

Recrystallization and Intracrystalline Crystal-plastic Deformation of Naturally Deformed Hornblende

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1. Introduction

- For most minerals, deformation by dislocation creep results in a crystallographic preferred orientation (CPO) and grain size reduction via dynamic recrystallization.
- However, hornblende does not exhibit a clear transition from semi-brittle deformation mechanisms to dislocation creep at elevated P-T conditions unlike other minerals (e.g., calcite, olivine, quartz), and its ubiquitously observed CPO may reflect various deformation conditions (e.g., Topaz et al., 2021).

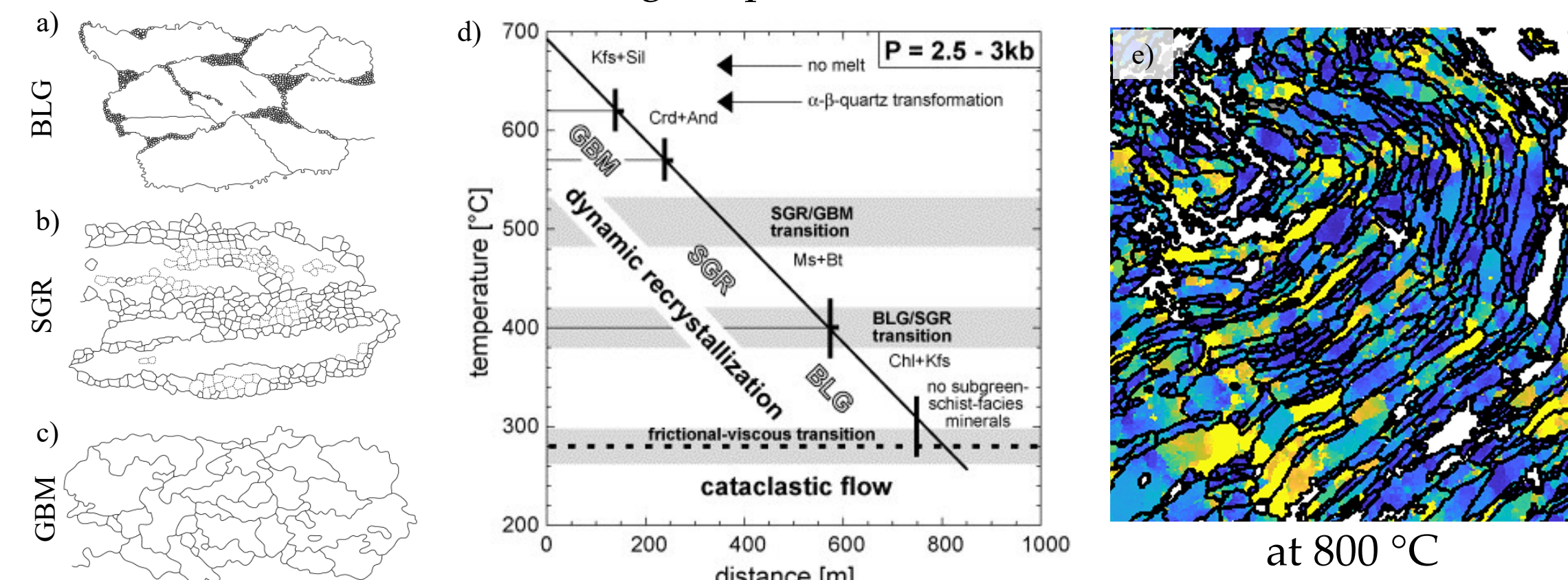


Fig. 1 | (a-c) Schematic representation of dynamic recrystallization mechanisms in quartz, illustrating the transition from bulging to grain boundary migration and subgrain rotation with increasing temperature; (d) after Stipp et al. (2002), and (e) No evidence of recrystallization in hornblende, after Meher et al. (2026).

- Recent experiments on hornblende-rich natural samples at 400-800 °C reveal a semi-brittle behavior with increasing contribution of dislocation-mediated deformation. However, no recrystallization was observed experimentally.
- Here, we investigate hornblende microstructural properties from four hornblende-rich samples to characterize their recrystallization processes under a range of P-T conditions.

2. Sample occurrence

a) **Bath of Aphrodite, Mamonia complex, Cyprus:** ~ 0.5 GPa and ~ 600 °C

- 45-52% hornblende, 3-10% calcite, 10-15% albite, minor accessory phases.
- Mm-scale type-3 refold structure and conjugated kink bands in hornblende.

b) **Koralpe, Austrian Alps:** ~ 2.1 GPa and ~ 750 °C

- 40-60% hornblende, 25-35% zoisite, 5-10% kyanite, minor accessory phases.
- Sigmoidal hornblende porphyroclasts with smaller tabular elongated grains.

c) **Mayodiya, India:** ~ 0.78-0.82 GPa and ~ 770-820 °C

- ~97% hornblende with minor zoisite.
- Needle-shaped grains with serrated boundaries tapering between two bladed porphyroclasts (>1 mm).

d) **Koraput, India:** 0.76-0.84 GPa and ~ 860-883 °C

- >90% hornblende with plagioclase and clinopyroxene.
- Exhibits recrystallization of a cm-scale porphyroclast with smaller grains and lobate boundaries forming a core-mantle microstructure.

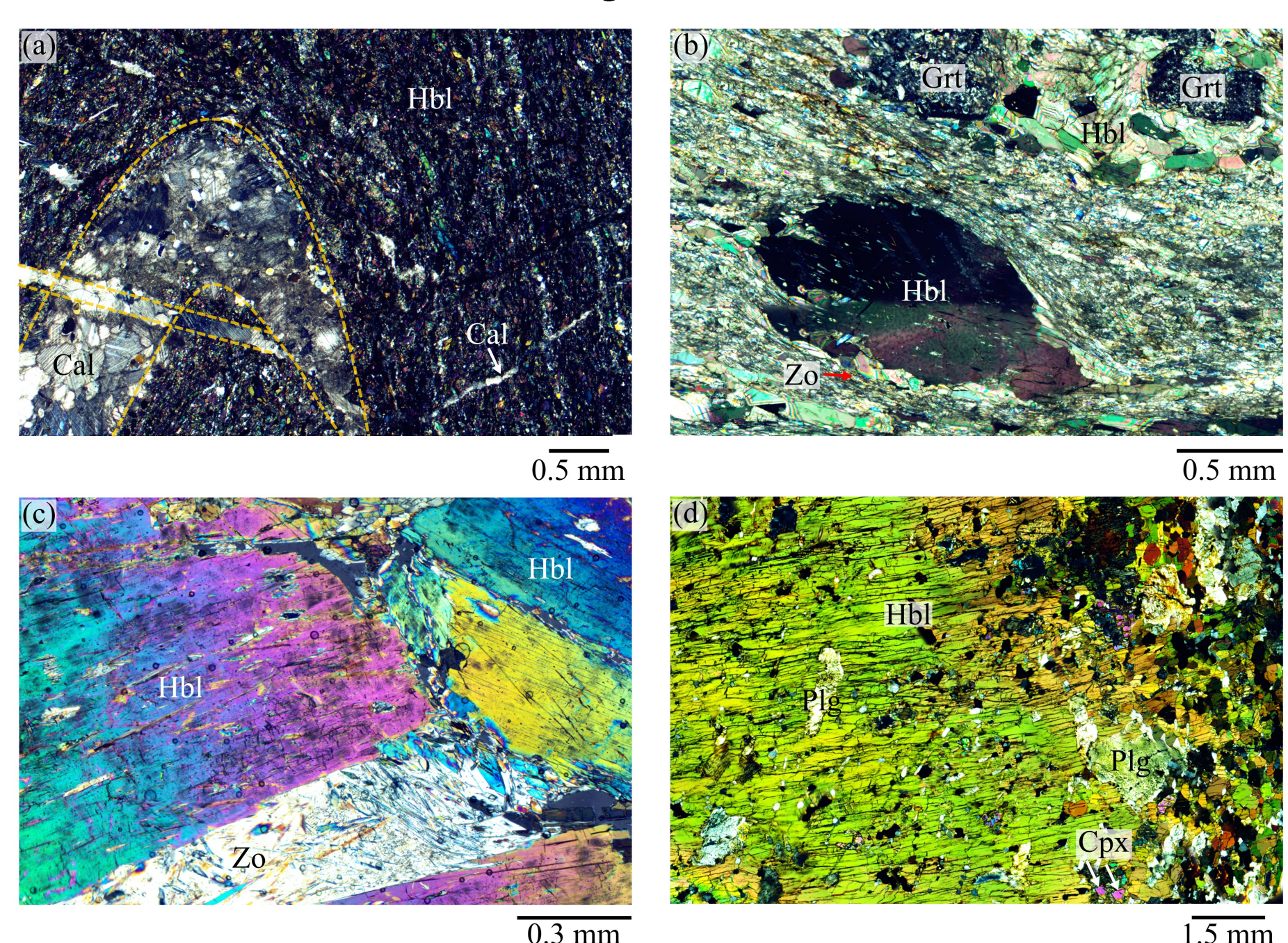


Fig. 2 | Typical microstructure of different samples exhibiting distinct microstructures under crossed polarized light microscope.

3. Results – EBSD analysis

Mamonia complex, Cyprus (~ 600 °C)

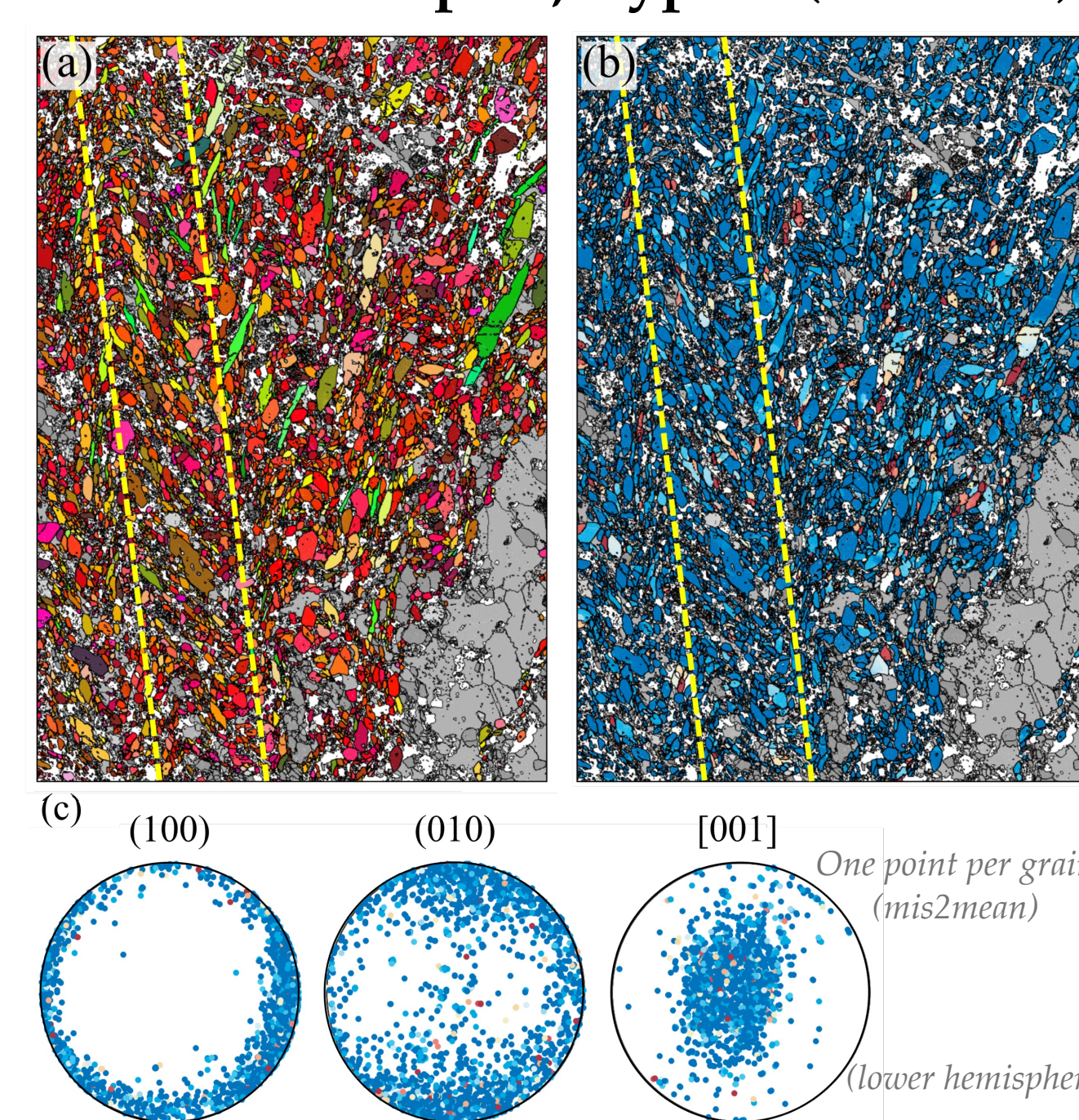


Fig. 3 | (a) Hornblende's orientation with z-axis. (b) Intragrain misorientation (mis2mean). (c) CPO of hornblende (one point per grain).

- Deformation through fractures and kink bands, with no evidence of recrystallization.

Koralpe, Austrian Alps (~ 750 °C)

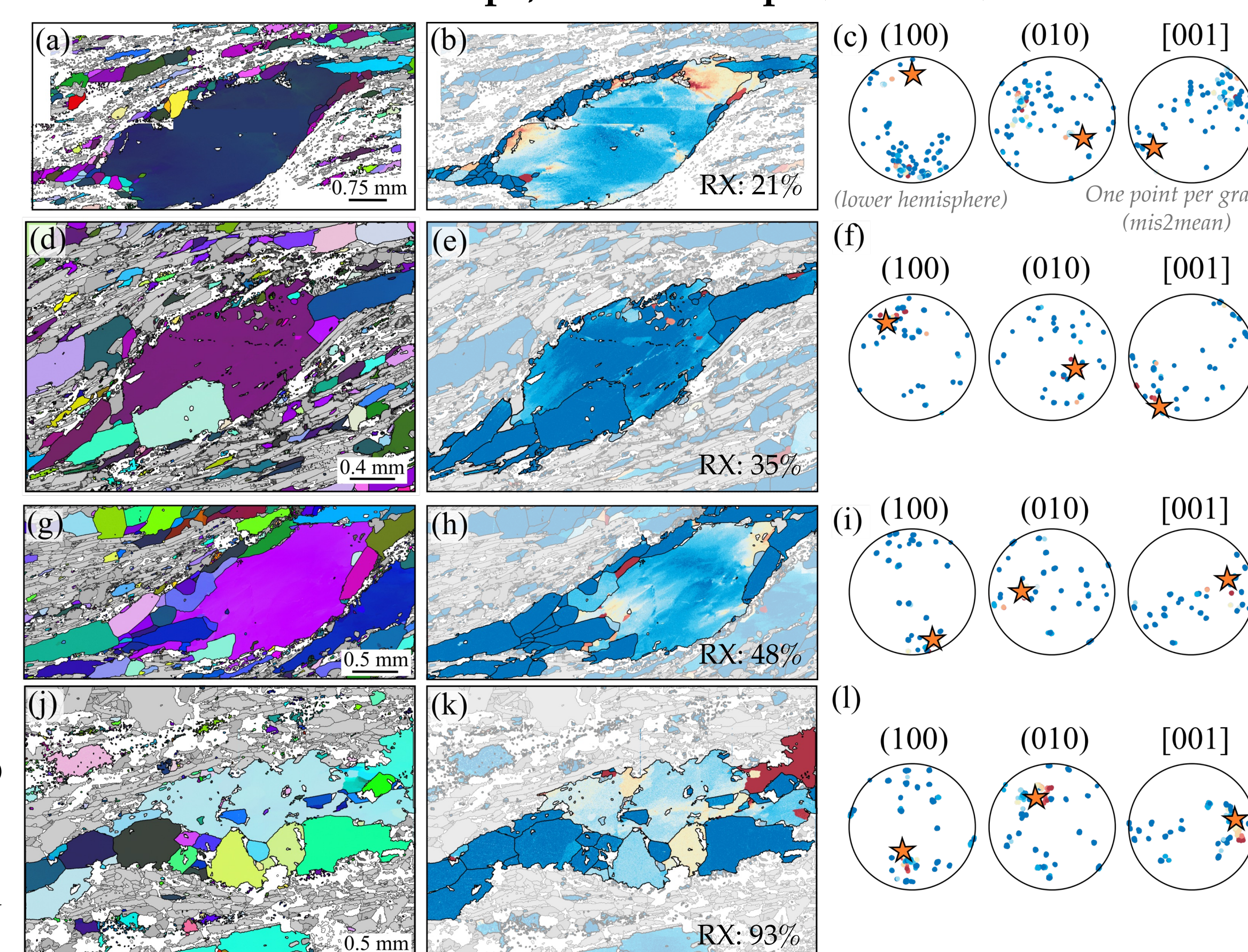


Fig. 4 | (a, d, g, j) Orientation maps of hornblende with the x-axis. (b, e, h, k) Intragrain misorientation maps of hornblende, showing strong misorientation in porphyroblasts and strain-free grains surrounded it lacking intragrain misorientation, ordered by recrystallization fraction (%) and their crystallographic preferred orientations (c, f, i, l).

- Core-mantle recrystallization microstructure with strain-free grains around large and highly strained porphyroclasts.
- Notice the tabular, elongated recrystallized grains. grow preferentially via grain boundary migration.

Mayodiya, India (~ 770 – 820 °C)

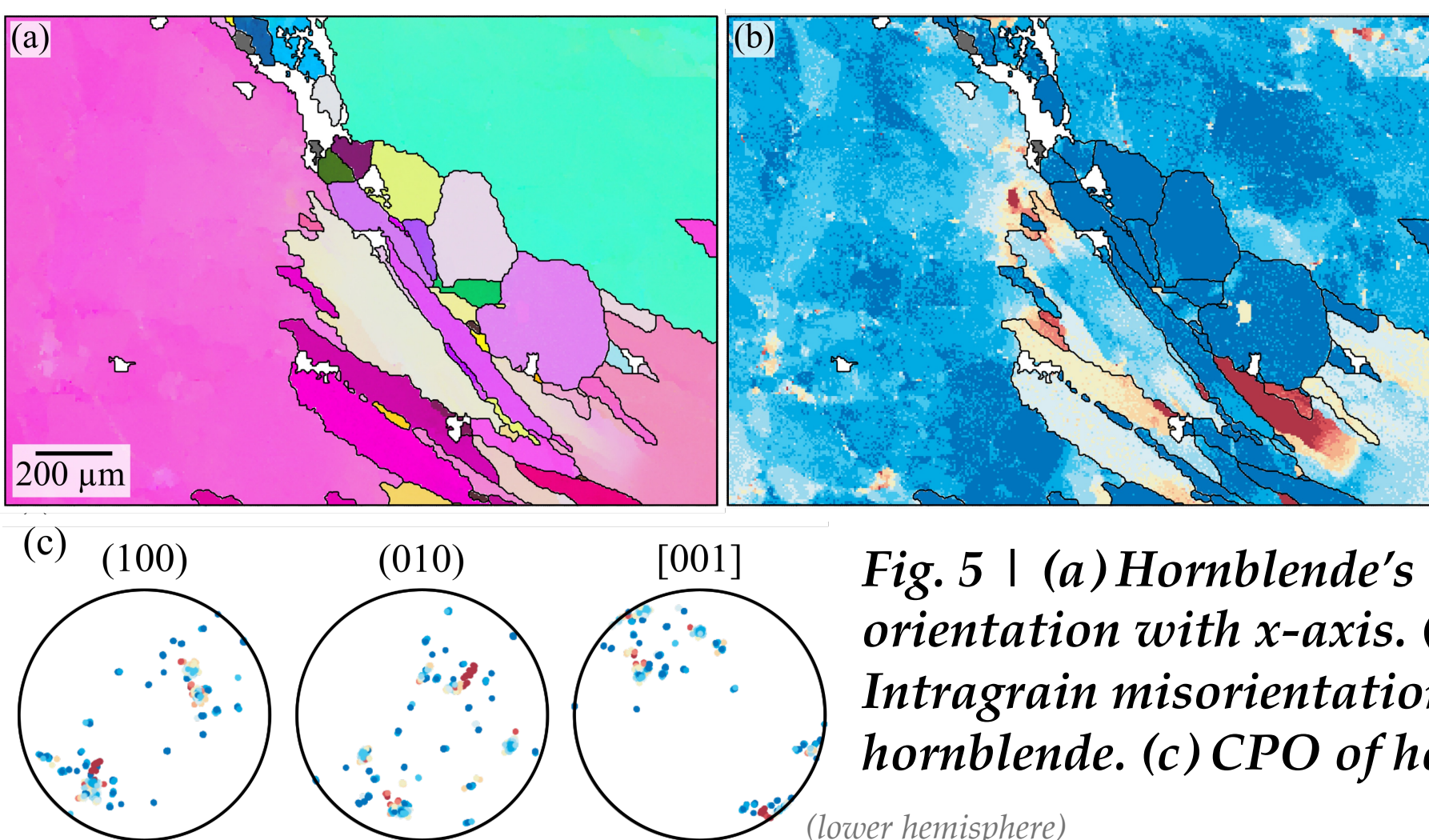


Fig. 5 | (a) Hornblende's orientation with x-axis. (b) Intragrain misorientation of hornblende. (c) CPO of hornblende.

- Porphyroclasts show high intragranular misorientation (strained grains), whereas recrystallized grains are largely "strain-free".
- Taper-type, needle-shaped recrystallized grains at the periphery of porphyroclasts.

Koraput, India (~ 860 – 883 °C)

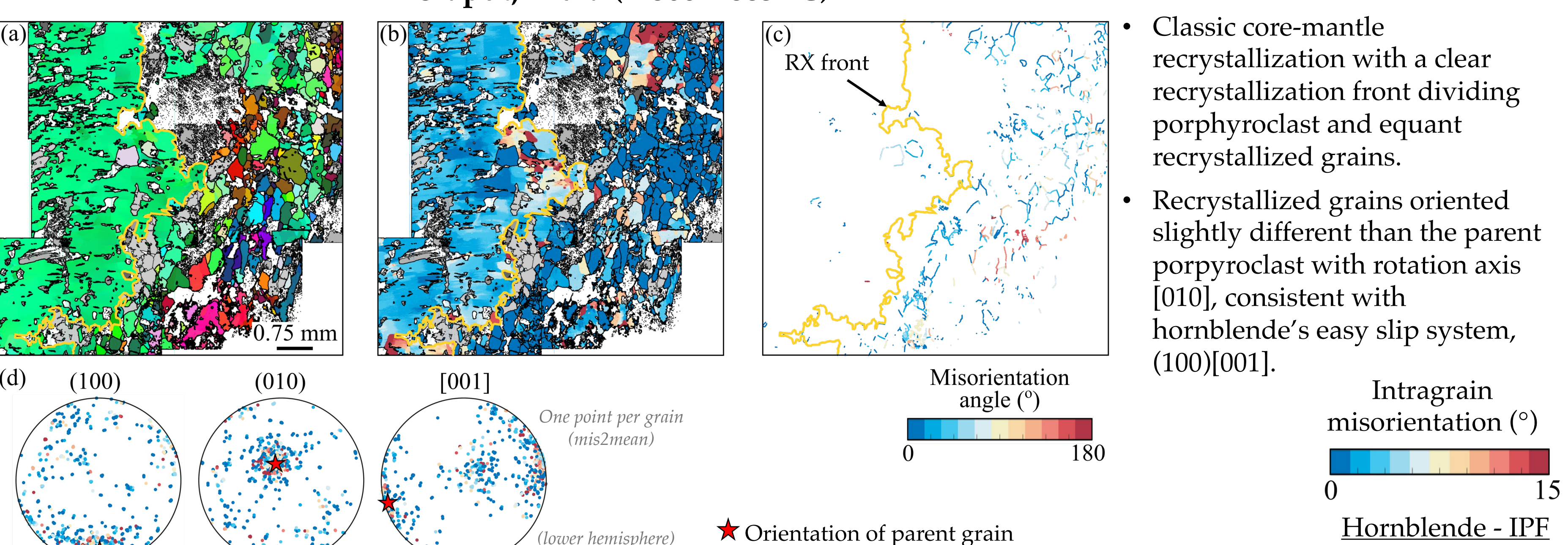


Fig. 6 | (a) Hornblende's orientation with the z-axis. Yellow lines denote the recrystallization front. (b) Intragrain misorientation of hornblende showing high misorientation in parent grains and comparatively lower misorientation in recrystallized grains. (c) Grain-boundary misorientation illustrating the transition of grain boundaries development from parent to recrystallized grains. (d) Hornblende's CPO indicating rotation about [010] while (100) and [001] is rotating.

4. Discussion

Recrystallization by grain boundary migration

- Koralpe** – Tabular recrystallized grains, followed by subsequent preferential grain growth.

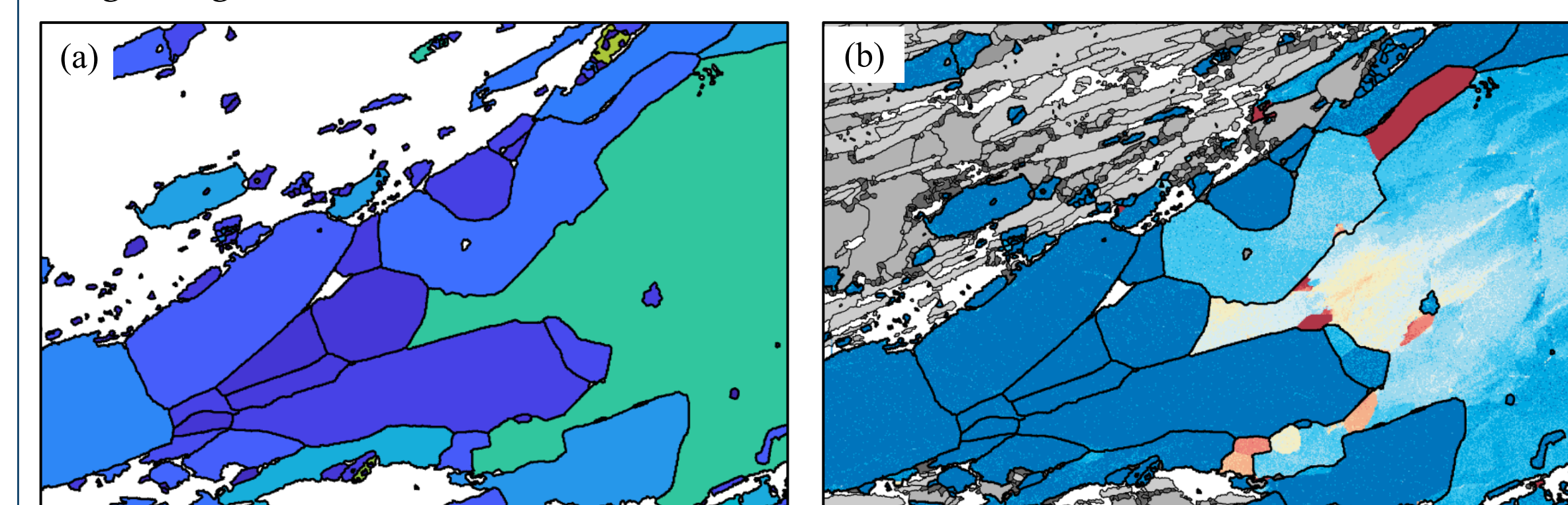


Fig. 7 | (a-b) Example of oriented grain growth. Tabular grains exhibit the lowest PARIS number and straight grain boundaries. (c-f) Subgrain boundary formation in hornblende from the highest-temperature samples, indicating activation of easy slip systems along (100)[001].

This study

- ★ **Bath of Aphrodite, Mamonia complex, Cyprus** – Semibrittle deformation mechanism with no RX
- ★ **Koralpe, Austrian Alps** – Tabular recrystallization via grain boundary migration
- ★ **Mayodiya, India** – Tabular recrystallization induced by strain energy
- ★ **Koraput, India** – Dynamic recrystallization, core-mantle structure with equant grains and crystal rotation that fits dislocation glide in the hornblende's easy slip system (i.e., (100)[001]).

Hornblende's deformation mechanisms and their P-T conditions

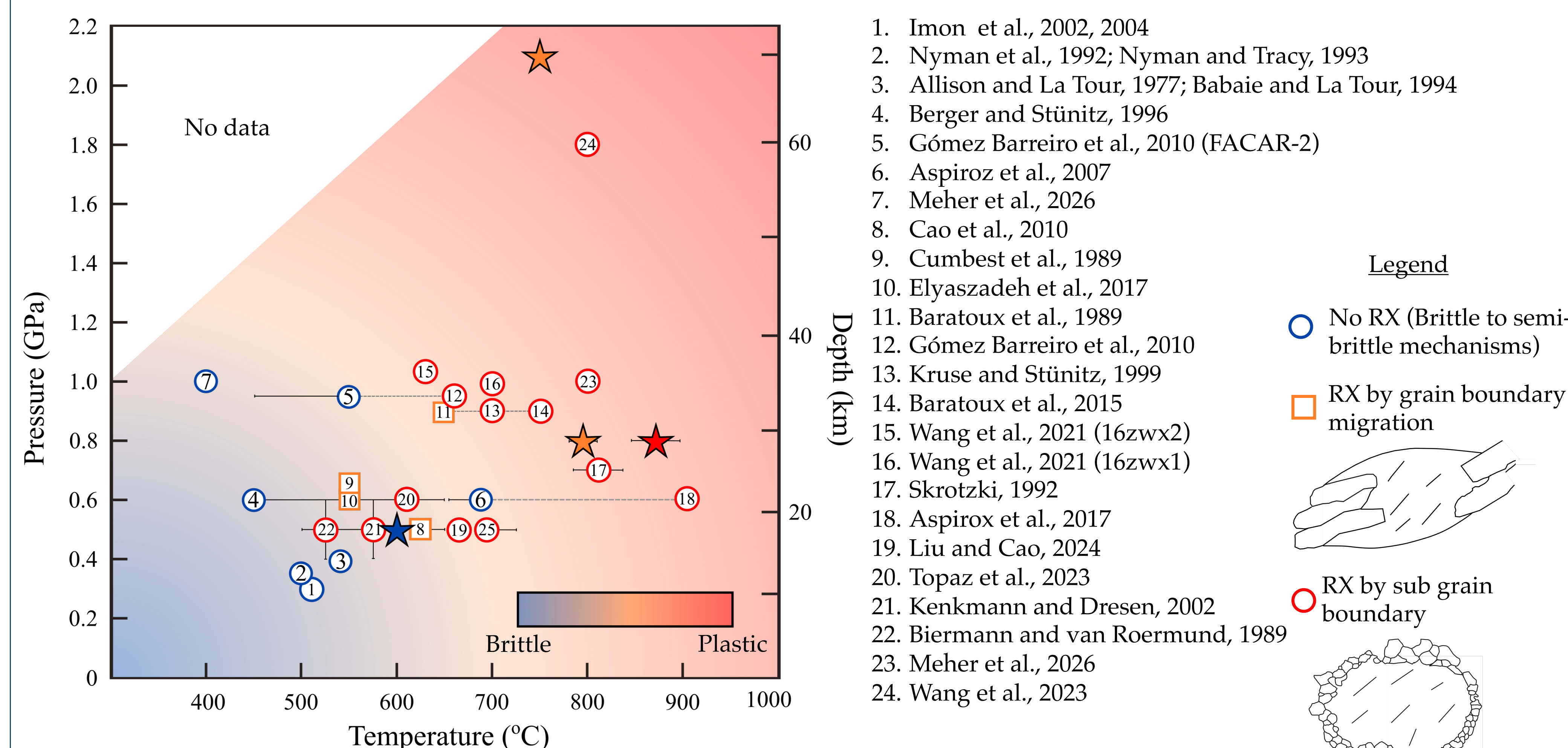


Fig. 8 | A synthesis of microstructural observations from this study (stars) and as inferred from the literature according to the grain shape (see schematic on the right). The different recrystallization behaviors reflect the ability to deform plastically.

5. Key findings

- Here we distinguish between two important recrystallization mechanisms: recrystallization via **grain boundary migration** producing tabular strain-free grains and recrystallization by **subgrain rotation** resulting in equant-shaped grains.
- At T < 600 °C, deformation is mainly semi-brittle, characterized by kink bands and bending.
- Between 600 and 800 °C, recrystallization is more likely to be by grain boundary migration.
- At T > 800 °C, grain-size reduction through subgrain boundary recrystallization, producing equant grains.

References

- Stipp et al. (2002). The eastern Ionian fault zone: a natural laboratory for crystal plastic deformation of quartz over a temperature range from 250 to 700 °C (JSC).
- Meher et al. (2026). Experimental deformation of textured amphibolites in the semi-brittle regime: Microstructural signatures of dislocation-mediated deformation (JGR).
- Topaz et al. (2023). Natural fabrics of a hornblende-rich amphibolite: Implications for hornblende crystallographic preferred orientation and seismic anisotropy of the lower crust (Tectonophysics).