# Impact of volatiles and variations in local bulk composition on deformation and magma emplacement processes in the deep crust and upper mantle parts of continental rift systems

Bjorn Eske Sorensen[1], Rune Larsen[2], Thomas Grant[2], Eric Ryan[1], Alf Andre Orvik[1], and Jørgen Sakariasen[1]

[1]Norwegian University of Science and Technology
[2]NTNU

November 24, 2022



**Abstract**

The coupling of CO2 emissions and tectonic activity in active plate margins is becoming increasingly prominent, as remote sensing techniques make this relationship readily observable on a global scale. However, direct observations of the processes that link emissions and seismicity are lacking. This study documents observations from the deep part of an ancient continental rift system, now exposed at the Earth's surface. We demonstrate how volatiles and preexisting magma chamber structures affect the influx of new magma and how magma induced deformation plays a key role during the shift from initial plume related magmatism to rifting, by altering the rock rheology and facilitating strain localization. The outcrops are comprised of ultramafic cumulates, intersected by mafic dykes. The ultramafic cumulates consist of three units: the central series, upper layered series and the lower layered series, with the central series being the youngest and partly replacing the upper and lower layered series. The dykes intersecting the upper layered series are partially remolten and replaced by the influx of the central series cumulates. This is especially evident in mafic dykes in wherlitic cumulates of the upper layered series. Younger melts of the central series used the contact between the dykes and host wehrlite as a pathway. The heating caused partial melting of the mafic dyke, which acted as a lubricant during deformation. In addition to the lubrication effect of the melt, volatiles within the mafic dykes, including CO2 react with the mafic minerals within the host ultramafic rocks, leading to fracturing and brecciation, and locally followed by diffusion creep in the finer-grained material. PT-estimates indicate that this brecciation took place under lower crustal/upper mantle conditions. Hence, conditions of deformation can shift from low strain rate plastic creep to ultrafast localized seismic creep in a short time due to local structural and compositional inhomogeneities.

# Impact of volatiles and variations in local bulk composition on deformation and magma emplacement processes in the deep crust and upper mantle parts of a continental rift system

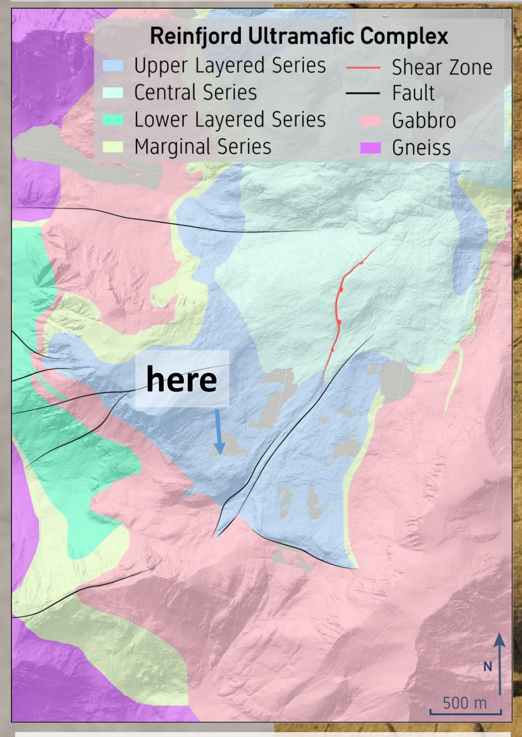
NTNU
Department of Geoscience and Petroleum
Norwegian University of Science and Technology

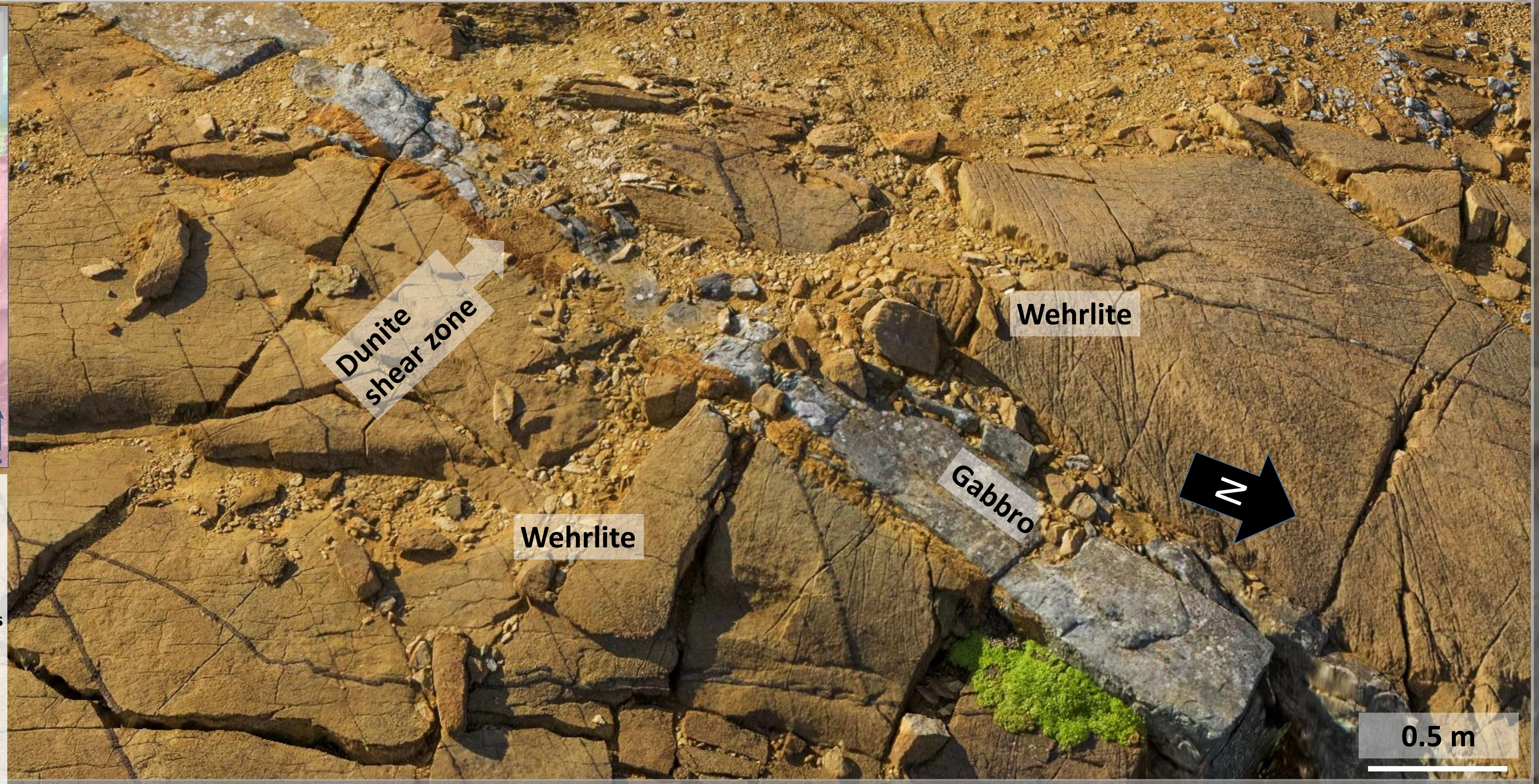
Bjørn Eske Sørensen (bjorn.sorensen@ntnu.no), Eric James Ryan, Jørgen Sakariassen, Alf Andre Orvik, Rune Larsen, Department of Geoscience and Petroleum, Norwegian University of Science and Technology

1

## 1. Introduction

**We observe extreme shear localization between gabbroic dykes in wehrlite in the upper layered series of the Reinfjord Ultramafic Complex (see regional geology insert), with oblique striation lineations on steep shear planes. A distinct orange yellow material occurs between the dyke and the wehrlite. There is a correlation between the amount of yellow material and shearing of the gabbro dykes, which appear locally almost undeformed, whilst they are boudinaged and pulled into flame like structures nearby. The contact between the yellow dunitic material and the dyke consists of dark flinty material, inferred to be remolten gabbroic dyke. Locally, the dykes are completely boudinaged and we are only left with black flinty stripes of what was once 50 cm thick gabbro dykes. This study investigates the processes controlling this extreme strain localization, which plays an important role in the initiation of the major shear zone in the area (see geological map) and in other deep crustal-mantle shear zones.**



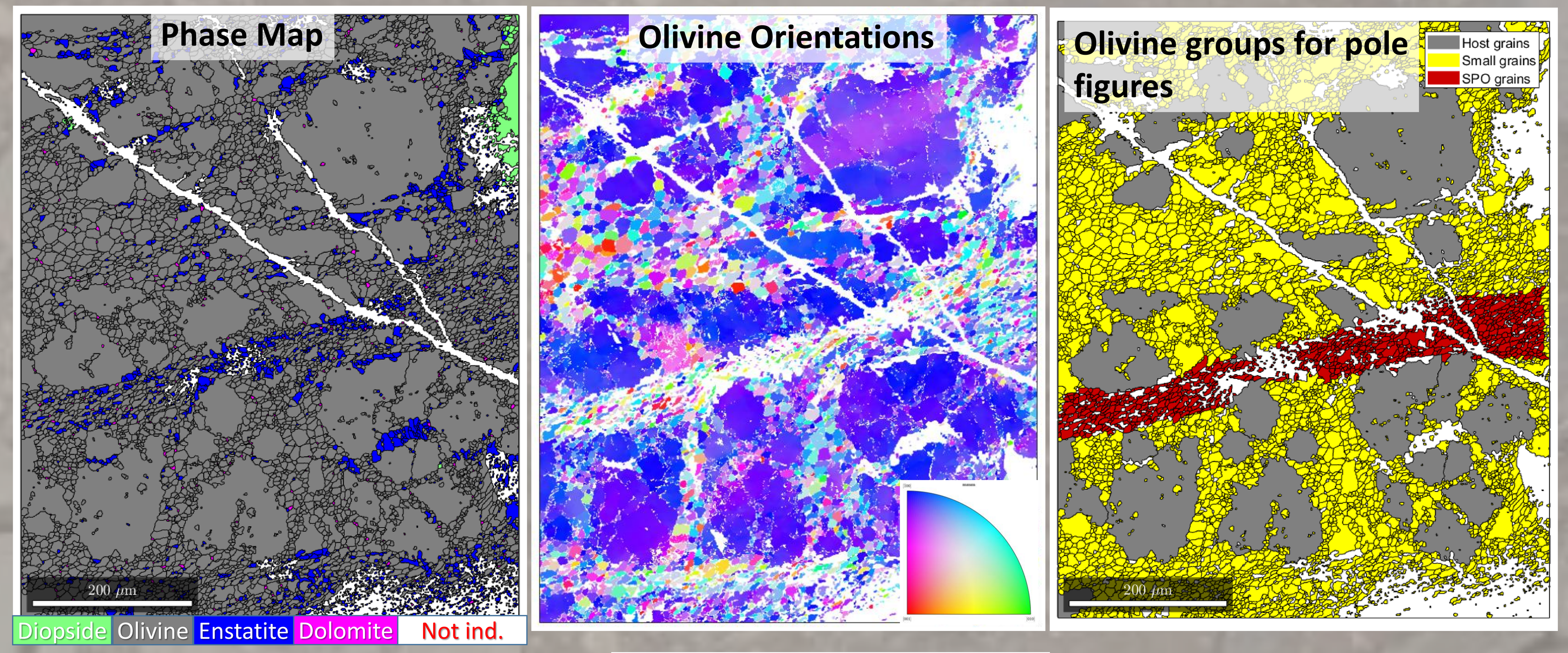



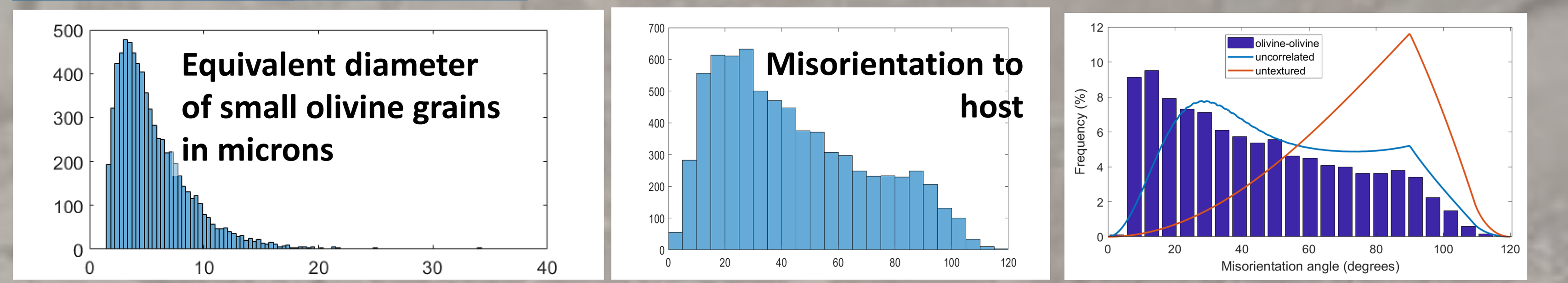

**1b. Regional geology**

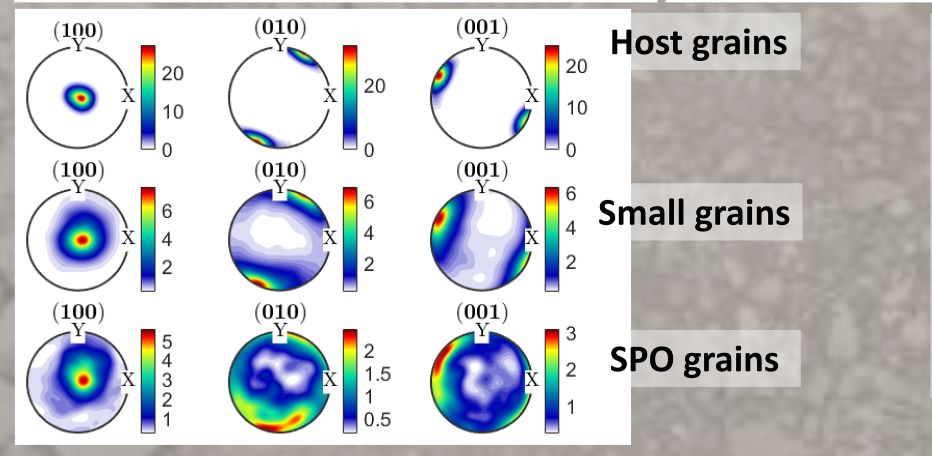
**The samples comes from the upper layered series of the Reinfjord Igneous Complex (RUC), comprised by the ULS wherlites, CS dunites and the LLS wherlites, encapsulated within gabbros with a marginal series between, that formed by interaction between the ultramafic melts and the mafic hosts. Read more in the Larsen et al. (2018), scan QR to download**

3

## 3. EBSD

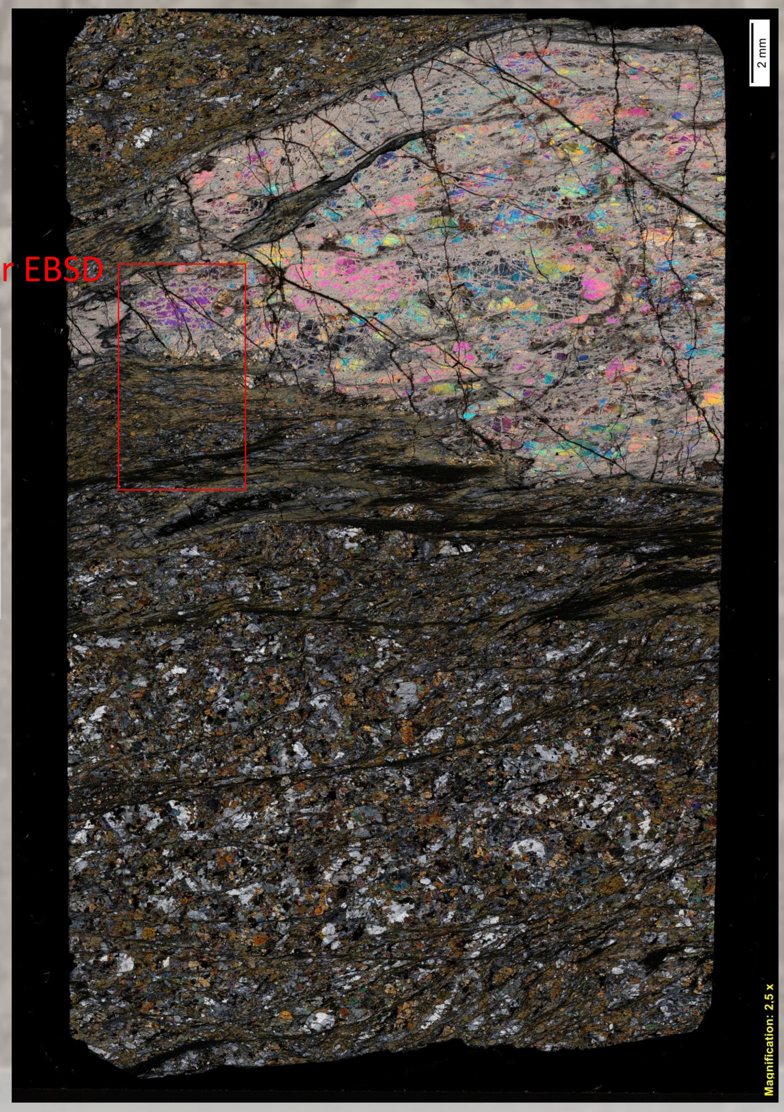




**EBSD documents that the dominating deformation mechanisms were brecciation of large grains followed by diffusion creep accommodated grain boundary sliding, as seen in the absence of a new crystallographic preferred orientation of the new grains, in spite of grain size reduction from mm down to less than 10 um equivalent diameter.**

2

## 2. Petrographic observations

**Influx of dunite mush, brecciation of olivine phenocrysts, melting og gabbro. Grainsize from phenocrysts reduced from mm's down to tens of µm.**



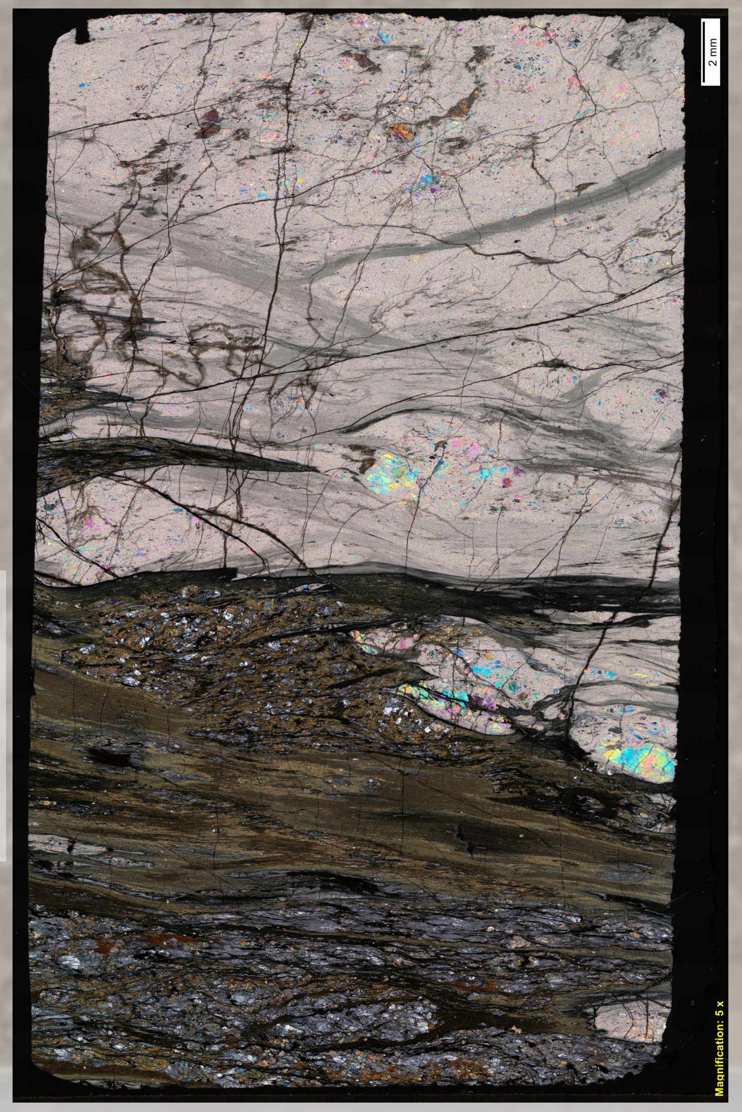

**Gabbro dyke Ultramylonite, increased hornblende, compared to original**

**Gabbro dyke**

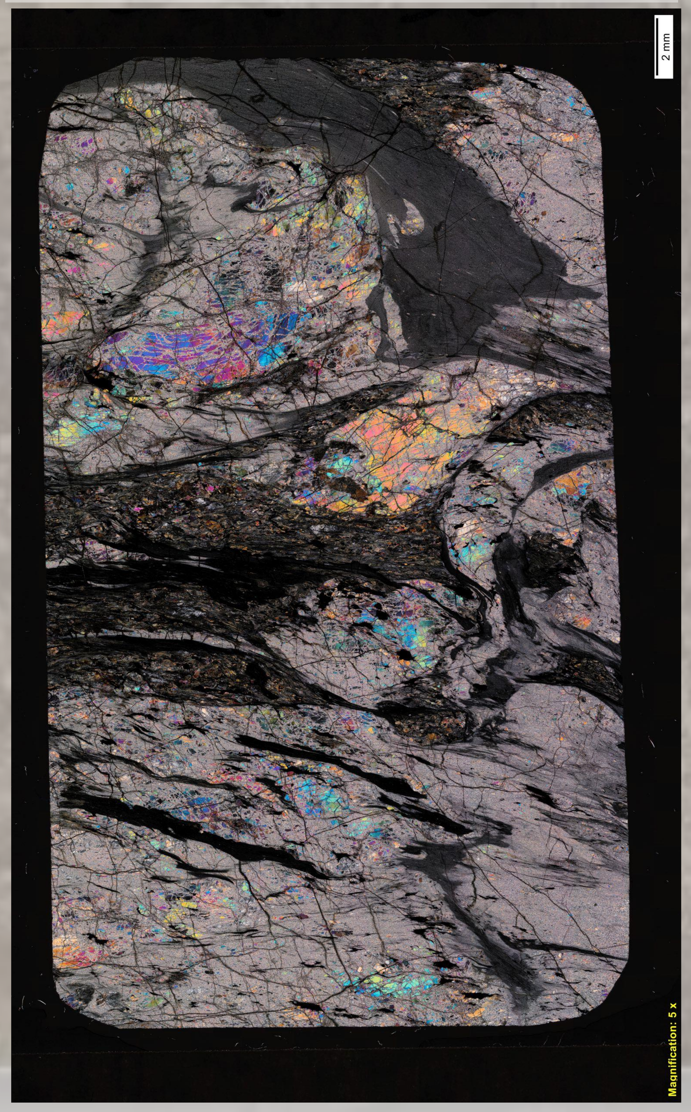
**Continued deformation, melts from gabbro migrate through the fine-grained ultramylonite, here diffuse melt pathways are observed as dark gray "ghosts". 😊**

**Gabbro dyke Ultramylonite, increased hornblende, compared to original**

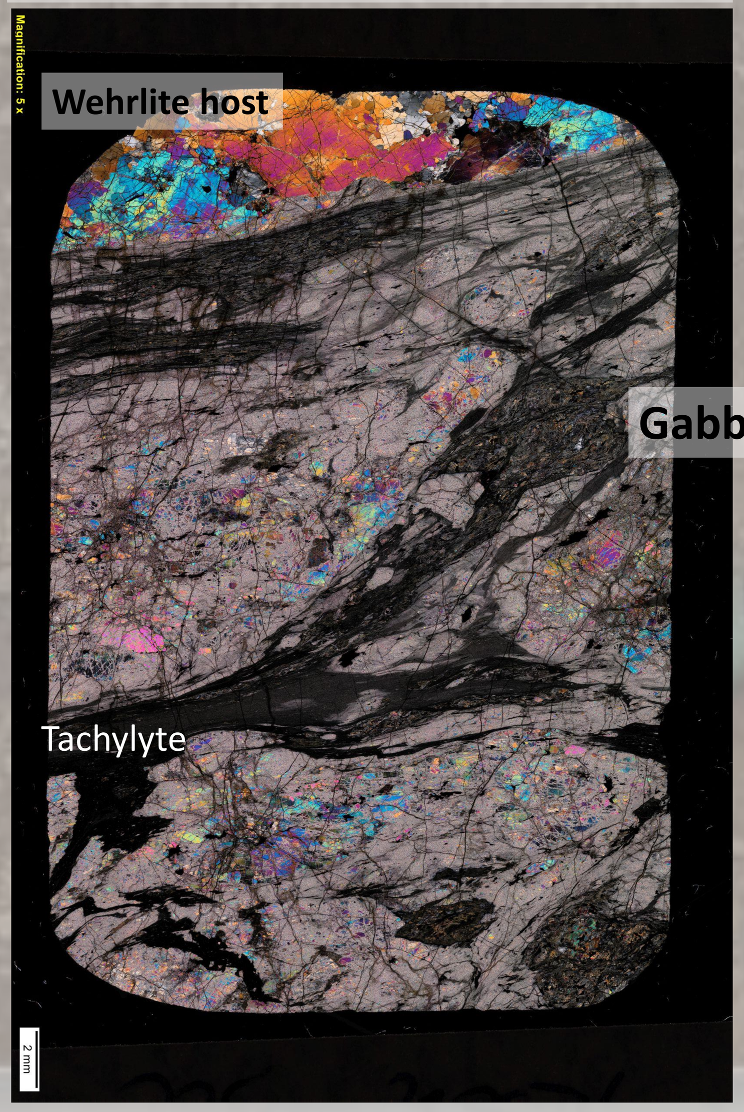
**Gabbro dyke mylonite**



**Continued deformation, melts from gabbro migrate through the fine-grained ultramylonite, concentration of melt in pressure shadows around olivine porphyroclasts.**



**Wehrlite host is also affected by the remelting and deformation (upper part). Note also ghosts of olivine phenocrysts and gabbro dykes within the dunitic shear zone, which are partly transformed to tachylyte.**



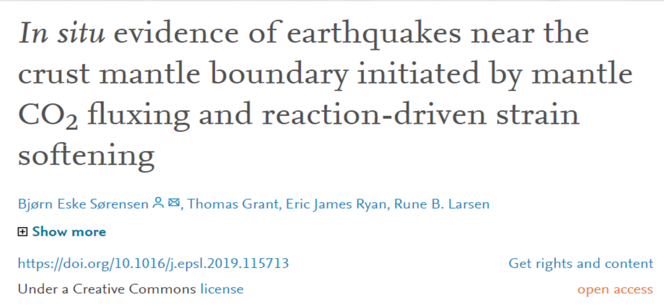

**Gabbro ghost**

4

## 4. Conclusions

**Melt-infiltration along the contact between gabbro dykes and host wehrlites generated shear localization, which was controlled by several processes:**

1. The hot, picritic olivine-rich mushes generated melting of the gabbro dykes, hence creating a slippery surface that was exploited by deformation.
2. The melting of the gabbro consumed heat from the picritic cumulates, causing shock-cooling of the olivine phenocrysts, that were shattered like undercooled glass under stress.
   a) This generated a superfine aggregate, much softer than the coarse-grained surrounding as also shown by Sørensen et al. (2019). Other phases than olivine in the fine-grained ground mass acted as grain growth limiting material assisting in keeping the grain size fine during creep (Sørensen et al., 2019).
3. Melts migrated along the shear zone during deformation, both early and late in the deformation.
   a) Melt-solid interaction along the cumulate-gabbro interface reacted with the olivine generating hornblende and orthopyroxene, that was deformed into an ultramylonite
   b) Melt migrating in the shear zone formed orthopyroxene and dolomite when reacting with the olivine, causing strain softening by assisting grain breakage as shown by Sørensen et al. (2019).
1. The melt generated in these shear zones has a very similar appearance to pseudotachylites, however detailed field exposures enables us to recognize them as tachylites and the strain-localization problem is turned upside down compared to pseudotachylite formation with the melt generating high strain rates, causing the formation of ultramylonites.


*In situ* evidence of earthquakes near the crust mantle boundary initiated by mantle $CO_2$ fluxing and reaction-driven strain softening

Bjørn Eske Sørensen, Thomas Grant, Eric James Ryan, Rune B. Larsen

Show more

https://doi.org/10.1016/j.epsl.2019.115713 Get rights and content

Under a Creative Commons license open access

**You can download our related paper here:**
**[https://www.sciencedirect.com/science/article/pii/S0012821X19303991](https://www.sciencedirect.com/science/article/pii/S0012821X19303991)**
**Or scan the QR code ☺**