGONITE-BEARING MYLONITIC SHEAR ZONES

In the study area (Fig. 1C), contractional calcmylonitic shear zones cut across the Precambrian organic-matter-rich carbonate of the Hajir Formation (Fig. 2; Fig. S1). Strain localised in 1) discrete, up to 20cm thick mylonitic to ultramylonitic shear zones (Figs. 2A-B; S1) that discordantly cut across the bedding and 2) thinner shears along bed-bed interfaces within NE-verging folds in response to a flexural slip folding mechanism (Fig. 2). In the former, the mylonitic foliation is penetrative and defined by lenses and laterally continuous films of graphite (Figs. 2C; S1), dips to the SW (Fig. 2B) and is invariably associated with a SW-plunging stretching lineation and thrusting-related top-to-NE S/C-structures and oblique foliation (Fig. 2B). The mylonitic foliation commonly transposes quartz and calcite veins (Fig. 2B). Carbonates exhibit a strong shape preferred orientation (SPO, Fig. 2C) with grains elongated parallel to the transport direction and contained within the foliation. They preserve a peculiar "rod-like" shape (Fig. 2C), which is commonly reported as typical for calcite pseudomorphs after aragonite (e.g., Brady et al., 2004; Seaton et al., 2009; Giuntoli et al., 2020), and as ensuing during shearing at the calcite to aragonite phase transformation. Such rod-shaped fabric is not found within the less deformed Hajir Fm outside of the shear zones (Fig. S1).

Shear zones related to flexural-slip folding along bed-bed interfaces are extremely localised and thin (<5cm; Fig. 2D-E) and contain sheared quartz and calcite-aragonite veins and fibres (Fig. 2E). They exhibit a strong SPO with calcite and aragonite grains aligned parallel to the mylonitic foliation, embedding and transposing lenses and films of graphite (Fig. 2F).

All shear zones document broadly coeval brittle and ductile deformation, with the mylonitic fabric cut across by mode-I veins with opening directions subparallel to the regional SW-NE shear direction. These veins contain aragonite and quartz fibres (Fig. 2F; Fig. S2A-B) and are, themselves transposed along the mylonitic foliation, suggesting cyclic brittle-ductile deformation (Figs. 2B-F; S2C-D; S3A-B).

3.2 P-T CONSTRAINTS

Raman Spectroscopy on Carbonaceous Material (RSCM) spectra and high-resolution micro-Raman maps (see Supplementary Material) were acquired to discriminate calcite from aragonite in both mylonites and mode-I veins. Representative RSCM spectra from graphitic films and patches, which outline the mylonitic foliation, constrain synkinematic deformation temperatures in the 336-347°C range (Fig. 3A). Micro-Raman maps and spectra document aragonite (only partially retrogressed to calcite) in both mylonitic shear zones and mode-I veins (Fig. 3B-C), thus confirming inferences from the mylonitic rod-shaped fabric in the shear zones (Fig. 2C and F).

Based on the calcite-aragonite stability field (e.g., Johannes and Puhan, 1971), the obtained deformation temperature range requires 0.8-0.9GPa (Fig. 3D) as minimum pressure during shearing and coeval brittle deformation, thus within the range of blueschist facies conditions. Trace element analysis on aragonite fibres and grains in mylonites constrains Sr to <1wt% (Table S1; Fig. S4 and S5), thus excluding lower P values for the calcite-aragonite transformation (e.g., Carlson, 1980).

3.3 AGE OF DEFORMATION

In order to temporally place the formation of the studied shear zones in the evolution of northeastern Oman, we dated by U-Pb the described tectonic carbonates. Ages from mode-I carbonate fibres cluster at 96.5±31.6 Ma (2σ; Fig. S6A-C, E). Dating of the calcmylonitic shear zones defines two different clusters at 97.5±23.3 Ma and 573.3±27.6 Ma, respectively (2σ; Fig. S6D-F). The large analytical uncertainties notwithstanding, we interpret the new dates as related to the Cretaceous subduction-obduction of the Semail Ophiolite, whereas the Precambrian date as the age of the Hajir Fm protolith, which is ascribed to the early-middle Ediacaran (e.g., Scharf et al., 2021).

4. DISCUSSION AND CONCLUSIONS

This first documentation of blueschist facies conditions from genetically connected shear zones and mode-I veins within the JAD and the interpretation of this data require considering the possible role of non-lithostatic pressure during deformation. Tectonic overpressure may promote HP metamorphism, such that analytically obtained P estimates cannot be converted to depth. Several conditions are discussed as leading to tectonic overpressure, among which the following might affect our results: i) significant viscosity contrast between juxtaposed rock types, ii) heterogenous pressure conditions in folds and iii) fluid release (dehydration, decarbonation) in a closed system (e.g., Mancktelow, 2008; Schmalholz and Podladchikov, 2013; Luisier et al., 2019).

We tend to exclude a significant contribution of tectonic overpressure during the evolution of the studied shear zones in the JAD based on the following:

- Mode-I fracturing causes instantaneous pressure drops in dilatant fractures to conditions corresponding to the local lithostatic load. Coeval fracture infilling is, therefore, at equilibrium with the lithostatic pressure and aragonite in veins thus reflects the overburden.

- Mylonitic shearing occurred in the absence of a significant viscosity contrast between shear zone and the undeformed host rock, as evidenced by their similar composition and by aragonite occurring in both shear zones and mode-I veins.
- Shear zones locally formed by flexural slip along bed-bed interfaces on fold limbs, which are not prone to develop significant overpressure (e.g., Mancktelow, 2008).
- Shearing occurred at too low a temperature to release CO_2-rich fluids from decarbonation (e.g., Samtani et al., 2002).

Theoretically, aragonite might form even at low-pressure conditions in highly-strained domains, where shear strain would increase the internal energy of calcite crystals by densifying defects and dislocations in the lattice (Newton et al., 1969). This process, however, has been described for late calcite veins cutting across mylonitic fabrics and is thought to be rather unlikely in natural shear zones (Gillet and Goffé, 1988).

We therefore consider our minimum P estimate of 0.8-0.9GPa as indicative of at least 25-30km depth, which attests to reaching blueschist facies conditions in the dynamic context of the Oman Cretaceous subduction. This is consistent with the new U-Pb results, which, despite the large analytical errors (24-30%; Fig. S6E-F), fit available age constraints for the known HP and subduction-related metamorphism in northeastern Oman (Fig. S6G). We also exclude an Ediacaran sedimentary origin for aragonite because we deem highly unlikely its preservation over such a long time span due to the rapid kinetics of the aragonite/calcite transformation (e.g., Theye and Seidel, 1993; Hacker et al., 2005).

Cyclic brittle-ductile deformation under HP conditions in the JAD finds analogies with descriptions of similar deformation styles under blueschist facies conditions elsewhere in orogenic belts (e.g., Molli et al., 2017; Giuntoli and Viola, 2022) and allows us to present a conceptual model for the formation and preservation of aragonite within mylonitic shear zones (Fig. 4). Formation of aragonite is known to be both favoured and limited by the i) amount of strain, ii) dynamic evolution of the permeability tensor through time and fluid-rock interaction,

iii) temperature changes, iv) overall composition of the deforming system and v) exhumation modes (Fig. 4A). The interplay of these factors within the studied shear zones would have made it possible for aragonite to first form and then be preserved. We suggest that the mylonitic fabric triggered transient chemical/physical processes that were, instead, unable to operate in the less deformed Hajir Fm outside of the shear zones (as shown by the lack of aragonite therein; Fig. S1).

Shear zones cyclically accommodated broadly coeval ductile and brittle deformation, both taking place under blueschist facies conditions, as demonstrated by aragonite occurring in both coeval mylonites and mode-I veins. Progressive strain localisation within the initially undeformed Hajir Fm under increasing pressure and temperature (Fig. 4B) caused calcite recrystallization and grain size reduction (Fig. 4C). Fluids enhanced the calcite-aragonite transformation at favourable P-T conditions that were met as the Hajir Fm reached progressively greater depth during subduction (Carlson, 1980). We see this process as being favoured by enhanced permeability along the mylonitic foliation due to the progressive alignment of ordered graphite films along the mylonitic foliation planes (Fig. 4C; Upton and Craw, 2008). Fluid ingress and flow within shear zones was facilitated by broadly coeval fracturing and viscous deformation cyclically alternating under HP conditions (e.g., Molli et al., 2017) and by the establishment of a large foliation-parallel permeability, with shear zones thus acting as conduits (Fig. 4D).

Close to or at P-T peak conditions, rod-shaped aragonite grains formed (Fig. 4C-D) growing an interwoven network with graphite crystals to develop laterally continuous and extensive layers (Fig. 4E). This would have sealed the shear zones, eventually leading to lower permeability conditions compared to the less deformed hosting Hajir Fm. Low-permeability and sealed shear zones characterised the exhumation retrograde path of this part of the subducted slab (Fig. 4E). Finally, the Hajir Fm re-entered the stability field of calcite at T≤200°C (e.g., Hacker et al., 1992; Fig. 4A and F), with shear zones remaining relatively sealed and dry, thus fulfilling a key condition for aragonite preservation (e.g., Gillet and Goffé, 1988). When coupled with a low geothermal gradient (<10°C/km) typical of cold subduction zones and fast exhumation (~1-3mm/a), as indeed reported for NE Oman (e.g., Grobe et al., 2019), our proposed structural evolution explains the seldomly observed crystallographic and morphologic preservation of aragonite in the stability field of calcite.

In conclusion, we document for the first time the occurrence of metamorphic aragonite in the JAD, attesting to blueschist facies conditions during subduction to at least 25-30 km depth. Its preservation calls for a model based on structural capsules where HP phases selectively formed and were later preserved by the concomitant effects of regional (rapid exhumation) and local factors (low permeability horizons). Our results provide new insights into both the regional evolution of the JAD and the processes allowing for the preservation of HP phases in deeply subducted and exhumed carbonate(meta)sedimentary successions.

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CAPTIONS TO FIGURES

Fig. 1. A) Geographical setting and B) Geological setting of the southern Oman Mountains with the Jabal Akhdar (JAD) and Saih Hatat (SHD) Domes; from Searle, 2007. C) Geological map of the study area and local stratigraphy (from Callegari et al., 2020).

Fig. 2. A) Calcmylonitic shear zone cutting a NE-verging fold. B) Detail of mylonitic shear zone in (A). C) Ultramylonitic shear zone in (B), with rod-shaped aragonite crystals interleaved with semi-continuous graphitic films defining the foliation. D) NE-verging fold with flexural-slip related shear zones along bed-bed interfaces. Men for scale. E) Detail of shear zone in (D) deforming fibrous quartz and aragonite. F) Aragonite-calcite mylonitic foliation cut across by mode-I stretched fiber quartz and aragonite veins.

Fig. 3. A) Raman spectra from carbonaceous material (RSCM) on rock matrix with (black) and without (blue) polishing. B-C) High-resolution micro-Raman spectroscopy spectra, related microphotograph and phase map. Bright yellow aragonite in blue ellipses. D) Calcite-aragonite stability field. Different experimental stability curves are shown (from Clark Jr., 1957; Johannes and Puhan, 1971; Lin and Huang, 2004; Hacker et al., 2005). The estimated P-T conditions for studied JAD carbonates are indicated.

Fig. 4. Model for the formation/preservation of aragonite. A) P-T retrograde path. B) Undeformed Hajir Fm carbonate. C) Calcite dynamic recrystallization forming new grains. D) Shear zone structuring at P-T peak conditions and formation of rod-shaped aragonite grains. with Quartz and aragonite fibre mode-I veins locally transposed by mylonitic fabrics constrain brittle-ductile cyclicity under HP conditions. E) Shear zone sealing by high-ordered graphite coalescence, forming thin, permeable and laterally continuous layers. F) Present configuration of the JAD mylonitic shear zones, acting as sheltering structural capsules preserving aragonite.

Figure 1


Iran
N
0 km 250
Hormuz strait
Oman Gulf
UAE
Oman Mountains
Saudi Arabia
Oman
A
B
57°E
58°E
59°E
Saih Hatat Dome (SHD)
Muscat
0 km 50
Jabal Akhdar Dome (JAD)
Rustaq
Hawasina Thrust
C
Semail Gap
Oman Gulf
23°N
Nizwa
Semail Thrust
Quaternary
Semail ophiolite
Hawasina thrust sheets
Autochtonous B
Autochtonous A
Saih Hatat HP zoning
Carpholite
Garnet, glaucophane
Eclogite
Blueschists
Main thrust
Main inferred thrust
Lineation and main sense of the tectonic transport of the hanging wall block
57.40°E
57.45°E
Al Bardah
Wadi Bani Awf
23.25°N
23.23°N
Small Snake Gorge
0 km 4
Saiq Fm: limestones and dolostones
Fara Fm: ignimbrites and cherty marls
Kharus Fm: limestones and dolostones
Mu'aydin Fm: siltstones and slates
Hajir Fm: limestones and dolostones
Mistal Fm: diamictite, sandstones and dolostones
Hercynian unconformity
Trace of anticline axial plane
Trace of syncline axial plane
Trace of refolded anticline axial plane
Lineation and main sense of the tectonic transport of the hanging wall block
Bedding (S0)
Unconstrained fault
Thrust
upper Permian
lower Cambrian
Ediacarian
Cryogenian
Saiq Fm
Hercynian unconformity
Fara Fm
Kharus Fm
Mu'aydin Fm
Hajir Fm
Mistal Fm
Autoch. B
Autochthonous A
km
1
0

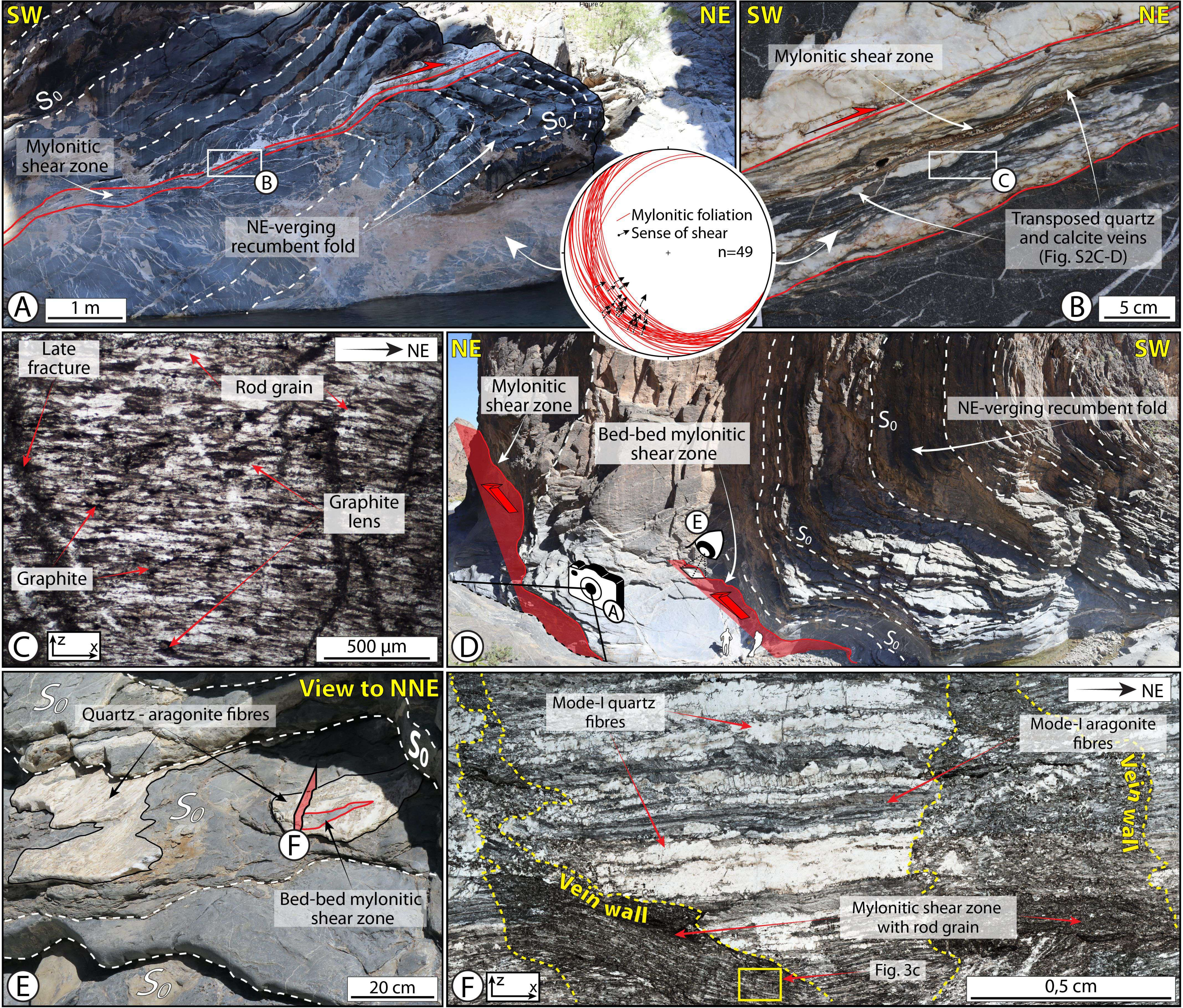
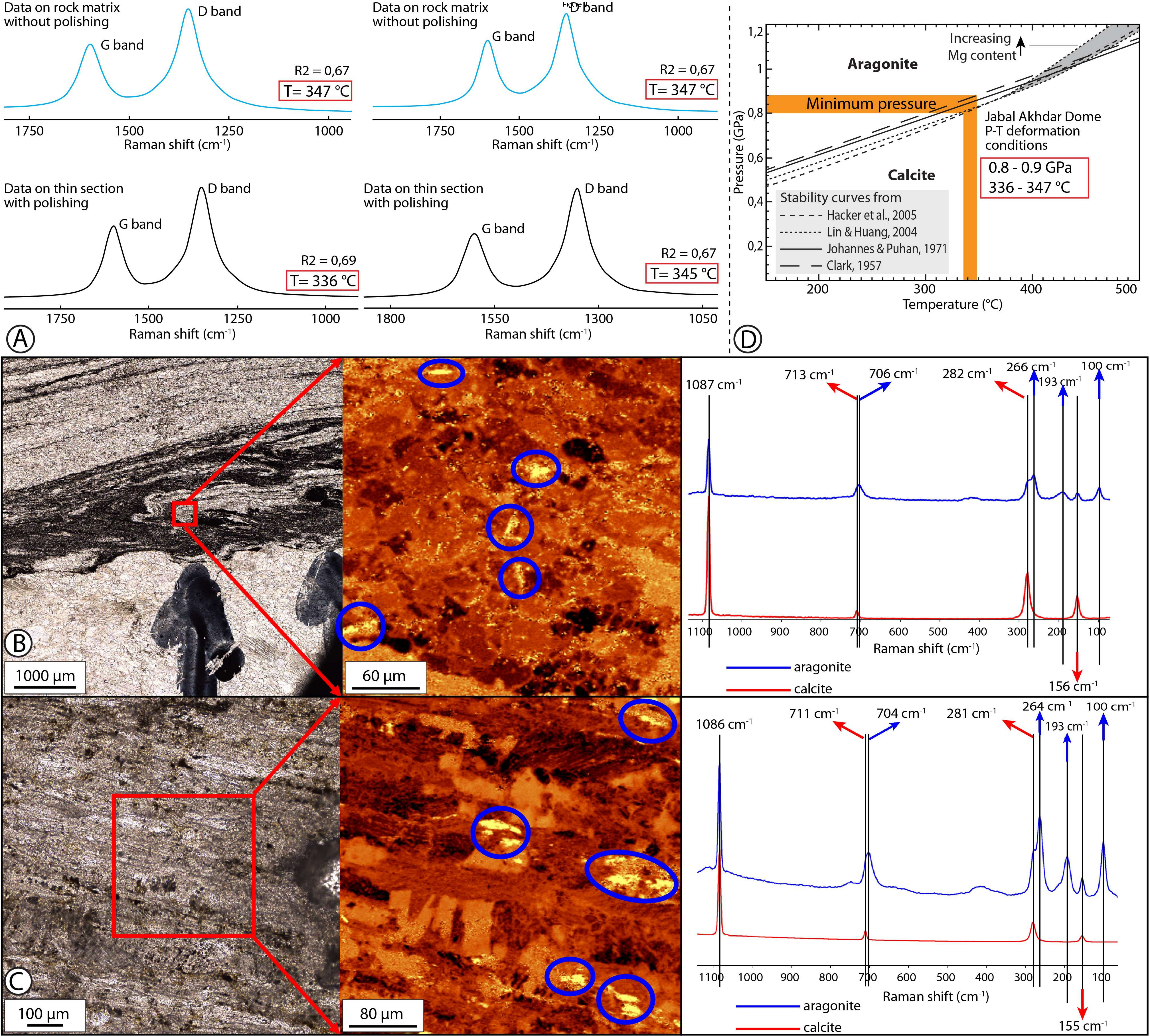
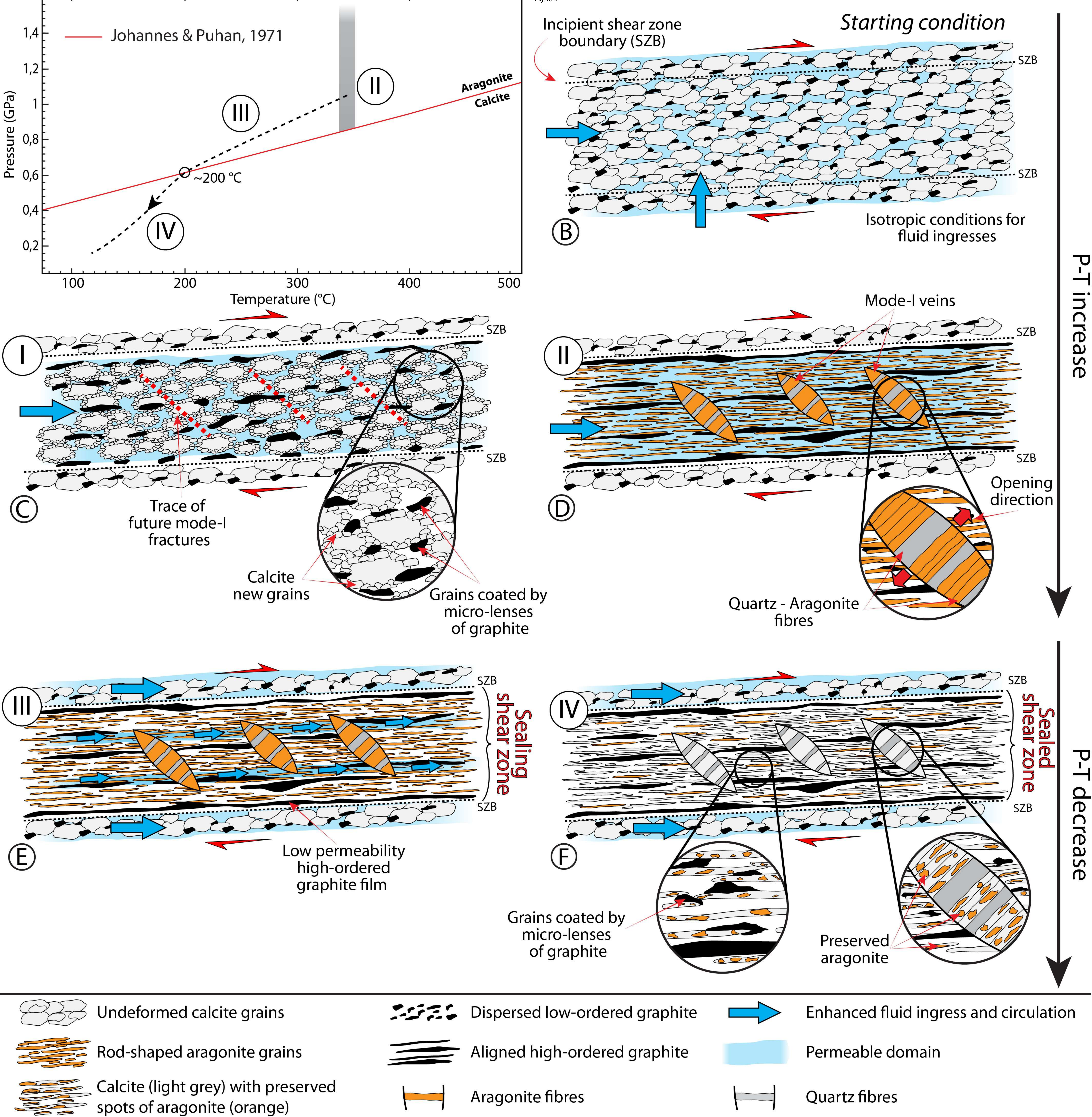


Figure 2
SW
NE
S0
Mylonitic shear zone
B
NE-verging recumbent fold
A
1 m
Mylonitic foliation
Sense of shear
n=49
SW
NE
Mylonitic shear zone
C
Transposed quartz and calcite veins (Fig. S2C-D)
B
5 cm
Late fracture
NE
Rod grain
Graphite lens
Graphite
C
z x
500 µm
NE
SW
Mylonitic shear zone
Bed-bed mylonitic shear zone
NE-verging recumbent fold
S0
E
A
D
S0
View to NNE
Quartz - aragonite fibres
S0
F
Bed-bed mylonitic shear zone
E
20 cm
Mode-I quartz fibres
NE
Mode-I aragonite fibres
Vein wall
Vein wall
Mylonitic shear zone with rod grain
Fig. 3c
F
z x
0,5 cm



Data on rock matrix without polishing
G band
D band
R2 = 0,67
T= 347 °C
Raman shift (cm-1)
Data on thin section with polishing
R2 = 0,69
T= 336 °C
R2 = 0,67
T= 345 °C
A
Aragonite
Calcite
Increasing Mg content
Minimum pressure
Jabal Akhdar Dome P-T deformation conditions
0.8 - 0.9 GPa
336 - 347 °C
Stability curves from
Hacker et al., 2005
Lin & Huang, 2004
Johannes & Puhan, 1971
Clark, 1957
Pressure (GPa)
Temperature (°C)
D
B
1000 µm
60 µm
1087 cm-1
713 cm-1
706 cm-1
282 cm-1
266 cm-1
193 cm-1
100 cm-1
156 cm-1
aragonite
calcite
C
100 µm
80 µm
1086 cm-1
711 cm-1
704 cm-1
281 cm-1
264 cm-1
193 cm-1
100 cm-1
155 cm-1

Figure 4


Johannes & Puhan, 1971
Pressure (GPa)
Temperature (°C)
Aragonite
Calcite
~200 °C
Starting condition
Incipient shear zone boundary (SZB)
SZB
Isotropic conditions for fluid ingresses
P-T increase
P-T decrease
Trace of future mode-I fractures
Calcite new grains
Grains coated by micro-lenses of graphite
Mode-I veins
Opening direction
Quartz - Aragonite fibres
Sealing shear zone
Sealed shear zone
Low permeability high-ordered graphite film
Preserved aragonite
Undeformed calcite grains
Rod-shaped aragonite grains
Calcite (light grey) with preserved spots of aragonite (orange)
Dispersed low-ordered graphite
Aligned high-ordered graphite
Aragonite fibres
Enhanced fluid ingress and circulation
Permeable domain
Quartz fibres