Microscale investigations of the evolution of deformation mechanisms in a low-temperature marble mylonite, NE Attica, Greece

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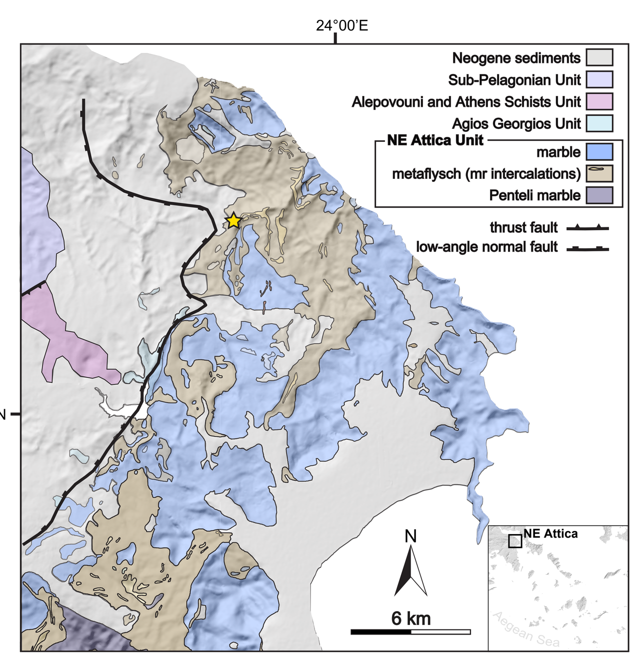
INTRODUCTION

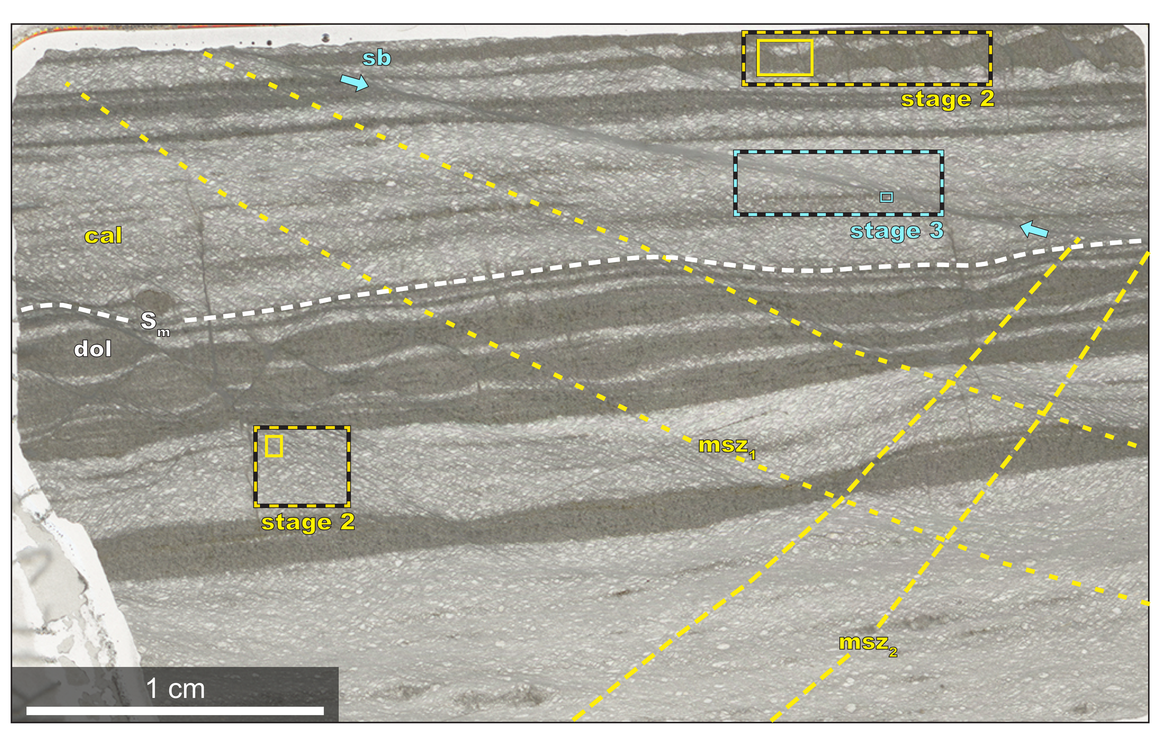
Carbonate rocks are important constituents of the Earth's crust and commonly host fault zones that accommodate kilometers of displacement. These intricate fault networks significantly influence fluid migration, further controlling crustal mechanics. We investigate the specific deformation mechanisms operating at the grain-scale in these high-strain zones through a series of microstructural analyses on a marble mylonite from the footwall of a major Miocene detachment system. The framework of the mylonite, which is exposed in a tectonic window north of the Greek Cyclades on the Attica peninsula, indicates deformation occurred under greenschist facies conditions (300-350°C and 7-8 kbar) during the late Oligocene. Through electron backscatter diffraction (EBSD), we clarify the interactions between brittle-ductile microstructures of three successive stages of deformation that are defined by clear cross-cutting relationships.

GEOLOGIC SETTING



We studied a low-temperature marble mylonite from the footwall of a Cycladic crustal-scale detachment in Greece (yellow star). The footwall consists of two dominant lithologies, a metaflysch and a structurally higher marble sequence. The detachment system contributed to Miocene exhumation of high-pressure metamorphic rocks in the back-arc of the retreating Hellenic subduction system.

STAGES OF DEFORMATION



PPL scan of thin section from studied mylonite. Sample was cut perpendicular to foliation (S_m) and parallel to the stretching lineation. Representative areas for deformation stage 2 and 3 are identified by dashed boxes. Areas analyzed with electron backscatter diffraction (EBSD) are identified by solid boxes. Abbreviations: cal: calcite; dol: dolomite

stage 1: Mylonitization (S_m) under greenschist facies conditions

stage 2: Formation of near-orthogonal conjugate micro-shear zones (msz; short dash: msz_1; long dash: msz_2)

stage 3: Formation of localized shear bands (sb)

WORKING HYPOTHESES

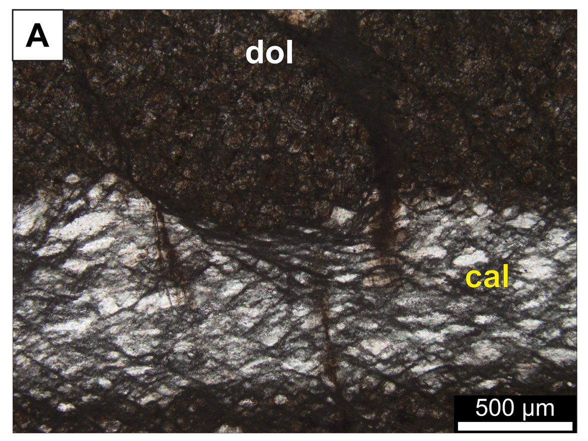
1. Under ductile deformation conditions, calcite may manifest brittle behavior at the microscopic scale, observed through the formation of cataclastic micro-shear zones.

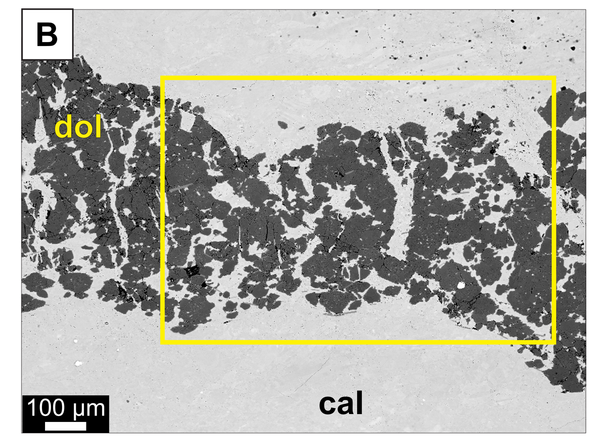
2. Micro-shear zones that have a preferential orientation aligned with the transport direction facilitate the localization of shear bands within calcite undergoing deformation.

STAGE 2

Brittle deformation of dolomite together with crystal-plasticity in calcite is consistent with low-temperature (~300-350°) greenschist facies deformation

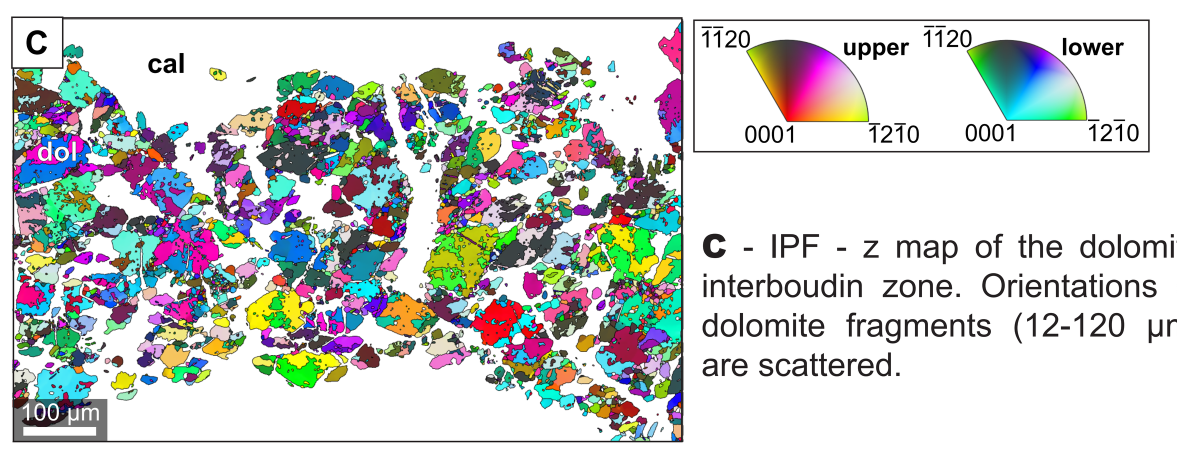
dolomite



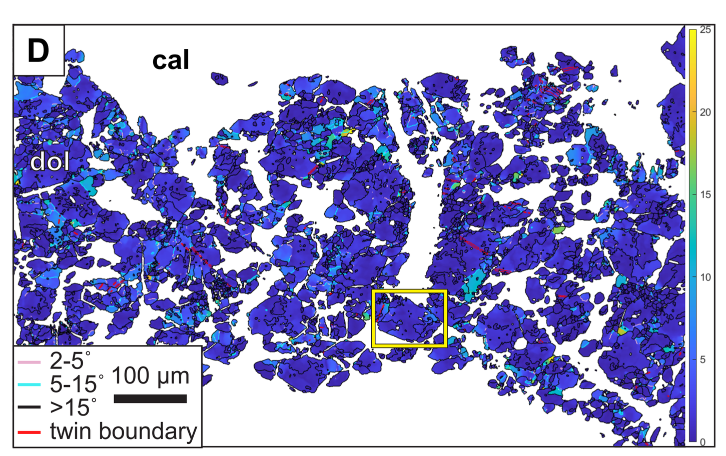


A - PPL photomicrograph of boudinaged dolomite in greenschist facies marble mylonite.

B - Backscatter electron (BSE) image of an interboudin zone. Dolomite is brecciated and separated by reprecipitation of dissolved calcite during deformation. Yellow box identifies area selected for EBSD mapping.

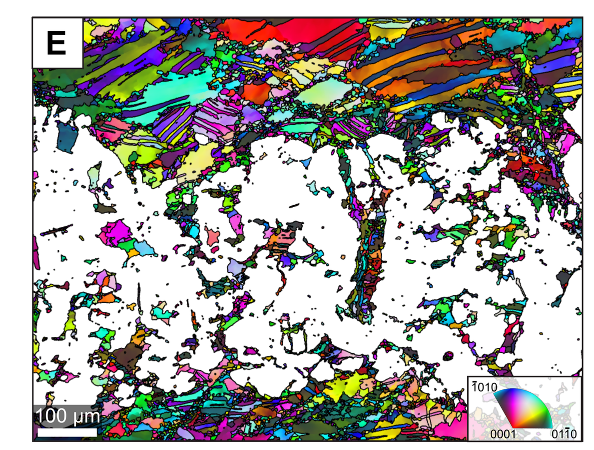


C - IPF - z map of the dolomite interboudin zone. Orientations of dolomite fragments (12-120 µm) are scattered.

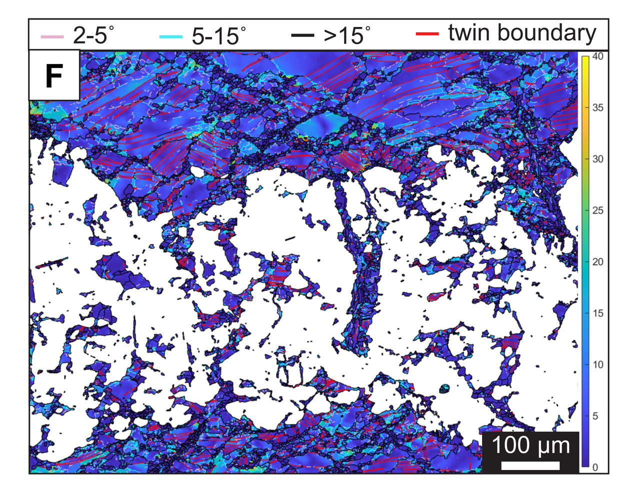


D - Grain reference orientation deviation (GROD) map of dolomite showing minor evidence of crystal-plasticity. Misorientation patterns are heterogenous with a maximum misorientation of 22° relative to the grain average. Growth twinning is characterized by a rotation of 180° around one of the [11$\bar{2}$0] axes (yellow box).

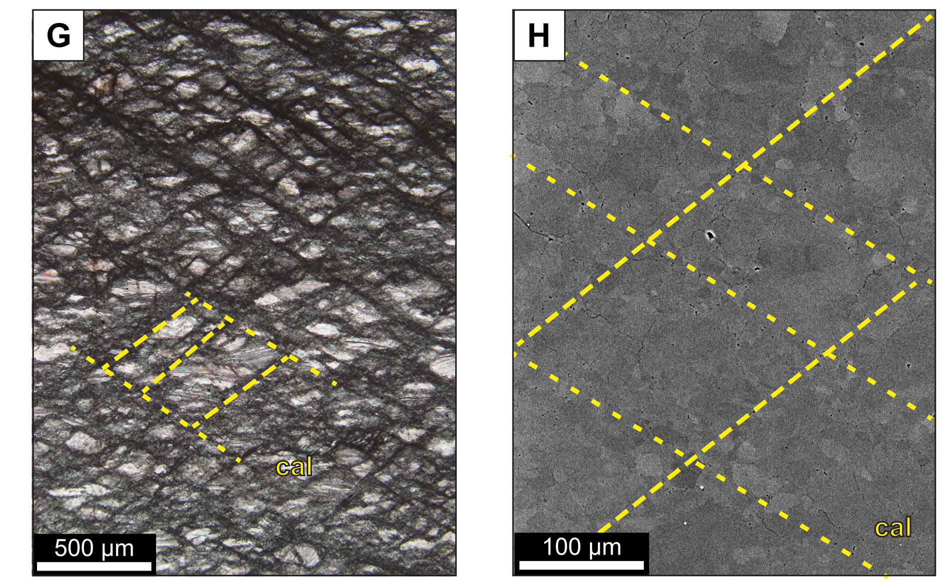
calcite



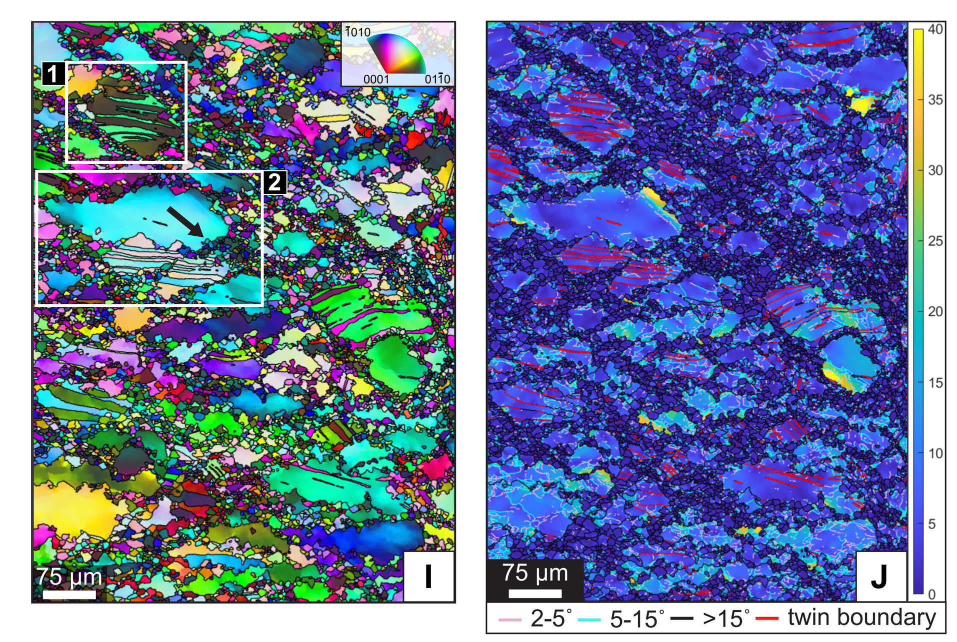
E - IPF-z map of calcite surrounding the boudinaged dolomite. Host calcite is (30-200 µm) yet fine grained (5-25 µm) calcite separate dolomite fragments.



F - GROD map of calcite surrouding boudinaged dolomite. Misorientations within the host calcite increase towards the rims, reaching maximum misorientations of 35° relative to the grain average orientation. Fine grained calcite separating dolomite fragments is strain-free and likely represents dissolution-reprecipitation. Grains display e-twins characterized by an 80° rotation about the [02$\bar{2}$1] axes.



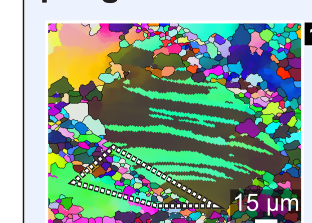
Close-ups of conjugate micro-shear zones. PPL photomicrograph (**G**) and BSE image (**H**) showing coarser calcite preserved in the wedges between cross-cutting micro-shear zones (dashed lines). Note the porosity within the micro-shear zones in BSE image.



I - IPF-z map of calcite wedges between micro-shear zones. Micro-shear zones sharply cut host calcite. Fine grains (<25 µm) in these zones can share similar orientation (i.e. colour) to proximal host calcite (black arrow).

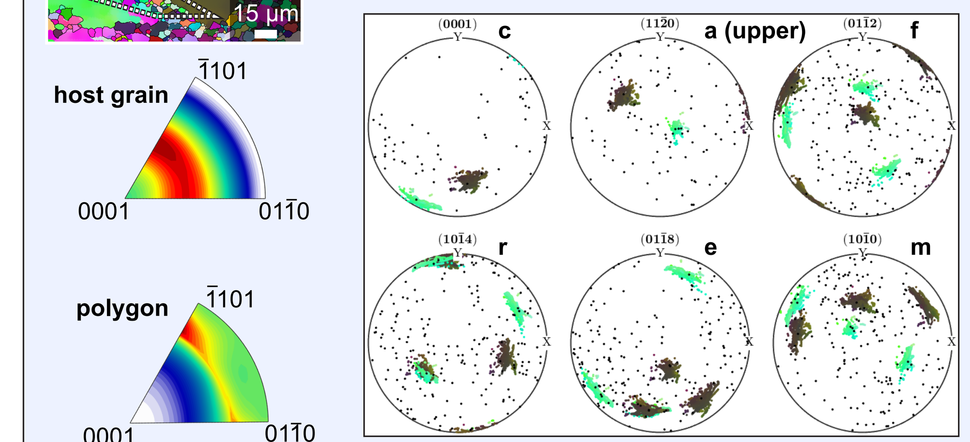
J - GROD map of calcite wedges between micro-shear zones. Low angle grain boundary (LAGB) density and misorientation angles of coarse grains increases towards the rims to a maximum of 35° relative to the grain average orientation. Fine calcite in the micro-shear zones are relatively strain-free (0°-8°).

Crystallographic relationship analysis between host calcite grains in micro-shear zones. Selected grains are identified by white boxes 1 and 2 in figure F. Colour of each point from host grain corresponds to the IPF-z map. One point (mean orientation; in black) is plotted per grain within the dashed polygon.



grain 1 + micro-shear zone 1

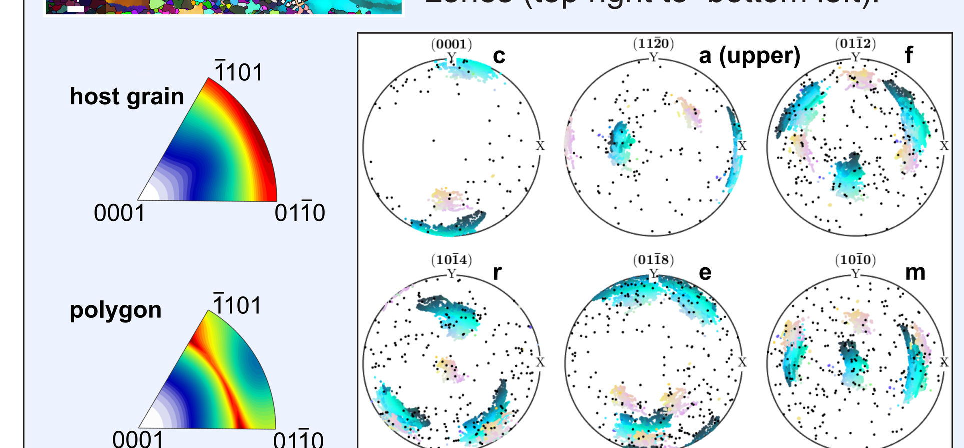
Enlarged IPF-z map of box 1 showing a calcite grain sharply cut by two parallel micro-shear zones (top left to bottom right).



Pole figures show lattice distortion of host grain described by rotation about the a axis and scatter of small grains.

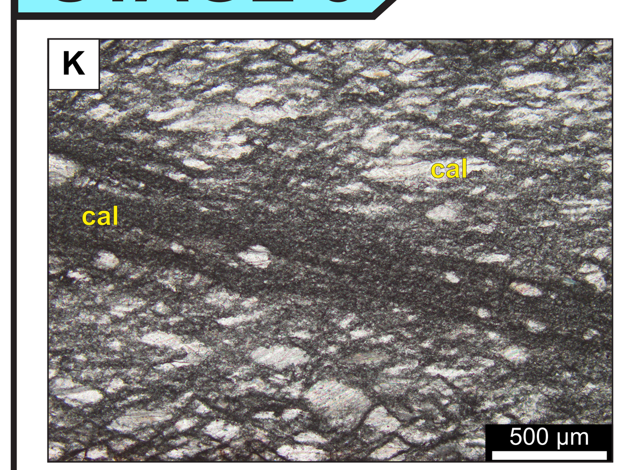
grain 2 + micro-shear zone 2

Enlarged IPF-z map of box 2 showing a calcite grain sharply cut by second orientation of micro-shear zones (top right to bottom left).

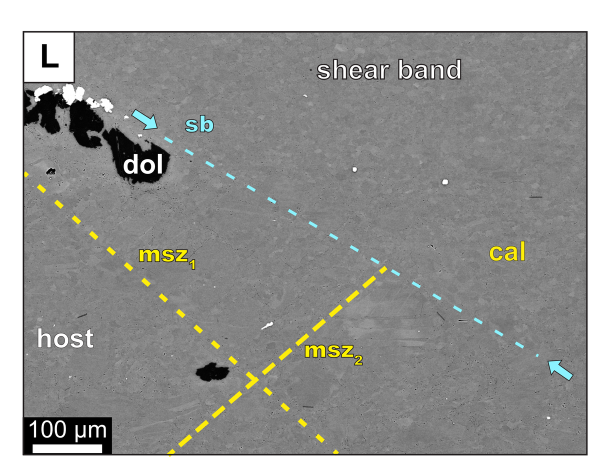


Pole figures and misorientation distribution function show lattice distortion of host grain described by rotation about the a axis. Small grains share a similar orientation to host grain with some scatter, possibly indicative of subgrain rotation recrystallization.

STAGE 3

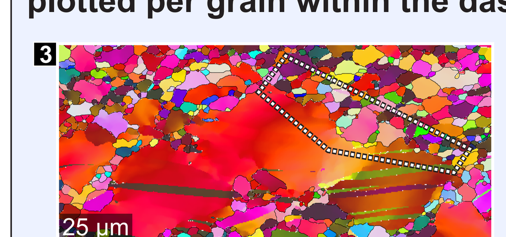


K - PPL photomicrograph of a diffuse section of a shear band cross-cutting both sets of micro-shear zones. The orientation of the micro-shear zone shallows with increasing proximity to shear band.



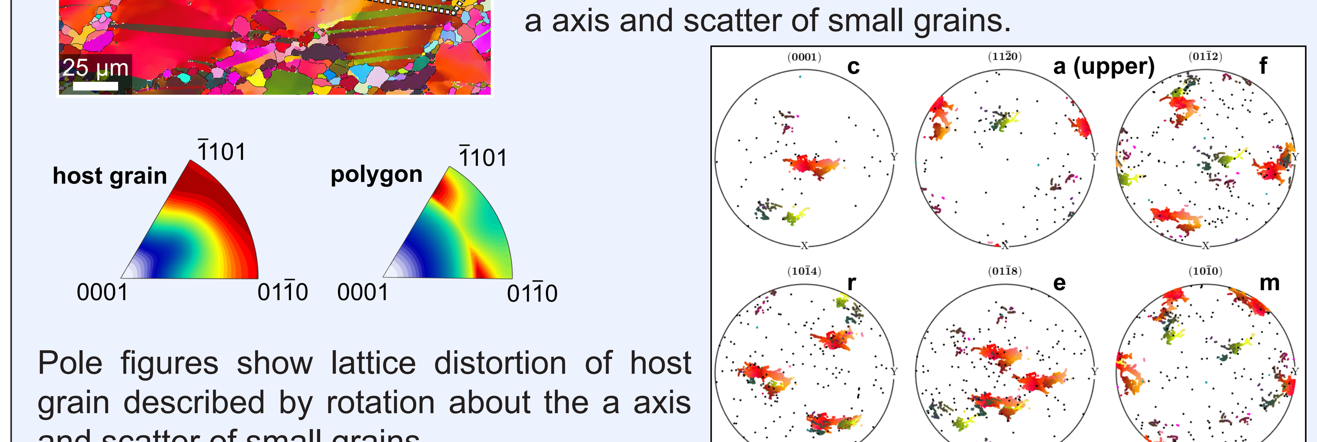
L - BSE image of the contact between the shear band and the mylonite (not in figure K). Field of view is the same as the EBSD maps (fig. M and N).

Crystallographic relationship analysis between host calcite and shear band. Selected grain is identified by white box 3 in figure M. Colour of each point from host grain corresponds to the IPF-z map. One point (mean orientation; in black) is plotted per grain within the dashed polygon.

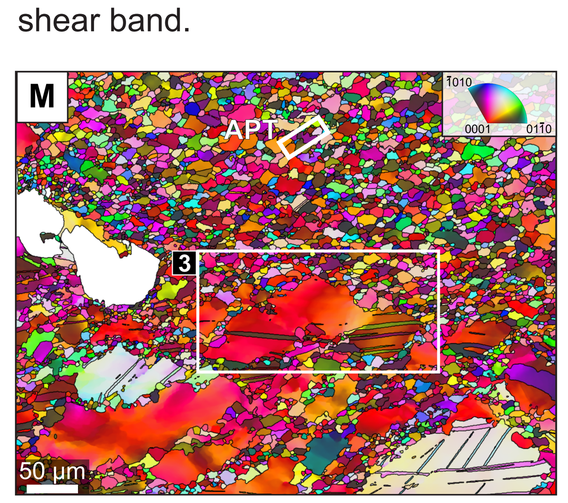


grain 3 + shear band

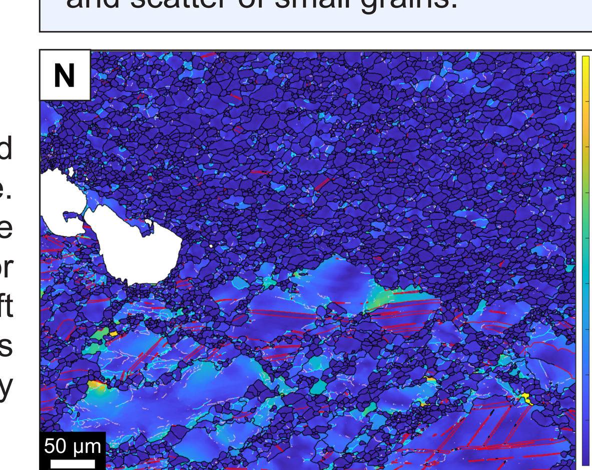
Enlarged IPF-z map of box 3 showing coarse calcite cross-cut by a shear band. Pole figures show lattice distortion of host grain described by rotation about the a axis and scatter of small grains.



Pole figures show lattice distortion of host grain described by rotation about the a axis and scatter of small grains.



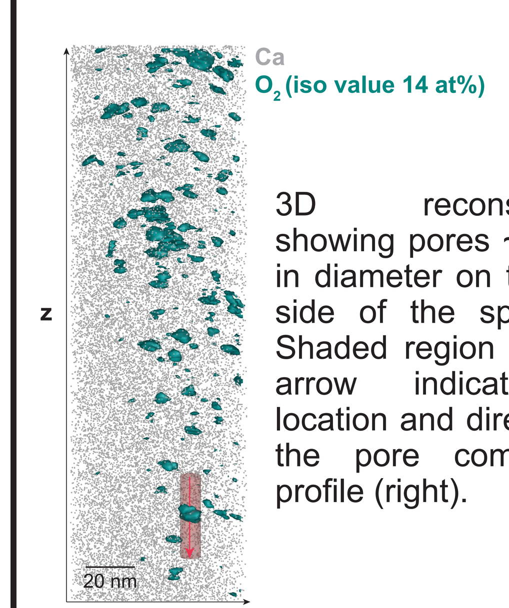
M - IPF-z map of calcite shear band cross-cutting marble mylonite. Orientations within the shear band are scattered. However, there is evidence for a grain shape preferred orientation. Lift out for atom probe tomography (APT) is from a calcite-calcite grain boundary within the shear band.



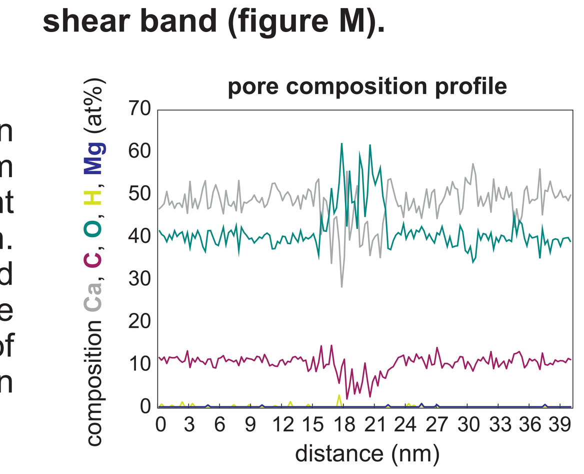
N - GROD map of calcite shear band cross-cutting marble mylonite. The maximum misorientation within host calcite proximal to shear band is 44° relative to the grain average orientation and higher than in calcite from areas distal to shear bands. Calcite in the shear band is fine grained (2-10 µm) with little internal misorientation except for a few sparse, 20-30 µm anhedral grains with minor lattice distortion (~8°).

FUTURE WORK

To investigate strain localization preocesses, we are conducting atom probe tomography on a calcite-calcite grain boundary within a shear band (figure M).



3D reconstruction showing pores ~ 10 nm in diameter on the right side of the specimen. Shaded region and red arrow indicate the location and direction of the pore composition profile (right).



Composition profile across one pore revealing marked enrichment in O and depletion of Ca and C across pore.

SUMMARY

Our findings reveal crystal-plasticity in calcite, characterized by consistent lattice distortion, alongside an increasing density of LAGBs and misorientation angles towards the rims of host grains. Yet, adjacent, strain-free fine grains forming the micro-shear zones lack a clear orientation relationship. Furthermore, the sharp cross-cutting relationship between these zones and host grains suggests brittle behavior. These observations support evidence for brittle deformation of calcite under conditions typically associated with ductile deformation (300-350°C), manifested as cataclastic micro-shear zones.