Evidence of phase nucleation during olivine diffusion creep: A new perspective for mantle strain localisation

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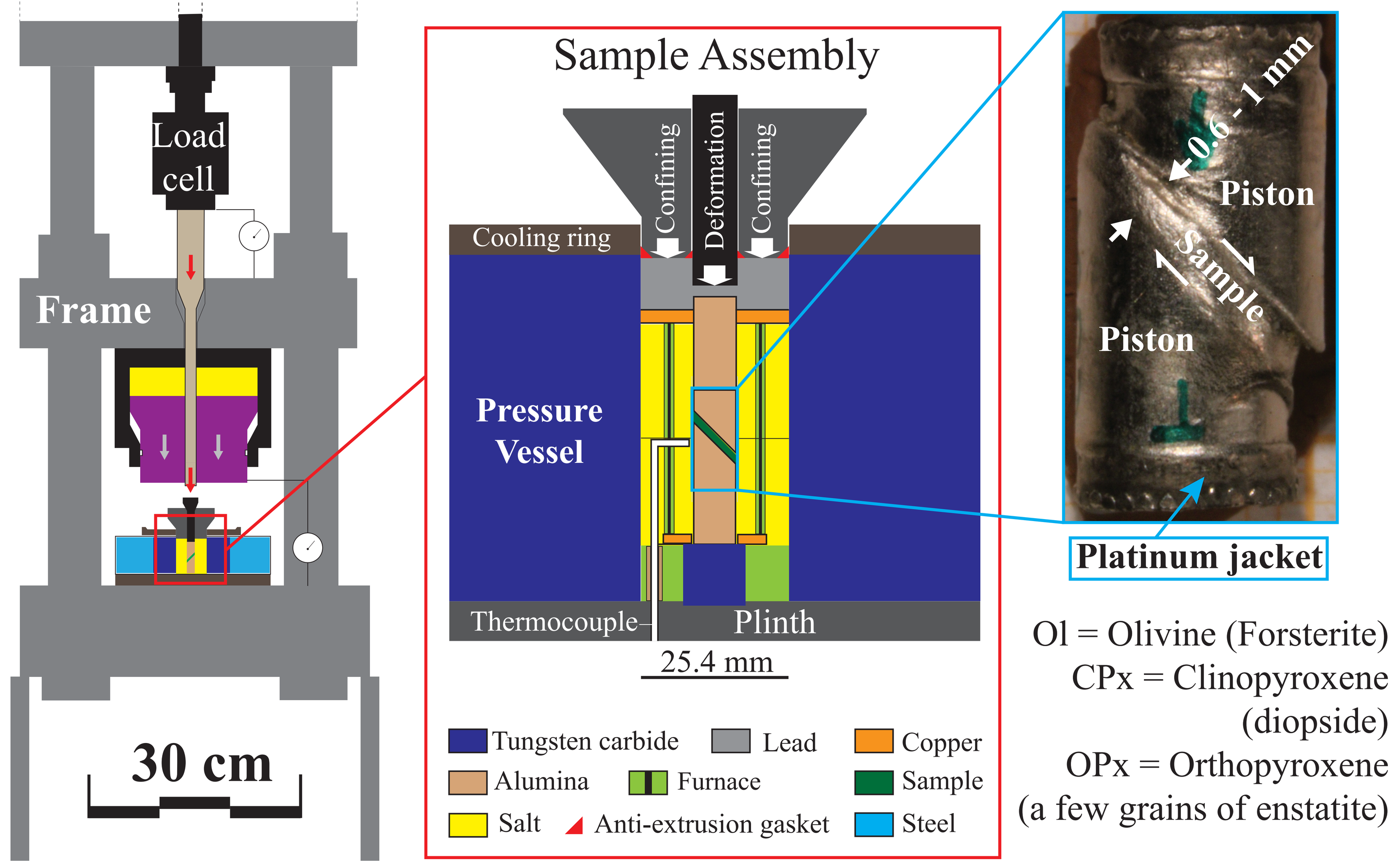
Introduction

As required for plate tectonics to occur, the deformation of the lithosphere needs to be localised across the stiff, viscous/ductile uppermost mantle[1,2]. In this latter, strain localisation originates from a restricted weakening that promotes strain rate to increase and grain size to reduce within a narrow zone, forming a so-called mantle shear zone. However, although many examples of mantle shear zone have been described in nature[3-6], the source of mantle weakening and subsequent strain localisation remains very elusive. Using a solid-medium Griggs-type deformation apparatus, we here explore the deformation of mantle rocks at temperature, pressure and grain size that involve dominant diffusion creep in water-rich conditions. We further investigate on the role of pyroxene for strain localisation, which still remains poorly constrained. Deformation experiments have been performed in direct shear at 900°C and 1.2 GPa on a hot-pressed powder composed of 70% olivine (forsterite[91]) and 30% clinopyroxene (diopside[97]) with selected grain sizes. We also deformed a pure olivine sample with the same conditions and grain size (~2 µm). For each experiment, we applied a bulk strain rate of 2.10^{-5} s^{-1} and we added 0.1 weigth % of distilled water.

Direct shear experiments in the Griggs-type apparatus

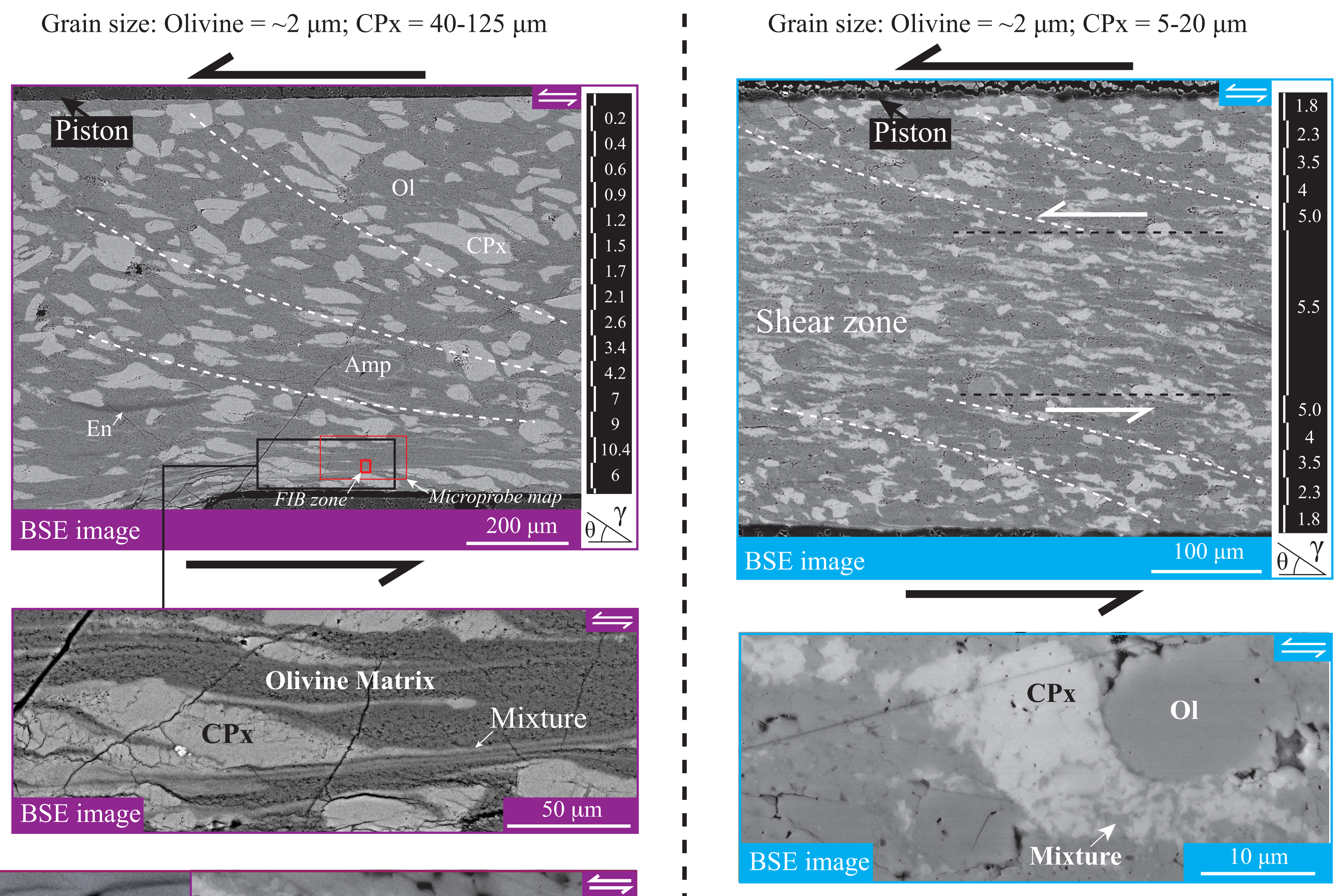


Experimental setting

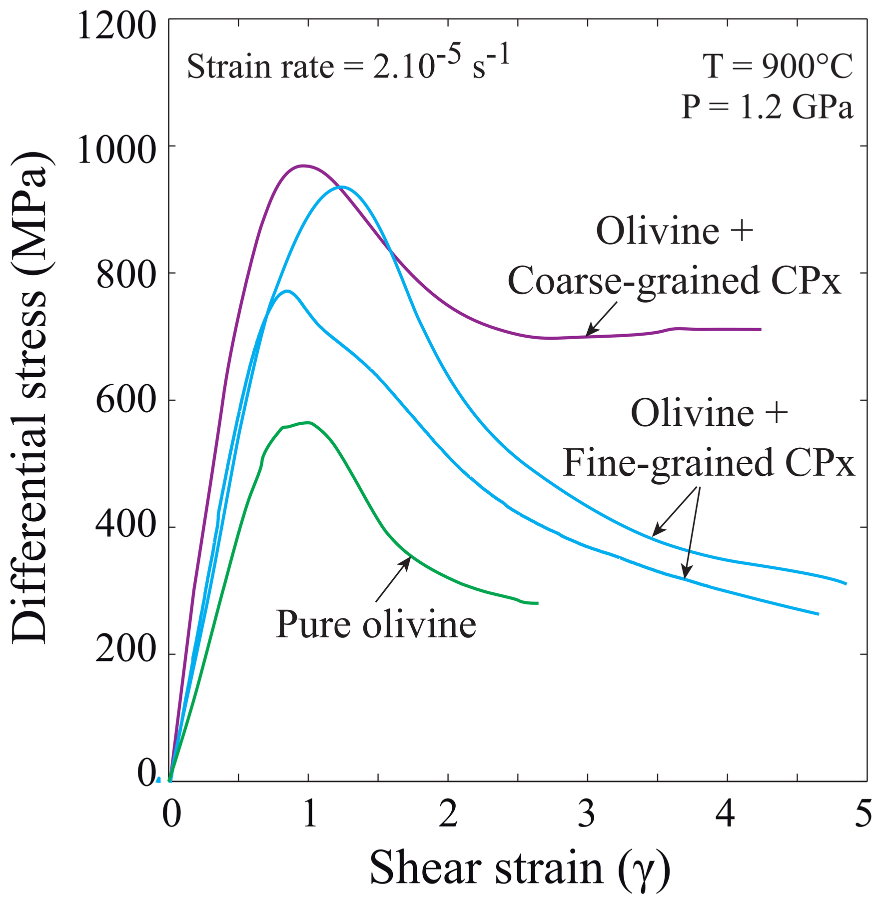
Hot-pressed powder of 70% forsterite[91] + 30% diopside[97] deformed at **900°C, 1.2 GPa** and **2.10^{-5} s^{-1}**

Water added = 0.1 W%

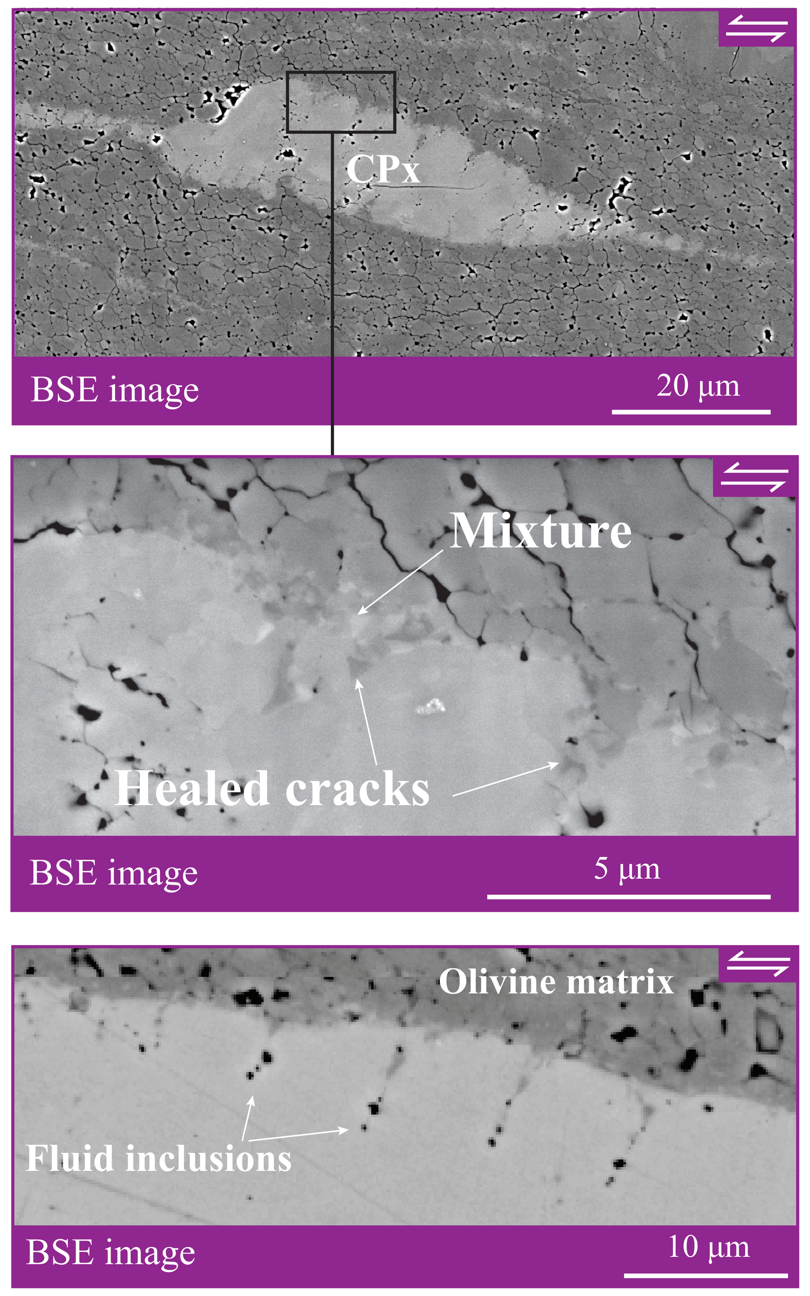
Ol = Olivine (Forsterite)
CPx = Clinopyroxene (diopside)
OPx = Orthopyroxene (a few grains of enstatite)

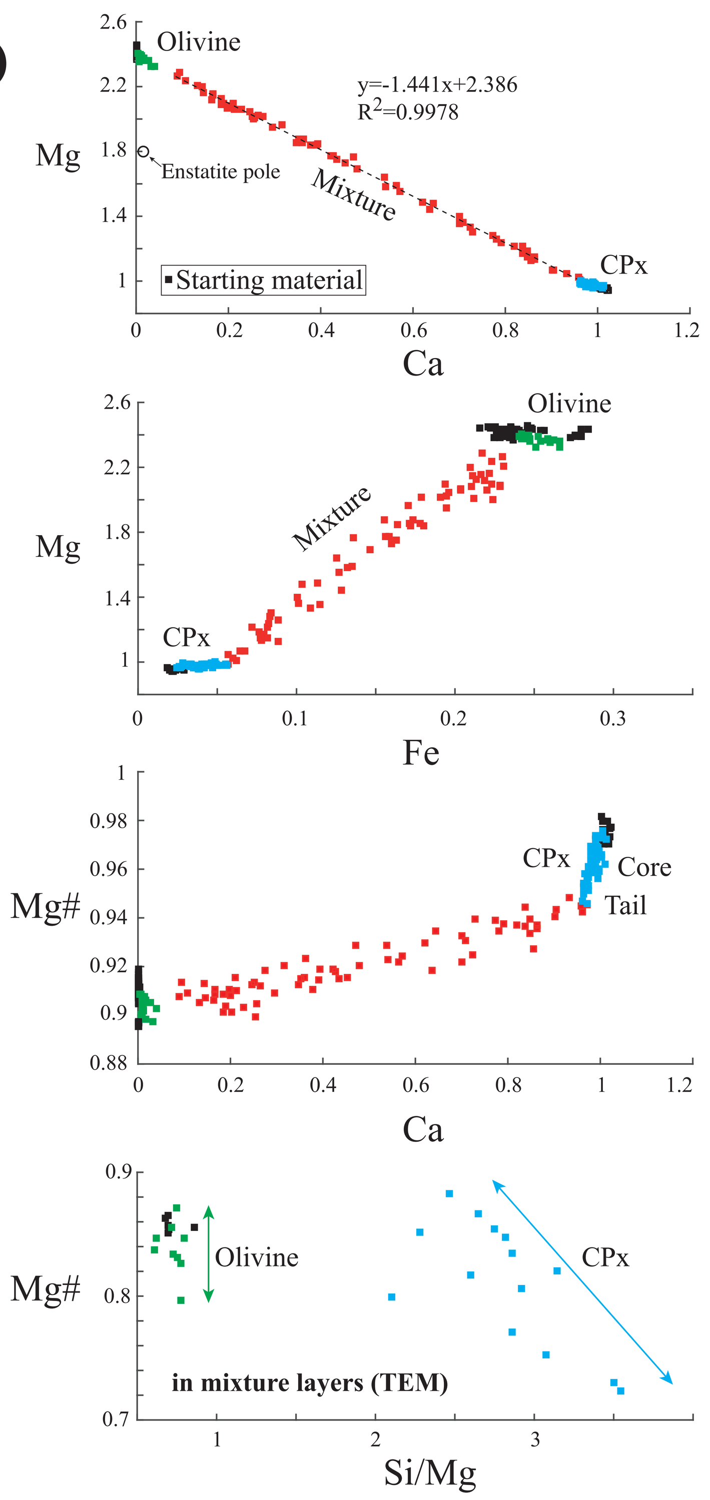


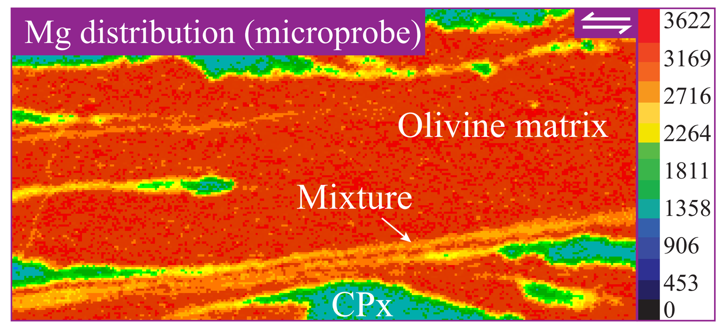
Strain - Stress curves

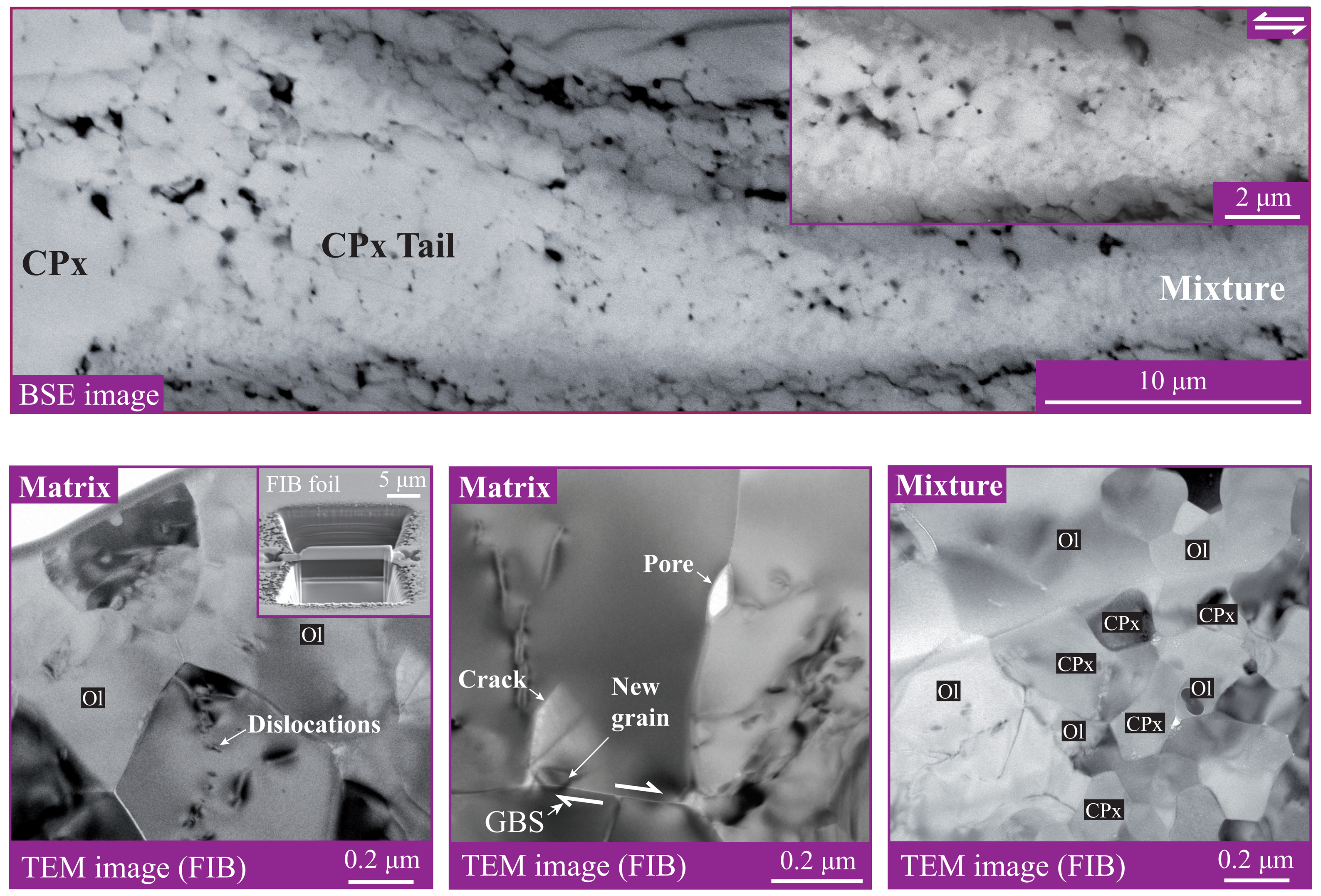


Mode-I cracks filled by phase mixture (including fluid inclusions)

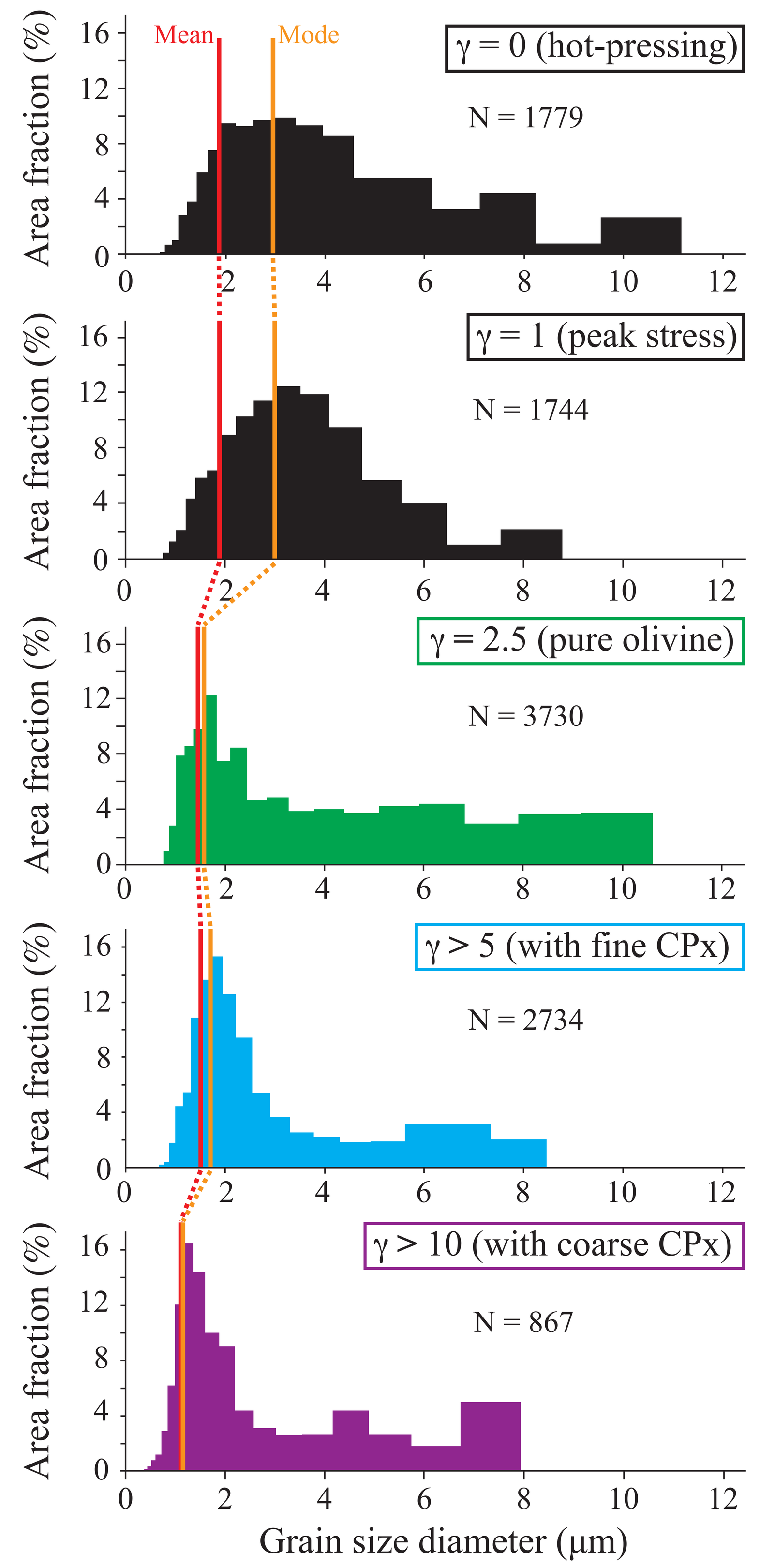




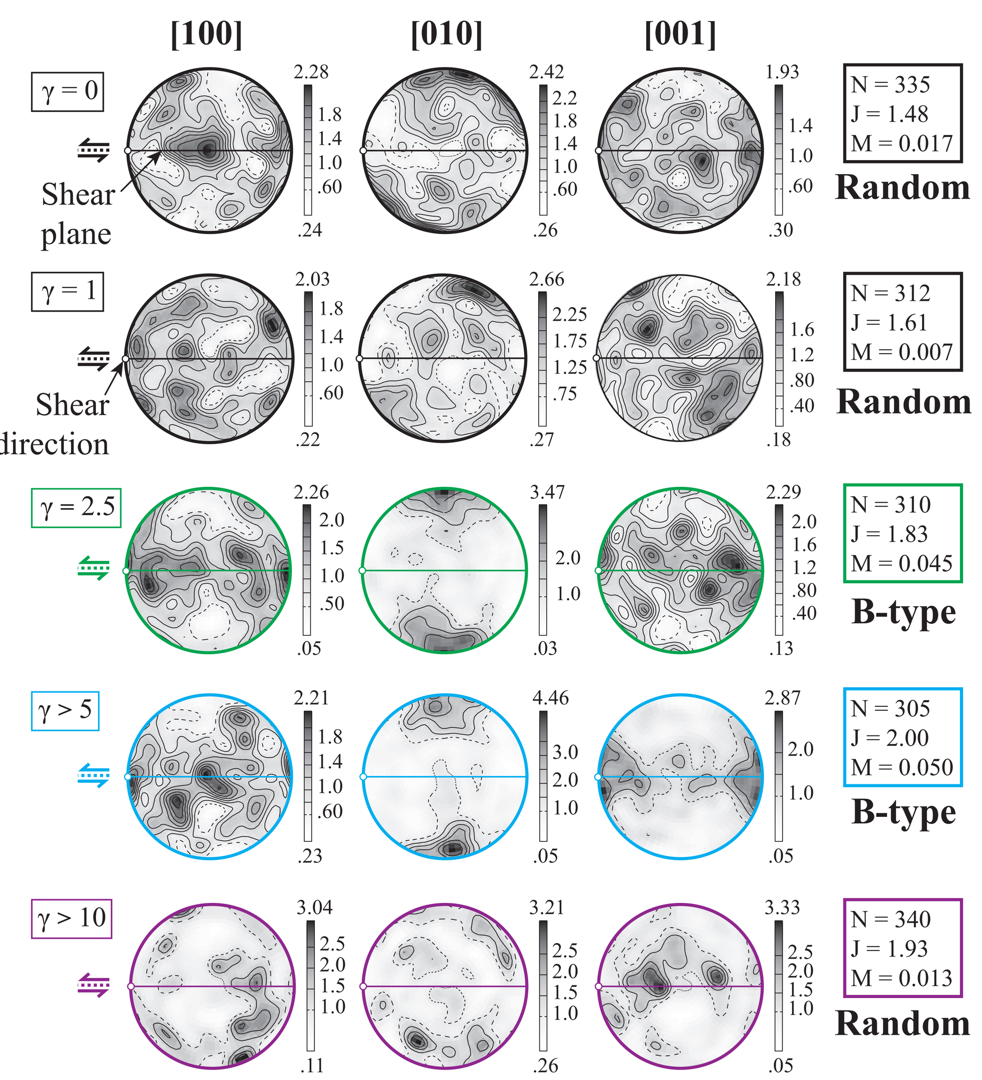




Grain size



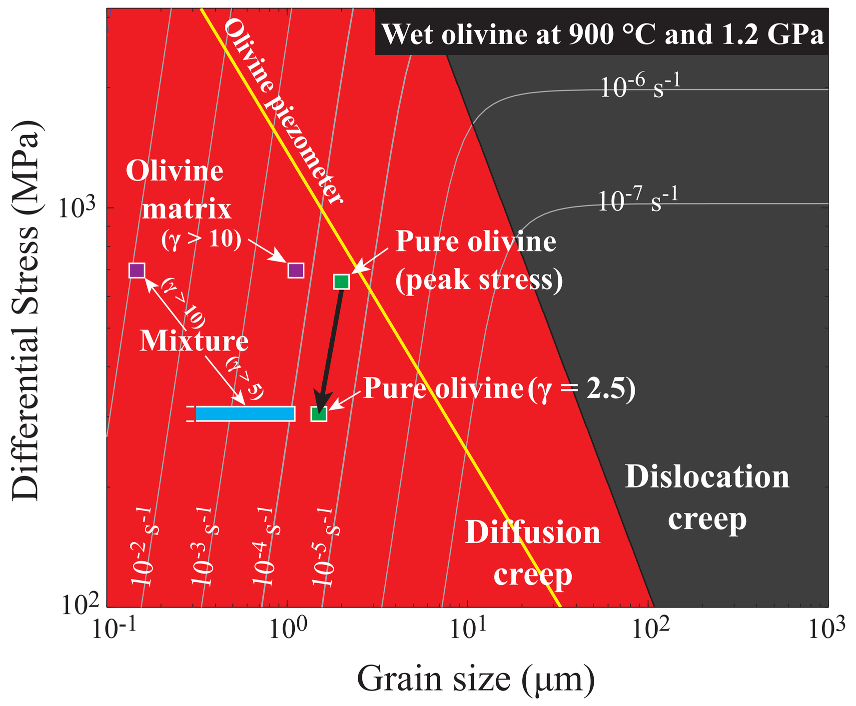
Olivine LPO



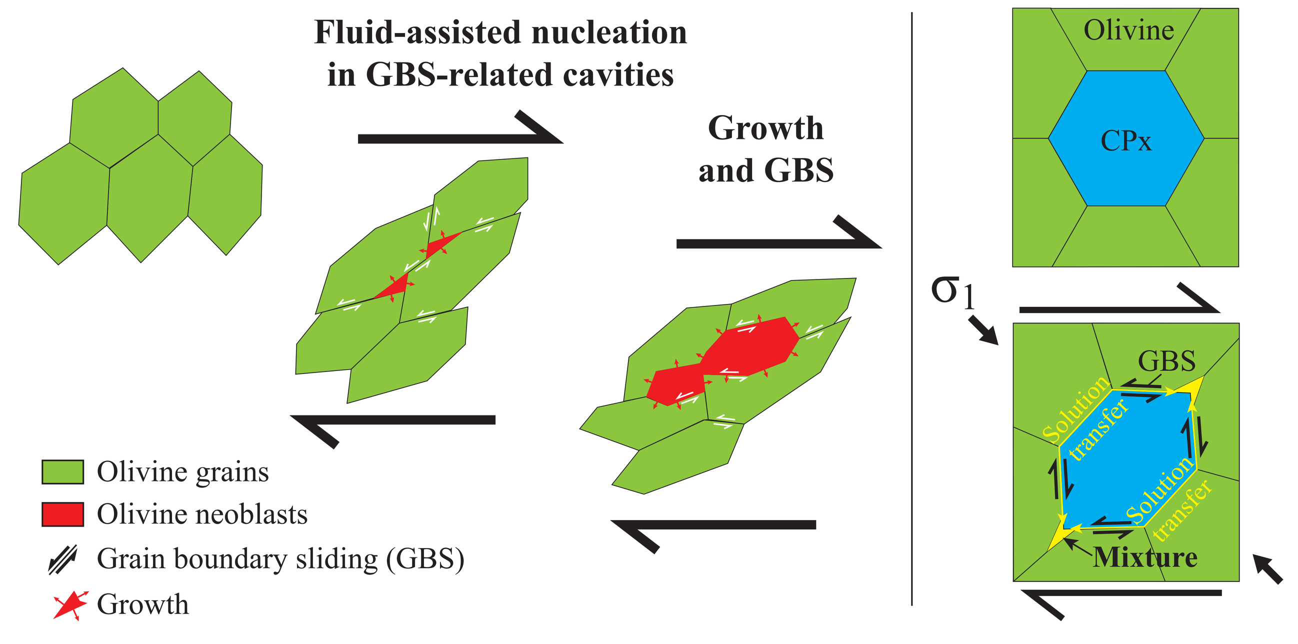
Results

For all samples, we record a peak of differential stress (σ_1-σ_3) followed by a substantial weakening until a plateau is reached (Strain - Stress curves). The more the CPx size is small, the more the weakening is important. At peak stress conditions, no strain is observed. In contrast, the weakening stage is coeval with major strain localisation, giving rise to a well-developed shear zone with high-strain deformation (γ > 5; see BackScattered Electron (BSE) images). This excludes the pure olivine sample where deformation did not localise despite important weakening. While the presence of coarse-grained CPx (40-125 µm) promotes intense strain localisation through a shear zone of around 100 µm thick, the presence of fine-grained CPx (5-20 µm) produces a shear zone of around 300 µm thick. In both cases, the grain size highly reduces within very fine-grained layers that start from the CPx boundaries, and then extend through the olivine matrix. These layers are composed of well-mixed olivine and clinopyroxene grains (mixture) of around 0.1-0.2 µm grain size, as shown by **1)** Transmission Electron Microscopy (TEM) images, and **2)** microprobe analyses that indicate an intermediate composition between olivine and CPx. While TEM images on FIB (Focused Ion Beam) section show the presence of dislocations in the olivine matrix, only a granoblastic texture without any dislocation is observed for the mixture layers. The olivine matrix also characterizes by strain-induced cracks partly filled by new olivine grains, as well as straight boundaries that result from grain boundary sliding (GBS). In addition, the presence of mixture and fluid inclusions in mode-I cracks of CPx highlights the presence of a fluid phase, the mixture of which nucleated from. All samples have a weak olivine lattice preferred orientation (LPO), but some developed a typical B-type fabric with [001] axes in the shear direction and [010] axes normal to the shear plane.

Deformation map



Phase nucleation induced by creep cavitation



Discussion/conclusion

The absence of olivine LPO or weak B-type fabric[7] despite intense finite strain confirms that olivine aggregates mostly deformed by diffusion creep. Although unexpected in this regime, our results show significant grain size reduction together with intense weakening, as well as strain localisation in presence of pyroxenes. The presence of mode-I cracks filled by phase mixture also shows that new phases result from phase nucleation. Indeed, 1) the same nature of mineral phases that compose both the newly formed mixture and starting material, i.e., olivine and CPx, precludes the occurrence of a net-transfer reaction, and 2) the olivine grain size ranges far below the predicted one by the olivine piezometer[8] (deformation map[9]), excluding dynamic recrystallization to form these new grains, although it has been previously proposed[10]. In contrast, the presence of new grains and fluid inclusions in cracks of both CPx and olivine strongly suggest that grain size reduced as a result of solution transfer[11]. Our evidence of GBS-related cracks further suggests the occurrence of creep cavitation, i.e., a transient opening of micro-cavities where GBS cannot be fully accommodated by plastic or diffusional processes. We therefore propose creep cavitation and related phase nucleation as sources for grain size reduction and phase mixing. Because of dominant diffusion creep (see deformation map), this accounts for substantial weakeaning and related strain localisation, provided that secondary phases (pyroxenes) are present. Such a phase nucleation also accounts for an absent or weak olivine fabric as new grains appear with random orientations.

References: [1]Frederiksen, S., and Braun, J. (2001) Numerical modelling of strain localisation during extension of the continental lithosphere. *EPSL* **188**: 241-251. - [2]Burov, E. B., and Watts, A. B. (2006) The long-term strength of the continental lithosphere: «Jelly sandwich» or «Crème brûlée». *GSA today* **16**(1): 4-10.- [3]Drury, M. R., Vissers, R. L. M., Van der Wal, D., et al. (1991) Shear Localisation in Upper Mantle Peridotites. *PAGEOPH* **137**, 439-460. - [4]Warren, J. M., and Hirth, G. (2006) Grain size sensitive deformation mechanisms in naturally deformed peridotites. *EPSL* **248**: 438-450. - [5]Précigout, J., Gueydan, F., Gapais, D., et al. (2007) Strain localisation in the subcontinental mantle - a ductile alternative to the brittle mantle. *Tectonophysics* **445**: 318-336. - [6]Skemer, P., Warren, J. M., Kelemen, P. B., et al. (2010) Microstructural and Rheological Evolution of a Mantle Shear Zone. *Journal of Petrology* **51**(1-2): 43-53. - [7]Sundberg, M., and Cooper, R. F. (2008) Crystallographic preferred orientation produced by diffusional creep of harzburgite: Effects of chemical interactions among phases during plastic flow. *JGR* **113**: B12208. - [8]Van der Wal, D., Chopra, P., Drury, M., et al. (1993) Relationships between dynamically recrystallized grain size and deformation conditions in experimentally deformed olivine rocks. *GRL* **20**(14): 1479-1482. - [9]Hirth, G. (2002) Laboratory Constraints on the Rheology of the Upper Mantle. *Rev. Min. Geochem.* **51**: 97-120. - [10]Farla, R. J. M., Karato, S.-I., and Cai, Z. (2013) Role of orthopyroxene in rheological weakening of the lithosphere via dynamic recrystallization. *PNAS* **110**(41): 16355-16360. - [11]Durney, D. W. (1972) Solution-transfer, an Important Geological Deformation Mechanism. *Nature* **235**: 315-317.