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Shear Faulting Mechanism of Deep-Focus Earthquakes: Experimental Evidence from Deformed Mn_2GeO_4 undergoing the Olivine – Wadsleyite Phase Transformation

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Background and Motivation

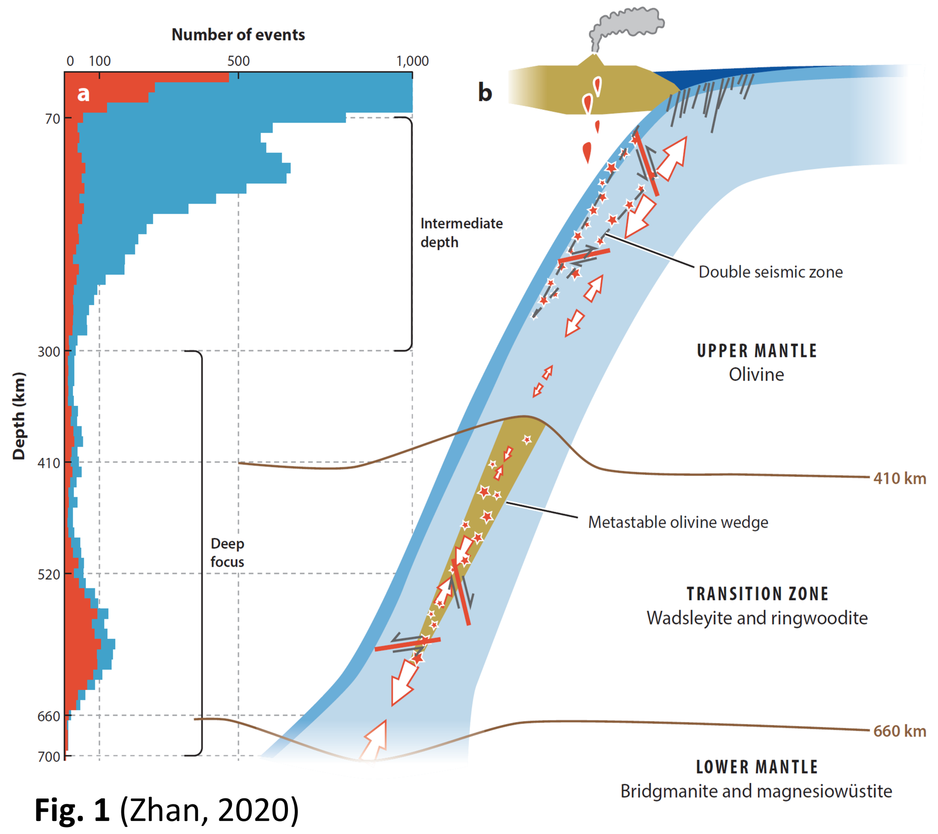


Fig. 1 (Zhan, 2020)

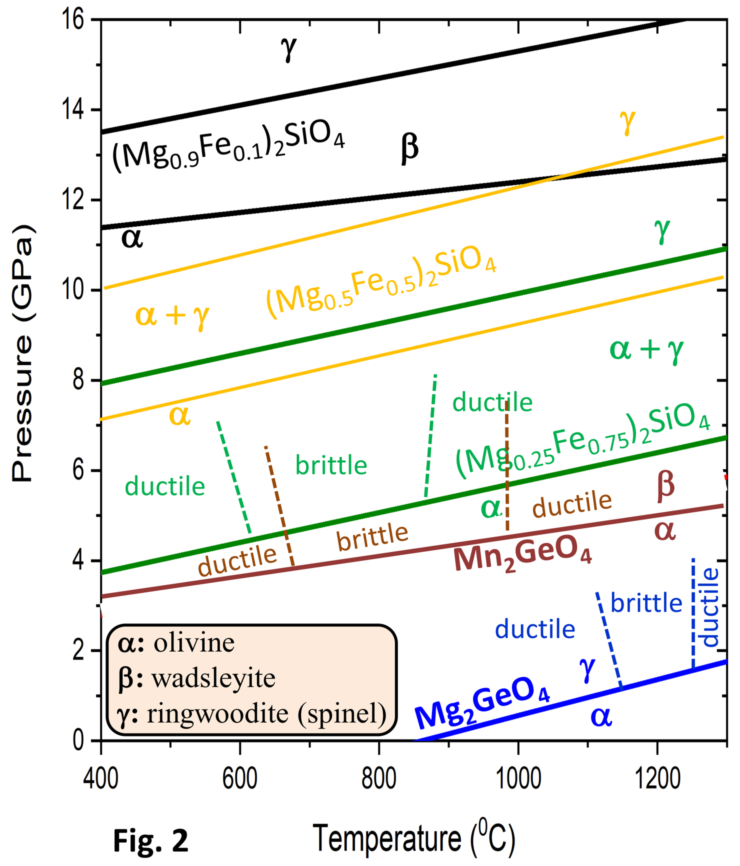


Fig. 2

- One hypothesis for deep-focus earthquakes is transformational faulting (**Fig. 1**). Experimentally, metastable olivines deformed in high-pressure stability field exhibit a brittle behavior only within a certain temperature range (**Fig. 2**; dashed lines are tentative boundaries between ductile and brittle responses).
- Micro-mechanisms of shear localization due to syn-deformational transformation from olivine to wadsleyite or ringwoodite remain poorly studied.
- We investigate microstructures in experimentally faulted Mg_2GeO_4, Mn_2GeO_4, and $(Mg,Fe)_2SiO_4$ olivines, which transform to γ, β, and α+γ phases, respectively.

Experimental

- Pre-sintered polycrystalline Mn_2GeO_4 and Mn_2GeO_4 olivine samples were deformed in the D-DIA apparatus with acoustic emission (AE) monitoring (**Fig. 3**), under pressure and temperature conditions corresponding to the respective high-pressure phase stability field.
- All the metastable olivine samples deformed in the brittle fields shown in **Fig. 2** emitted numerous AEs and recovered samples contain macroscopic faults (**Fig. 4**). In all cases, maximum axial strains are on the order of 25-30%.
- Microstructural characterization using microtomography, SEM, and TEM on recovered samples.

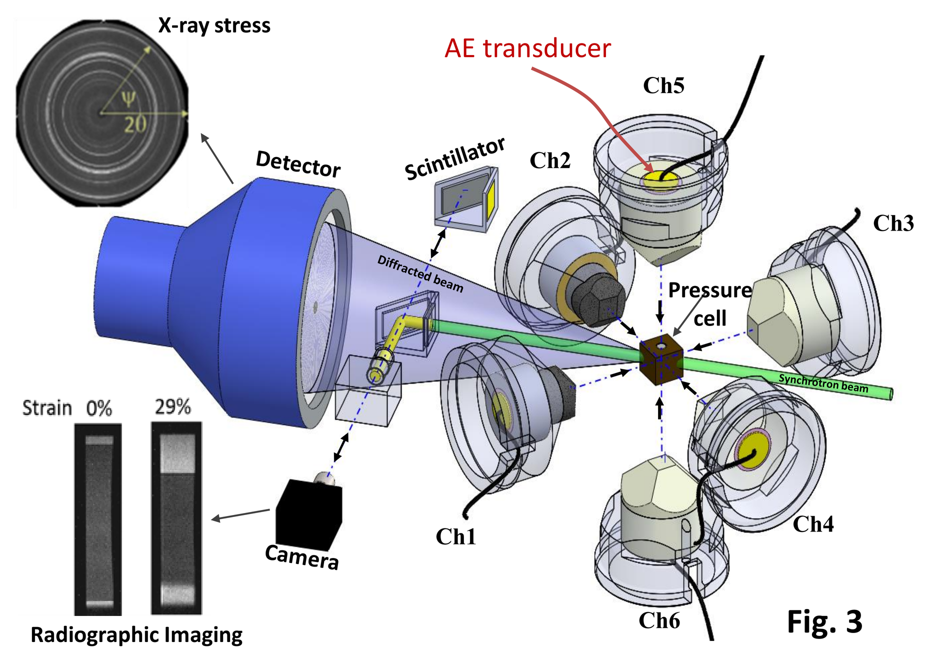
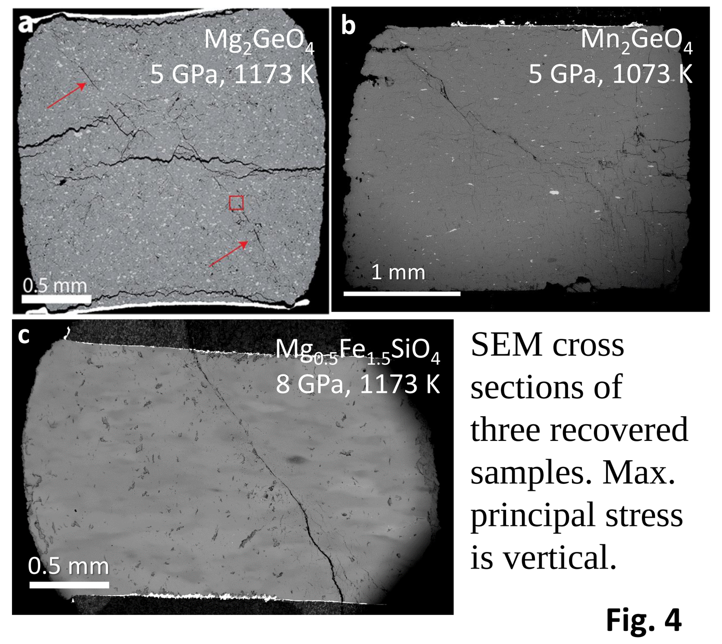


Fig. 3



SEM cross sections of three recovered samples. Max. principal stress is vertical.

Fig. 4

References cited: Burnley et al., *JGR*, 96:425-443, 1991; Burnley et al., *Am Min*, 98:927-931, 2013; Green et al., *Nature*, 341:733-737, 1989; Green et al., *Nat Geosci*, 8:484-489, 2015; Katsura & Ito, *JGR*, 94:15663-15670, 1989; Morimoto et al., *PEPI*, 3:161-165, 1970; Officer et al., This meeting (2:00 pm today; 208B); Riggs & Green, *JGR*, 110:B03202, 2005; Ross & Navrotsky, *PCM*, 14:473-481, 1987; Schubnel et al., *Science*, 341:1377-1380, 2013; Wang et al., *Sci. Adv.*, 3e1601896, 2017;Weidner & Hamaya, *PEPI*, 33:275-283, 1983; Zhan, *Ann Rev Earth Planet Sci*, 48:147-174, 2020.

Results

Mn_2GeO_4

SEM and EBSD show that newly nucleated β-Mn_2GeO_4 form extremely thin linear zones, often cutting olivine grains into subparallel bands, which have the characteristics of kink bands. Within the β-Mn_2GeO_4 phase zones, grain size is extremely fine, typically 100 nm or less.

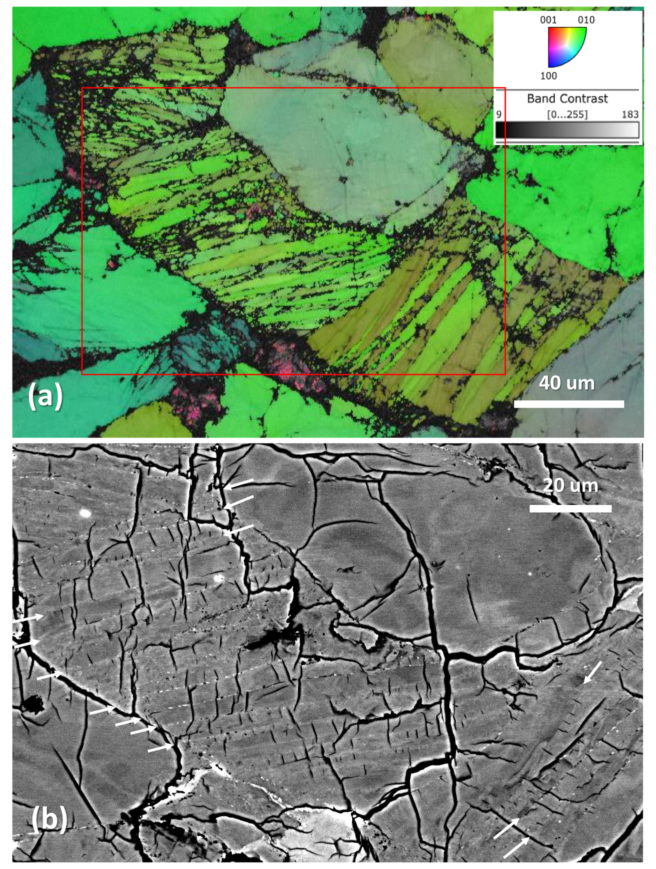


Fig. 5

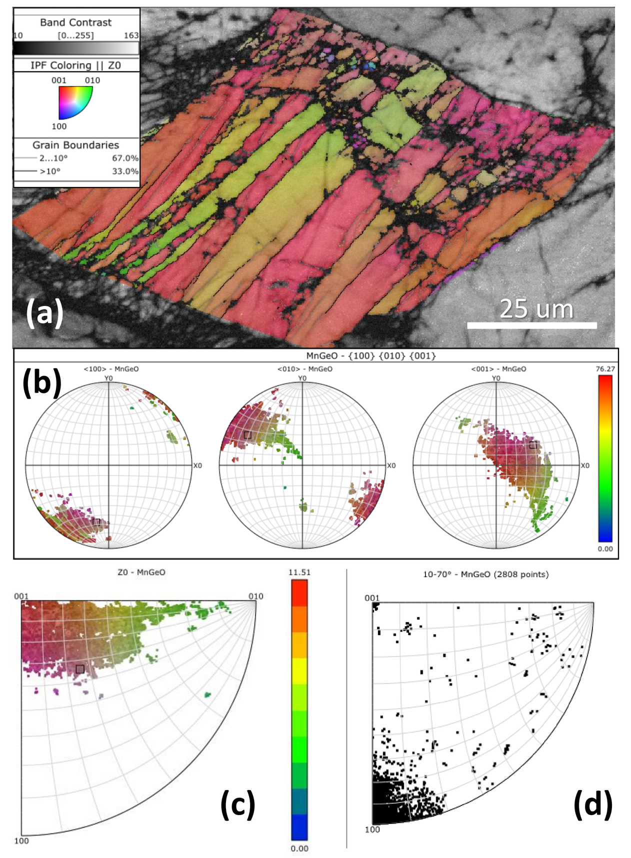


Fig. 6

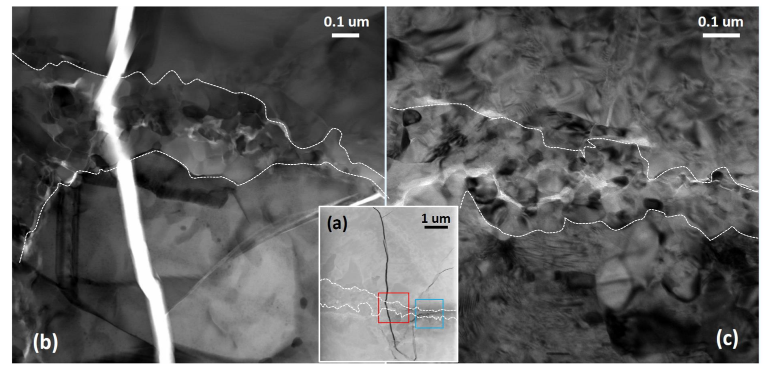


Fig. 7

5a: kink bands in Mn_2GeO_4 olivine. **5b**: kink band boundaries (KBBs) are filled with β-Mg_2GeO_4 (white dots). **6a**: the same grain shown in Fig. 5a (lower right). **6b**: pole figure of the kink bands in this grain. **6c**: inverse pole figure of the grain. Kink banks rotate towards 010 at various degrees. **6d**: rotation axes of the kink bands. Majority of the rotation axes are near [100]. **7a**: TEM image of an FIB foil capturing on of the KBBs. **7b&c**: enlarged view of the KBB (between white dotted lines). β-Mg_2GeO_4 grains are on the order of ~50 nm in size.

Kink band formation is related to metastability of Mn_2GeO_4 olivine. Olivine deformed within its stability field contains virtually no kink bands.

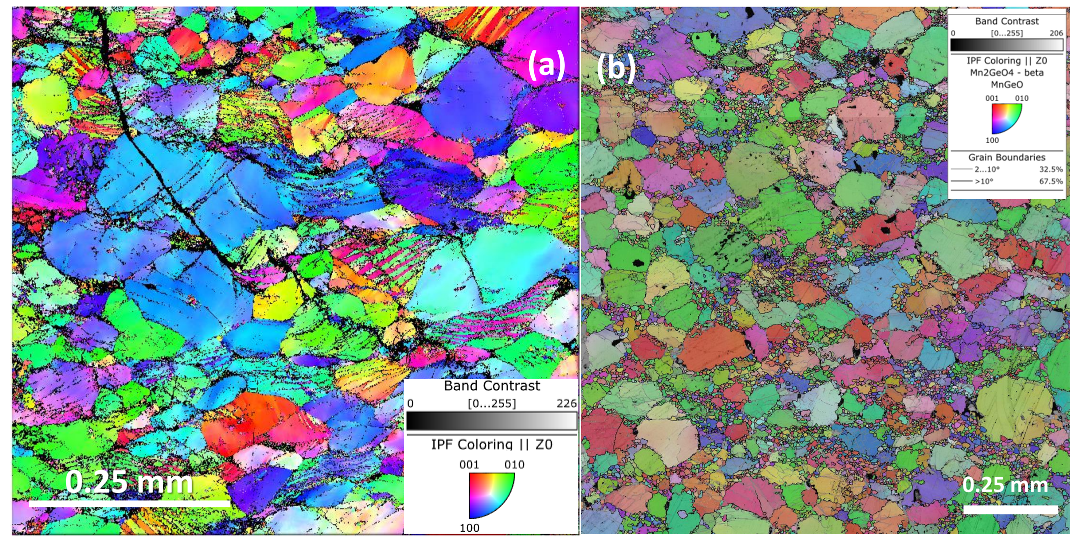


Fig. 8

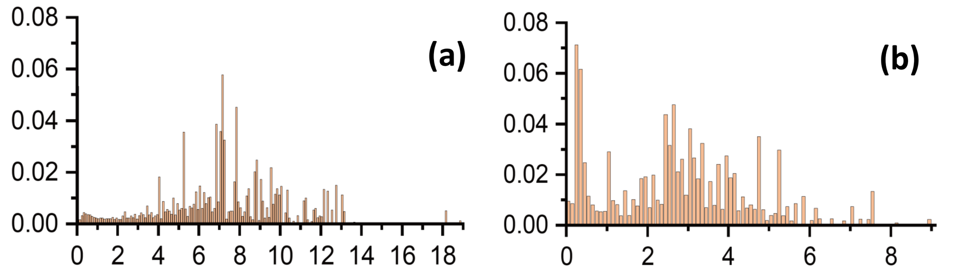


Fig. 9

Fig. 8a: kink bands in deformed metastable Mn_2GeO_4 olivine. **Fig. 8b**: very few kink bands in olivine deformed within olivine stability field. **Fig. 9a**: grain orientation spread (GOS) of the area in **Fig. 8a**. Max GOS near 7 - 8°. **Fig. 9b**: GOS of the area in **Fig. 8b**. Max. GOS is at ~0.5°. Note different horizontal scales in **Figs. 9a** and **b**. The contrast suggests that formation of β-Mn_2GeO_4 has caused significant intragrain deformation in metastable olivine.

Mg_2GeO_4

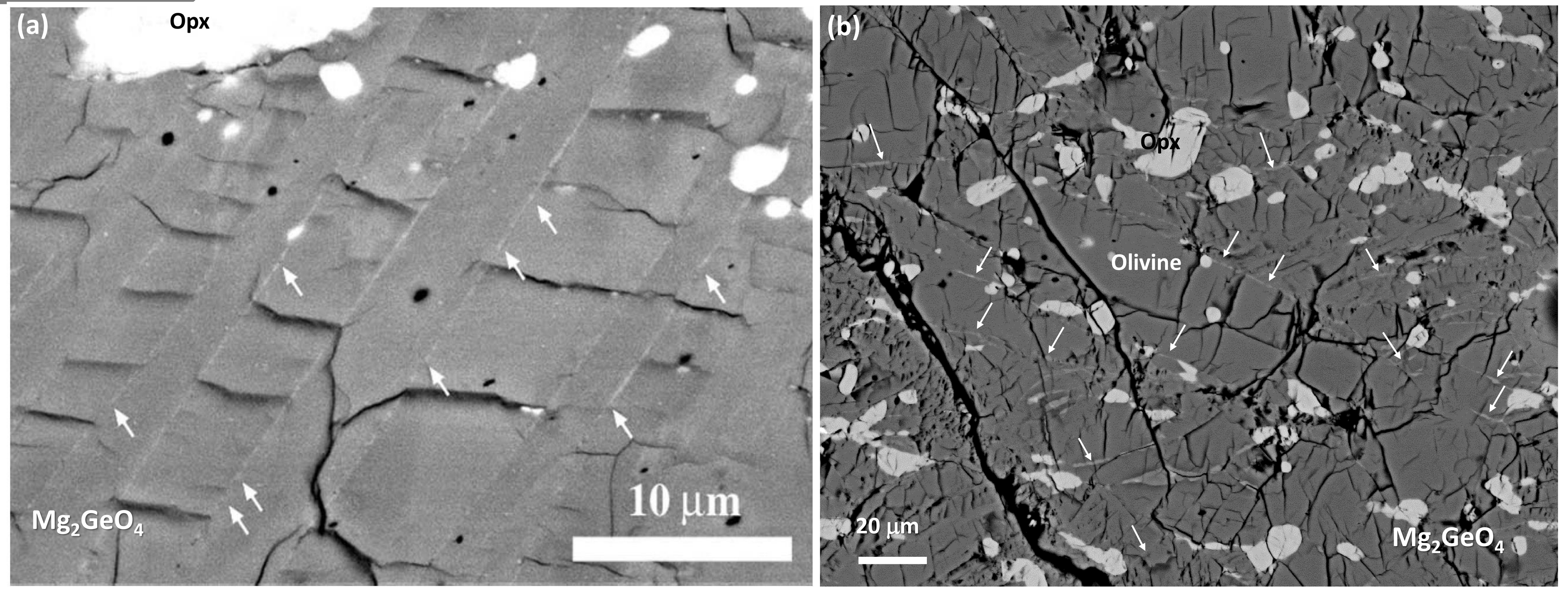


Fig. 10

Figs. 10a&b: metastable Mg_2GeO_4 olivine, reported by Riggs & Green, 2005 and this study, respectively. The grey phase is olivine; bright grains are orthopyroxene (Opx).

Discussion

Origin of kink bands

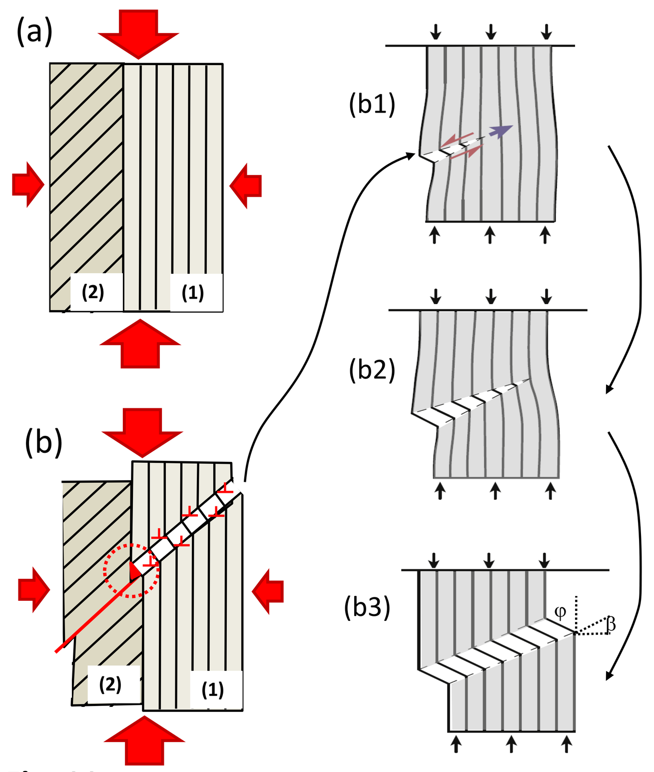


Fig. 11

Olivine has insufficient independent slip systems to satisfy von Mises criterion of plastic deformation. In **Fig. 11a & b**, the easy slip plane in grain (2) is parallel to the maximum shear stress, whereas the slip system in grain (1) cannot be activated. Slip in grain (2) creates stress concentration (red triangle in the circle), generating geometrically necessary dislocations (GNDs; red ⊥ symbols) in grain (1). Kink bands are a result of production and propagation of NGDs (**Figs. 11b1-11b3**). *Each KBB is a micro shear localization.*

Kink bands are less common in natural olivine under stable P-T conditions. The abundant kink bands observed in Mn_2GeO_4 and Mg_2GeO_4 olivines are related to their metastability when deformed in β-Mn_2GeO_4 or γ-Mg_2GeO_4 stability fields. Defects such as dislocations are preferred nucleation sites of high-pressure phases, which weaken the olivine lattice, making it energetically easier to form kink bands. The kink bands, in turn, help nucleate high-pressure phases. The nanometric high-pressure phases further lubricate kink band boundaries (KBBs), forming nano-shear zones (NSZs) at grain scale.

Faulting mechanism

Fig. 12 shows ubiquitous KBBs forming conjugated configurations. **Fig. 12a**: color scale shows grain orientation spread. Fig. 13b is the same area as in 13a, with band contrast indicating different orientations of the kink bands. α–β phase boundaries are dark blue. Thin layers of β-Mn_2GeO_4 phase in the KBBs are colored light blue. Areas for **Figs. 12c** and **d** are marked by their respective white boxes. **Fig. 12d & d**, β-Mn_2GeO_4 phase preferentially grow in the KBBs forming NSZs (see also **Fig. 10b, c**). Low-angle sub-grain boundaries (red lines) in kink bands resemble the shear strain configuration. As deformation increases, the network of NSZs provides ample nucleation sites of shear localization for large faults to self-organize, producing macroscopic faults shown in **Fig. 4**.

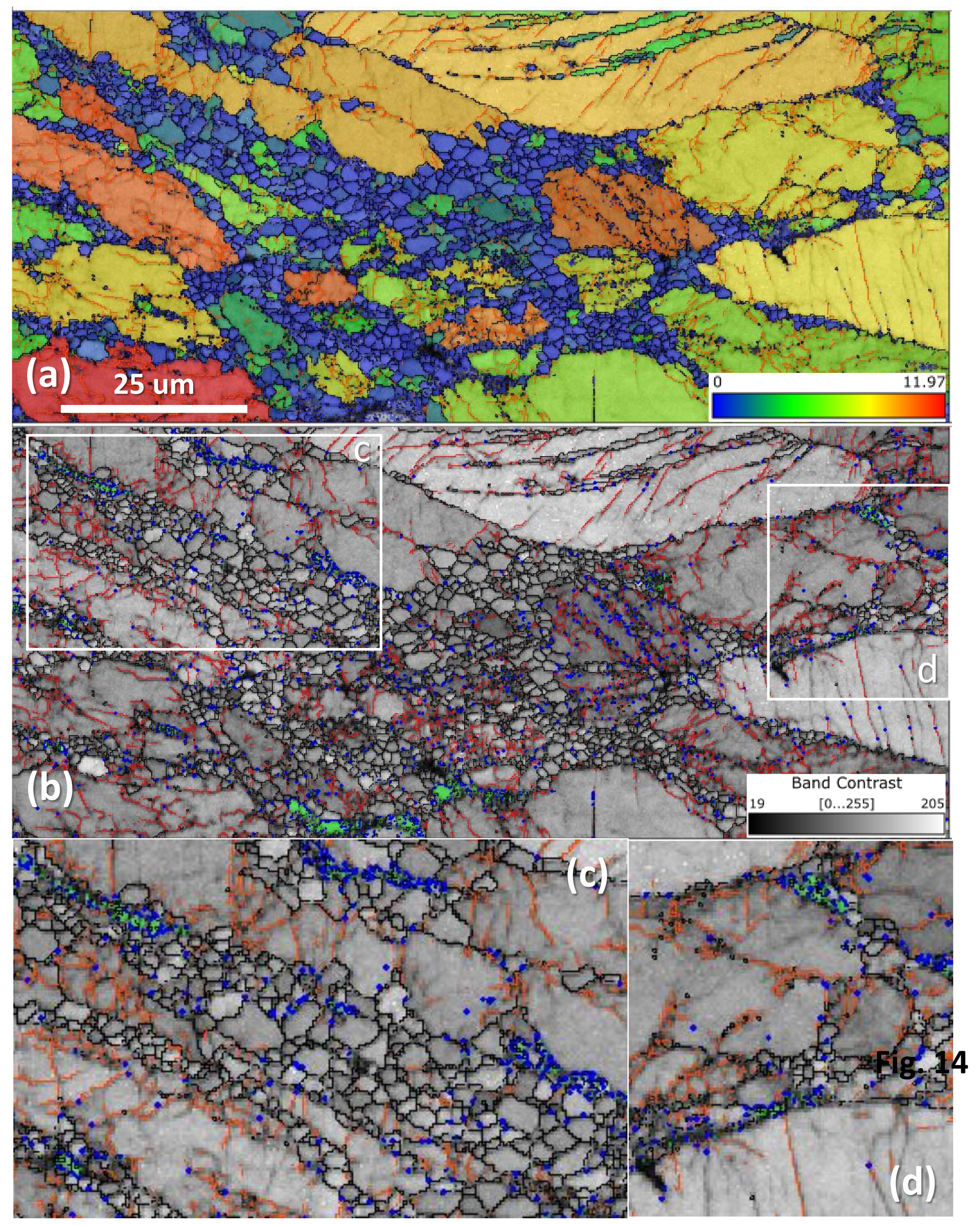


Fig. 12

Conclusion

Conjugated kink bands in deforming metastable olivine are the nucleation sites for the high-pressure phases (wadsleyite and ringwoodite). Nanometric high-pressure phases grow in kink band boundaries to form a network of nano shear zones (NSZs). The weak nanometric grains and latent heat released by the phase transformation focus deformation to the NSZ-network, promoting macroscopic shear failure. We have documented this mechanism in experiments on two olivines Mn_2GeO_4 and Mg_2GeO_4, which transform to wadsleyite and ringwoodite structures, respectively. This may be a vital mechanism for the nucleation of deep-focus earthquakes.

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