Twinned calcite within polymict impact breccias from the Nördlinger Ries impact structure, Germany – shock effects and post-shock annealing

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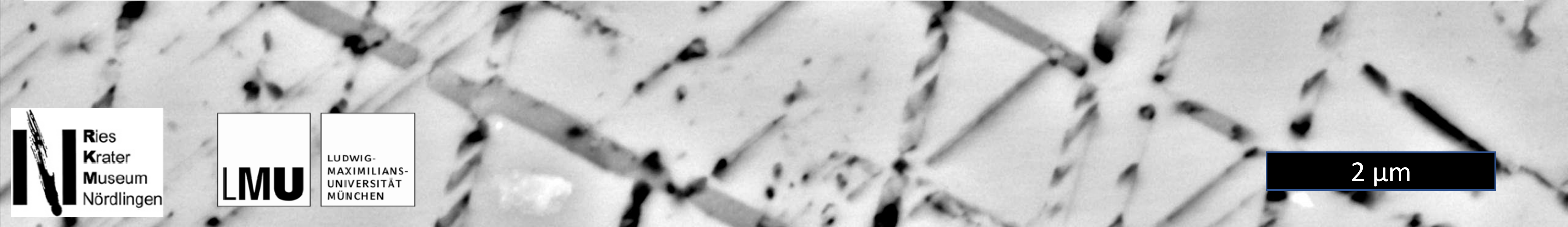
Motivation: Approximately one third of the worlds known impact structures are formed in carbonatic target rocks. However, the response of their main constituent mineral, calcite, upon shock loading and unloading is still not well understood (e.g., Stöffler et al., 2018).

Mechanical twins in calcite are described from natural impactites and shock experiments. Yet, reliable indicators to distinguish these shock effects from the very common calcite twins generated in tectonic fault rocks are missing.

Here, we present scanning electron microscopic investigations of twinned calcite within calcite cemented brecciated gneisses from the Ries impact structure.



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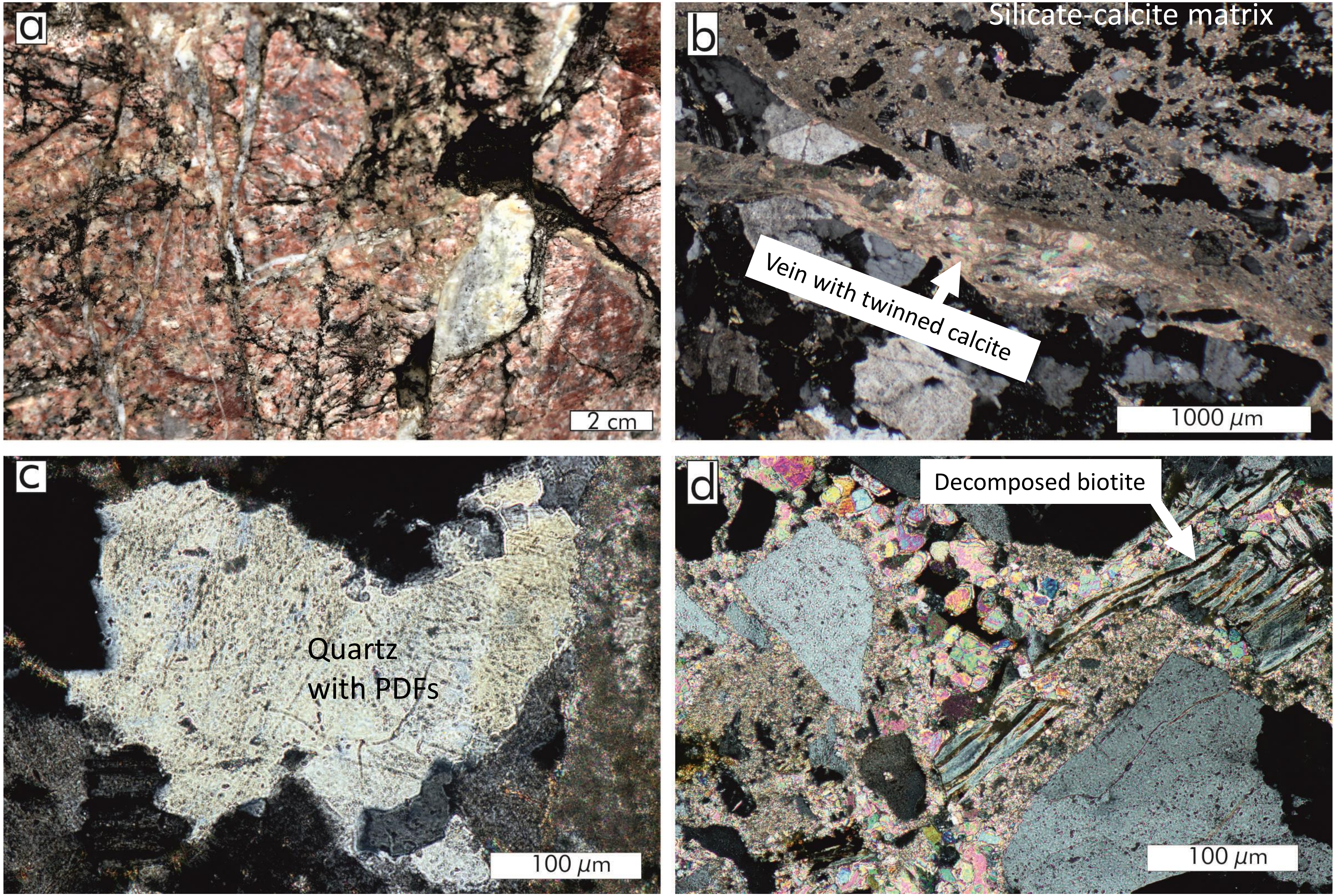
Calcite cemented brecciated gneisses from the Ries impact structure

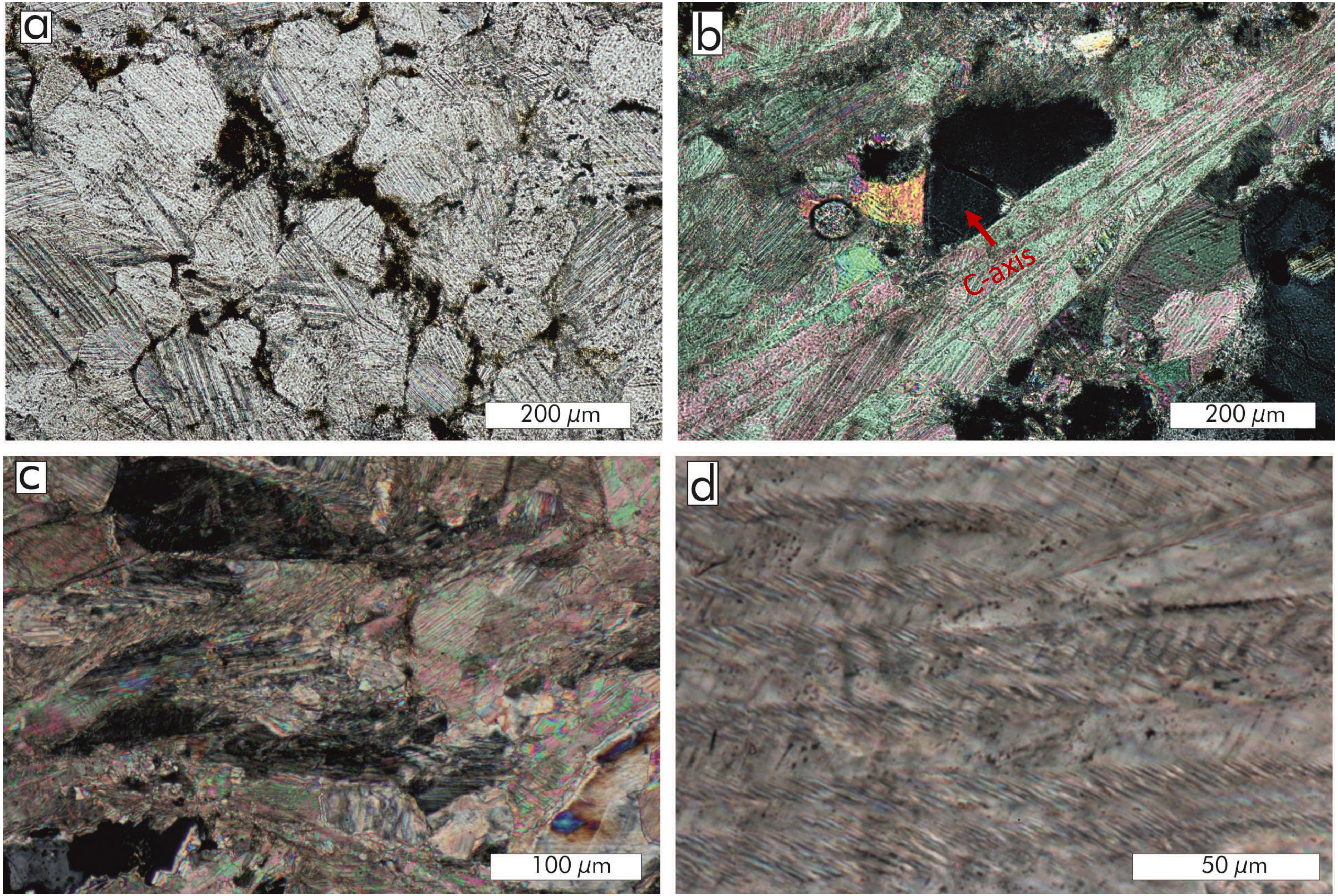


Sample (a) and polarized light micrographs (b-d) of **polymict impact breccia**, Langenmühle at Maihingen, NW' Nördlingen, cemented with calcite.

(b) Mixed silicate- calcite matrix and veins with twinned calcite.

(c) Quartz with planar deformation features and **(d)** decomposed biotite indicate **shock conditions of >10 GPa** (shock stage F3 according to Stöffler et al., 2018).

Twinned calcite grains within brecciated gneisses – optical light microscopy



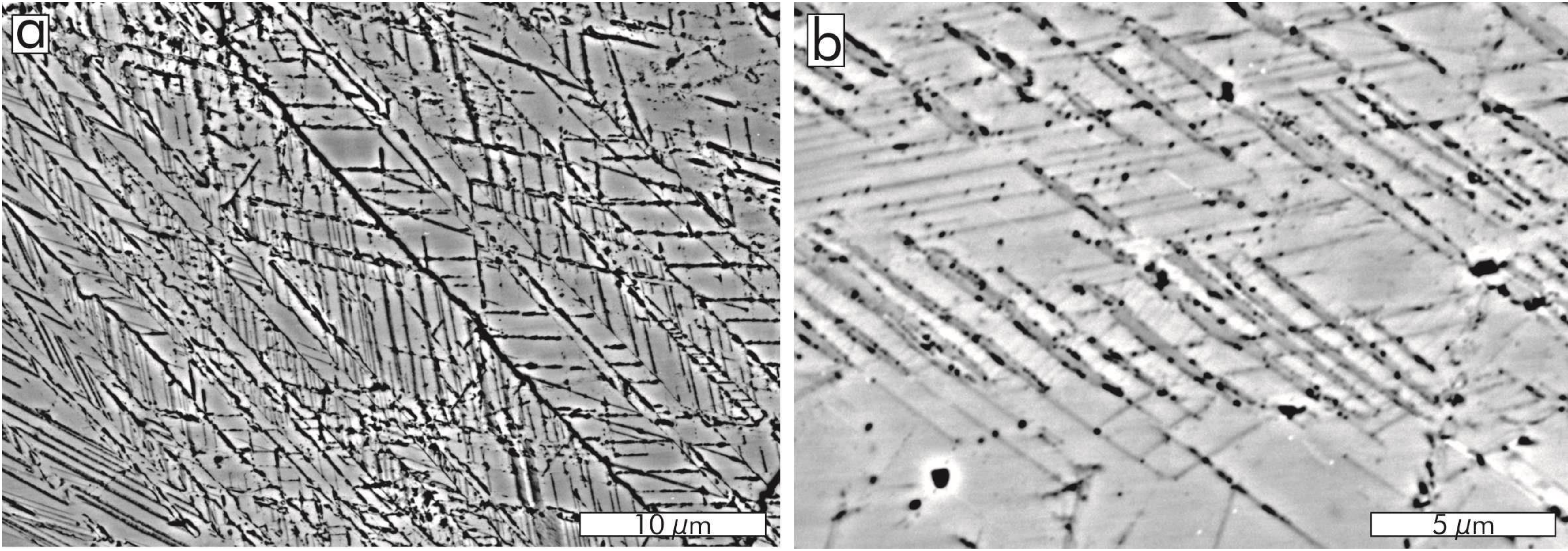
Polarized light micrographs with crossed polarizers **showing twinned calcite**, sample Jb2a.

(a) Opaque phases are enriched along grain boundaries

(b) Commonly occuring elongate calcite grains with c-axis oriented perpendicular to long axis of grains.

(c-d) High twin density in calcite.

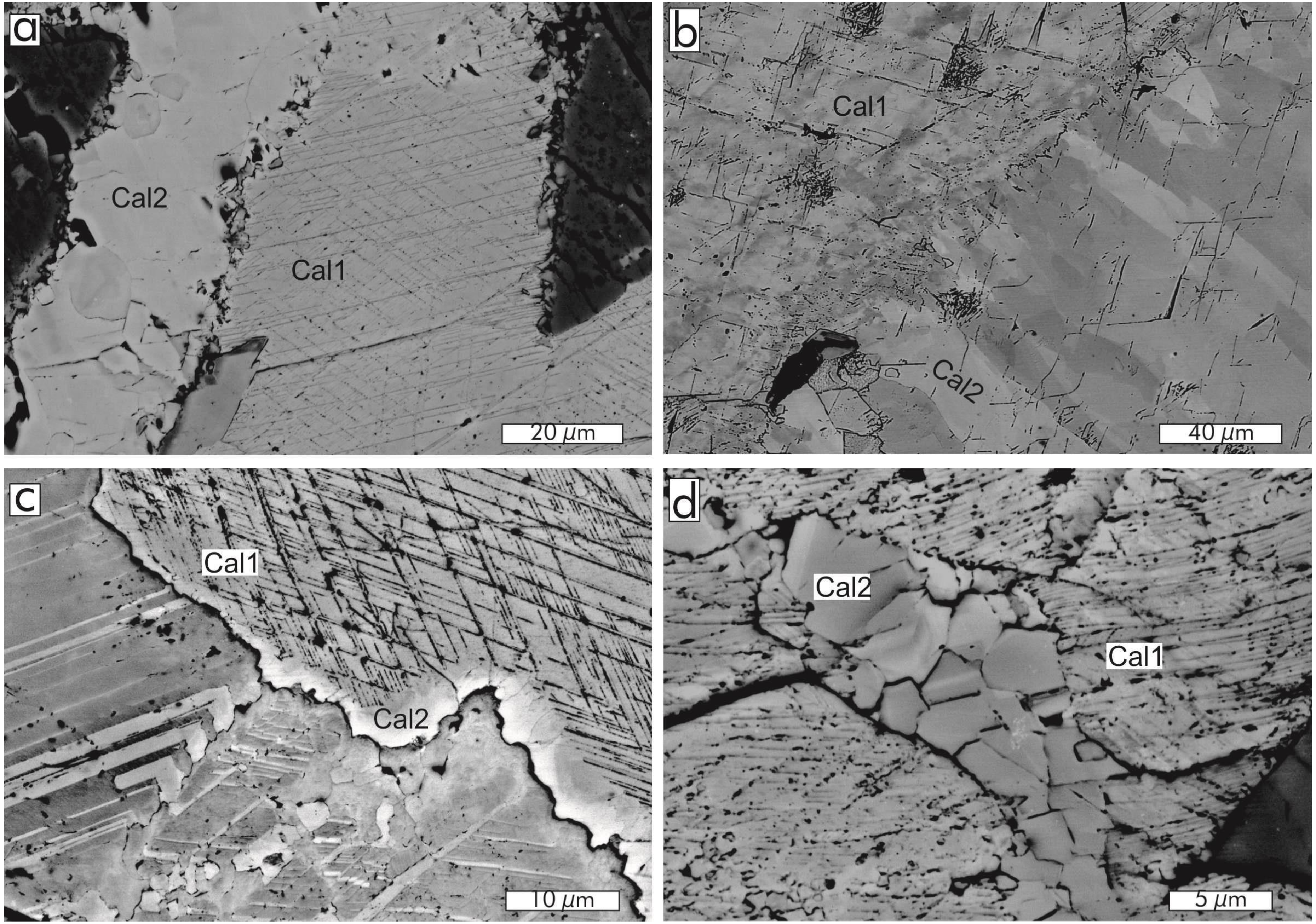
High twin density in twinned calcite grains within brecciated gneisses – scanning electron microscopy



(a, b) BSE micrograph of fine-lamellar planar microstructures and crosscutting twins (spacing less than 1 μm), sample Jb2a.

→ Twinning in calcite shows remarkably high twin density and small width of the twins. The twins are crosscutting each other, which may be a characteristic feature of shock-generated calcite twins (Langenhorst et al. 2003).

Different generations of calcite grains within brecciated gneisses – scanning electron microscopy



BSE images of different generations of calcite with different chemical composition.

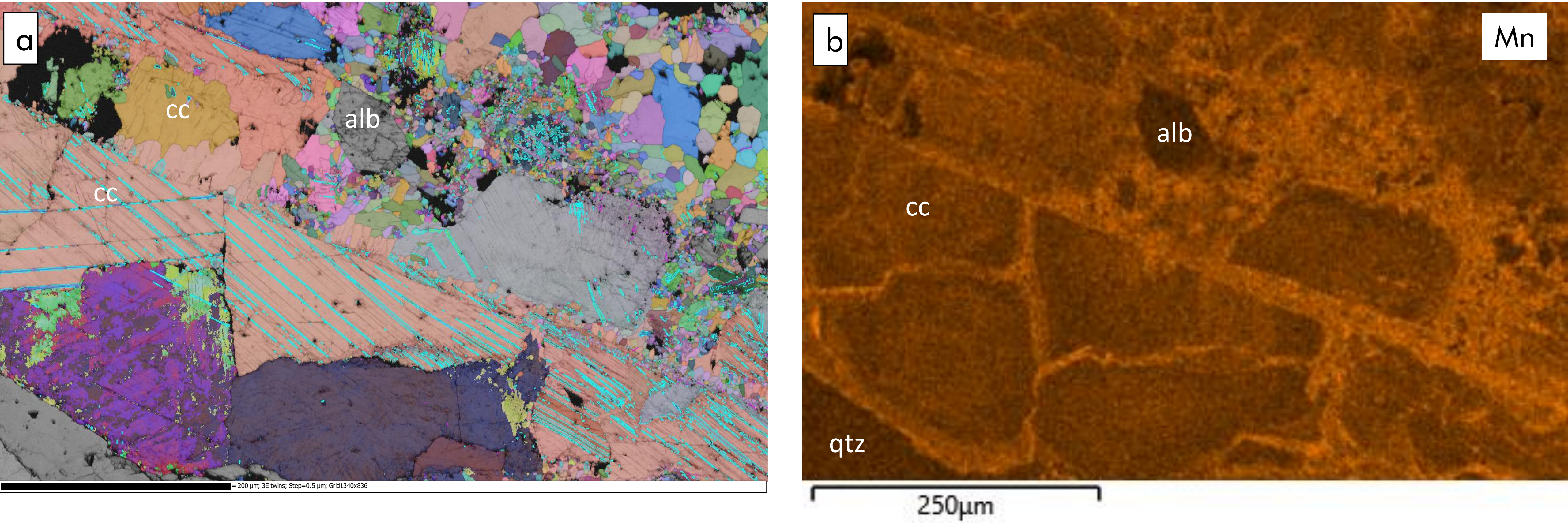
(a) Veins of untwinned (cal1) and twinned calcite (cal2).

(b) Left twinned calcite (cal1), right palisade shaped elongate calcite grains with increased Fe-content (cal2).

(c) Twinned calcite (cal1) with Fe-rich rim that does not show twins (cal2).

(d) Untwinned, fine-grained calcite (cal2) within twinned calcite (cal1).

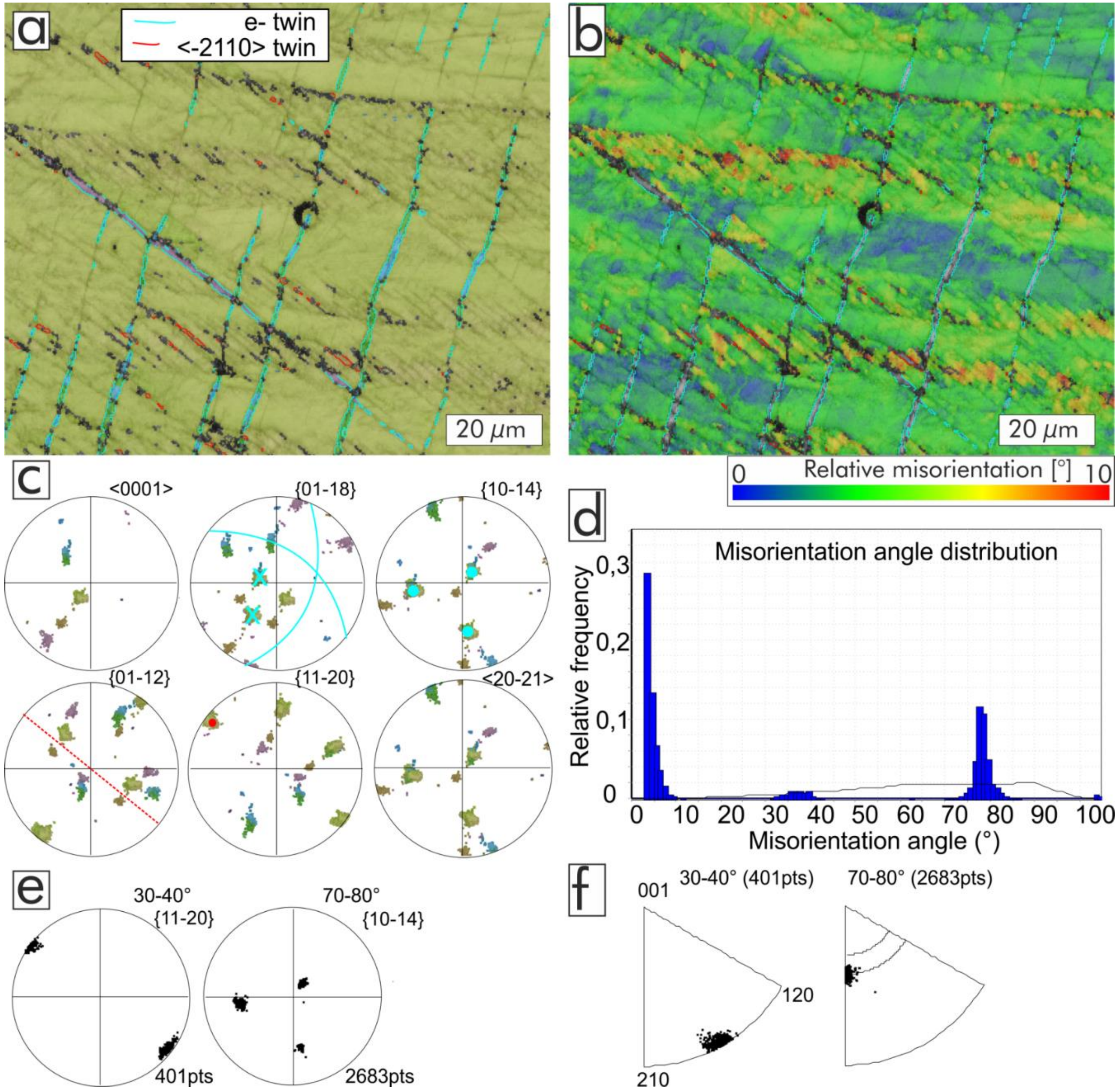
Different generations of calcite grains within brecciated gneisses



(a) EBSD map and (b) corresponding EDS Mn-distribution map showing Mn- (up to 0.6 wt% 0.2 a% Mn) and Fe- (up to 1.7 wt% 0.6 a% Fe) enriched second generation of calcite surrounding shocked calcite.

→ The untwinned (most probably later generation of) calcite is enriched with Mn and Fe.

EBSD data of twins I



(a) EBSD orientation map colour coded by euler angle with twin boundaries highlighted in turquoise (e-twin, pole to 10-14 is rotation axis, angle 78°, 01-18 twin plane) and red (twin with -2110 rotation axis, misorientation angle of 35° twin plane parallel -1012), sample Jb2a.

(b) Relative misorientation map of 10° relative to a reference orientation (blue colour).

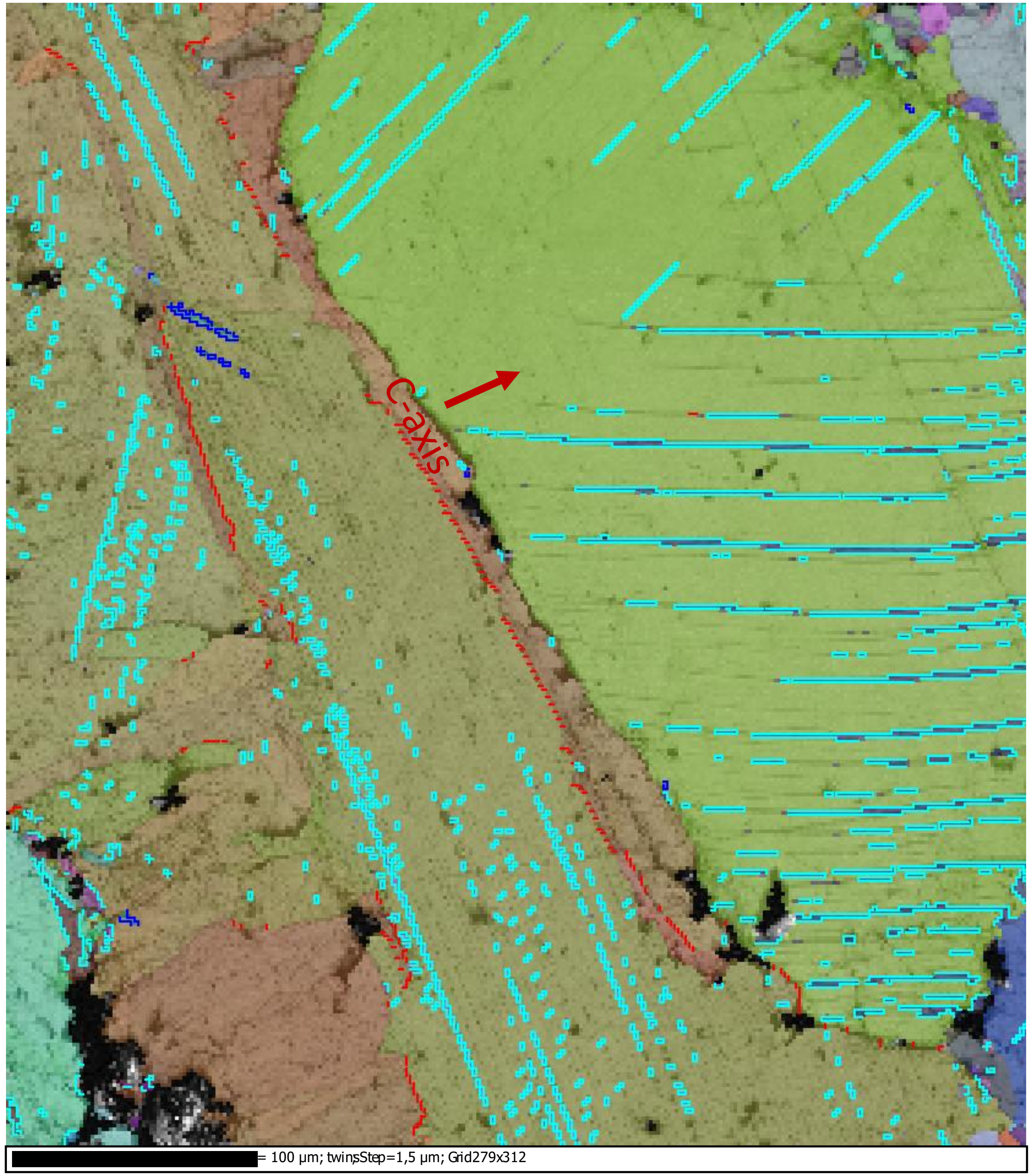
(c) Pole figures colour coded corresponding to the map in (a).

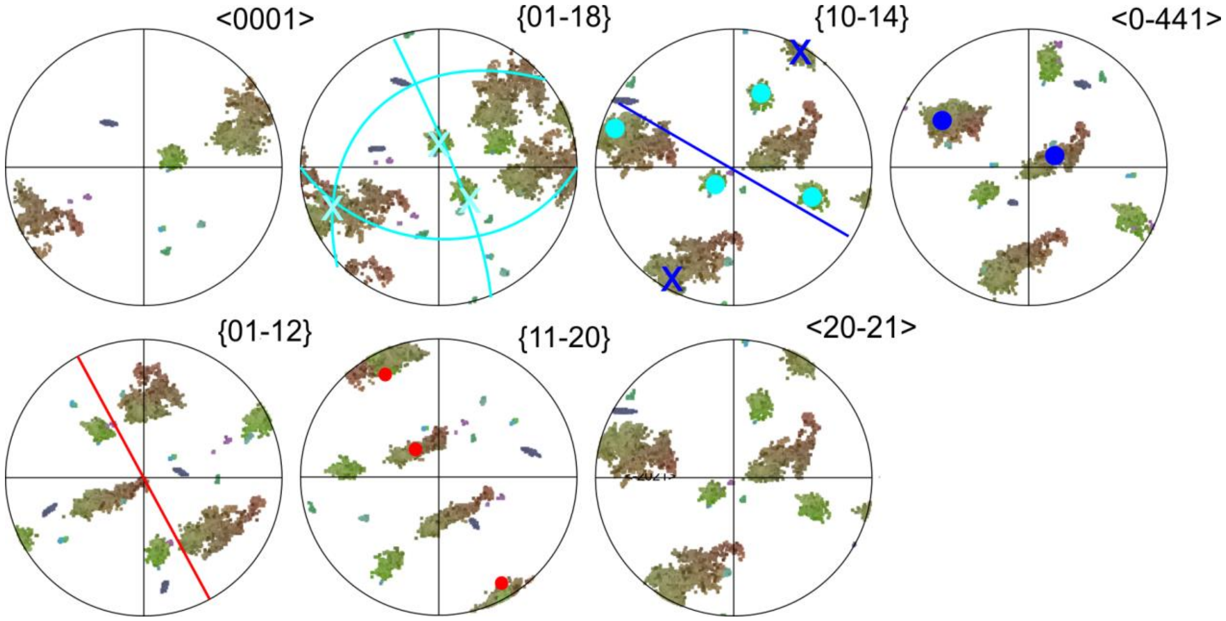
(d) Misorientation angle distribution showing peaks ca. 35° and 78° representing the rotation angles for the two observed twins.

(e, f) Rotation axes for the two angles in sample and crystallographic coordinates, respectively.

Twin	Twin plane	Rotation axis	Rotation angle	Occurrence
e-twin	01-18	20-21 pole to {10-14}	78°	Shocked rocks, Lindgren et al., 2013. Most common in fault rocks
x-twin	01-12 ?	-2110 pole to {11-20}	37°	unknown

EBSD data of twins II

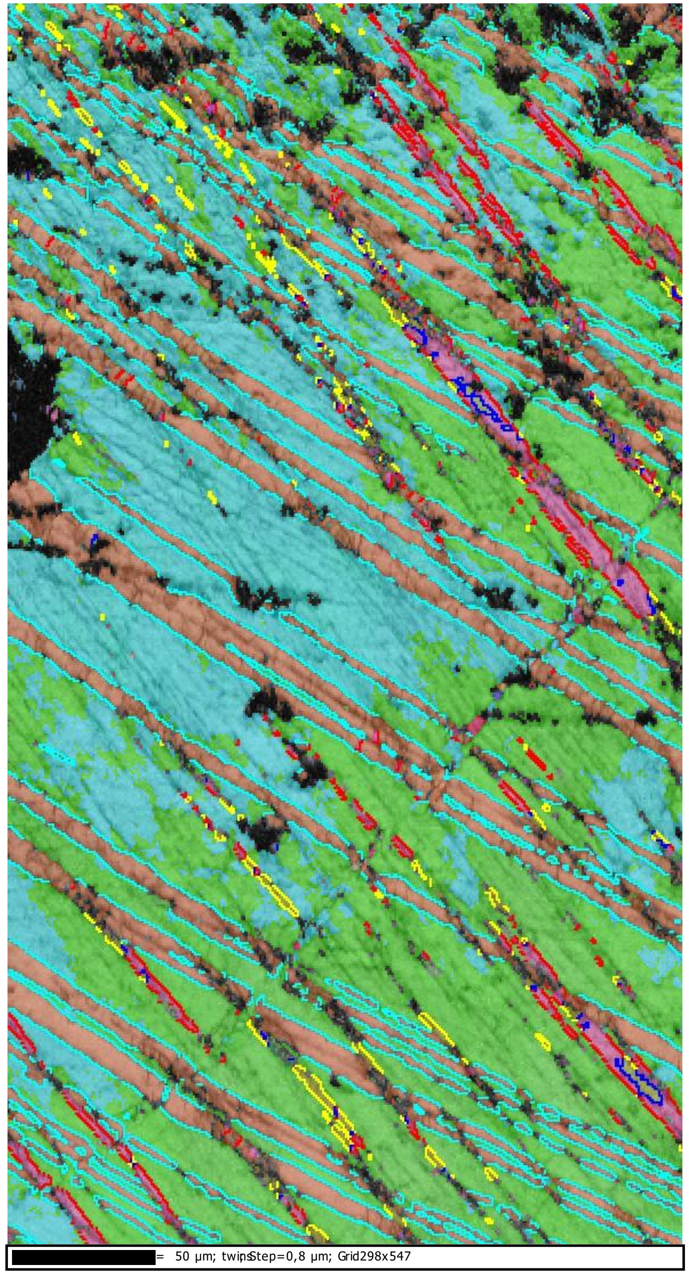


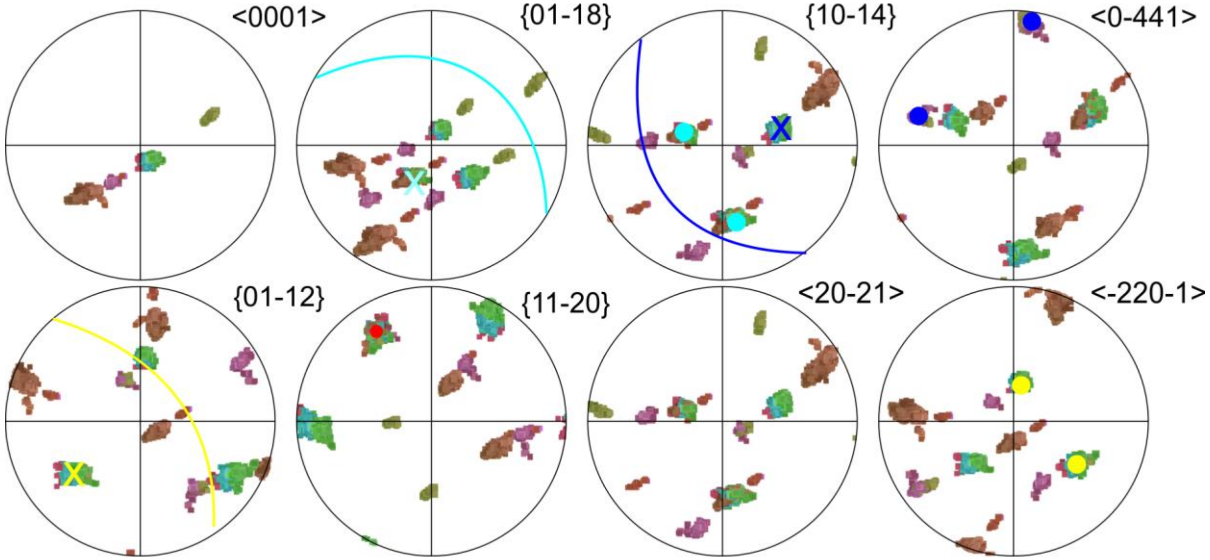


Twin	Twin plane	Rotation axis	Rotation angle	Occurrence
e-twin	01-18	20-21 pole to {10-14}	78°	Shocked rocks, Lindgren et al., 2013. Most common in fault rocks
r-twin	10-14	0-441=40-41	100°	
x-twin	0001?	-2110 pole to {11-20}	37°	unknown

Commonly occuring elongate calcite grains with c-axis oriented perpendicular to long axis of grains

EBSD data of twins III





Twin	Twin plane	Rotation axis	Rotation angle	Occurrence
e-twin	01-18	20-21 pole to {10-14}	78°	Shocked rocks, Lindgren et al., 2013. Most common in fault rocks
r-twin	10-14	0-441=40-41	100°	
f-twin	01-12	-220-1	78°	Shock experiments, Langenhorst et al. 2003
x-twin	01-12?	-2110 pole to {11-20}	37°	unknown

Twinned calcite,
clast in suevite from Aumühle:
Four different twin systems detected.

Shock induced or pre-shock twins?

Summary - microstructural characteristics of the twinned calcite

- High twin density and small width of twins
- Apparent cross-cutting of twins (has to be confirmed with TEM)
- Occurrence of several other twin systems beside the common *e*-twins in one grain
- Combined SPO and CPO of twinned elongate calcite grains with the c-axis perpendicular to the long axis of grains in veins obviously related to brecciation
- Two generations of calcite: twinned first generation and untwinned second generation of calcite

Conclusions:

→ The twins in calcite grains within veins cementing gneiss and granite breccias in the Ries are shock induced. This does not exclude that few twins might have been already present before the impact event.

→ Coarse calcite grains were already present before the impact, later generation formed during post-shock modification by a combination of precipitation and strain-induced grain boundary migration

→ Coarse calcite-bearing sediments and/or calcite vein-bearing granitic gneisses were brecciated and mixed during impact cratering

Open questions:

- Origin of the coarse calcite grains? Known carbonate-sediments are rather fine-grained and rich in second particles, marbles are not known from the Ries crystalline basement
- Influence of hydrous fluids and/or melting/devolatilization?