Reading stress from crystals

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Tectonic stresses lead to the deformation of the Earth's crust and upper mantle. They are the driving force behind plate motion and mountain building, and they control earthquake distribution and intensity. These stresses can be measured from deformation microstructures of previously deeply buried rocks using paleo-piezometers. A new assessment of microstructural data from naturally deformed quartz-bearing rocks indicates that the mechanism of recrystallization fundamentally affects the piezometers. Our findings point out major inaccuracies of stress estimates published in the last 40 years, and it prepares the field for a new piezometer generation that will provide a significantly improved assessment of the stress states in lithospheric plates and plate boundaries.

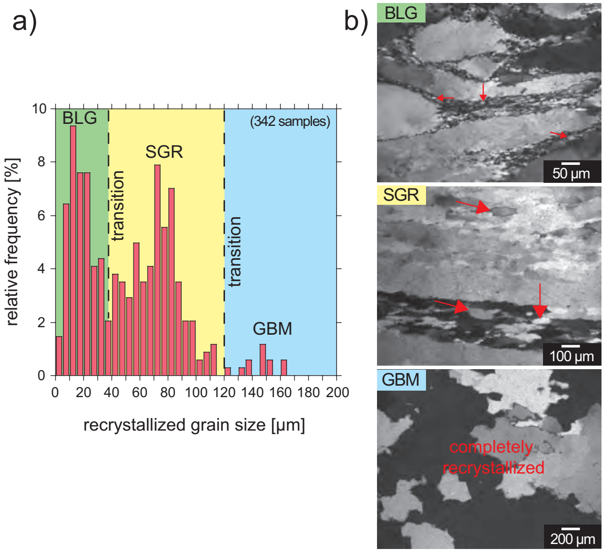

Figure 1: Dynamic recrystallization of quartz in crustal shear zones worldwide. a) Distribution of the mean recrystallized grain size in the range from 0 to 200 µm and related microstructural transitions.
b) The three characteristic recrystallization microstructures (light-optical microscope images, polarized light): bulging recrystallization (BLG; low temperature), subgrain rotation recrystallization (SGR; intermediate temperature), grain boundary migration recrystallization (GBM; high temperature, completely recrystallized). The size of the recrystallized grains (arrows) is inversely proportional to the stress.

Understanding the Earth´s deformation, from seismic rupture on discrete faults to aseismic plastic deformation in shear zones, requires careful quantification of the controlling parameters. Stress is the most critical parameter, but it is very difficult to measure. Direct stress measurements in the Earth´s upper crust can be made in boreholes and from GPS monitoring of Earth's surface deformation. At greater depths, only indirect measurements are possible. The most powerful tool is the examination of crystal microstructures in rocks exhumed from paleo-shear zones. The most reliable and widely used stress indicator (piezometer) is the dynamically recrystallized grain size resulting from dislocation creep, the dominant plastic deformation mechanism within the middle and lower crust and the upper mantle. Plastic deformation in shear zones is accommodated by a few rheologically critical minerals. In the crust, for example in the deeply subducted rocks at convergent plate margins, these are quartz, plagioclase, calcite, and mica. In the mantle, these minerals are olivine and pyroxene. To understand why deformation is localized in shear zones, how shear zones develop, and under which conditions the transition from aseismic to seismic behavior occurs, it is necessary to study deformation microstructures of these minerals.

Plastic deformation causes dynamic recrystallization in rocks. The microstructures formed in this way are "frozen" when the rocks are brought up to the Earth's surface by tectonic uplift and exhumation. Structural geologists and metamorphic petrologists can read this microstructural memory, and reconstruct the depth and temperature at which the rocks were deformed. Overprinting relationships and geochronology further allow dating of the deformation at depth. Most importantly, however, microstructures indicate if deformation was brittle (seismic) or plastic (aseismic). In the latter case, the paleostress and thus rock strength can be determined from the dynamically recrystallized grain size of the rheologically critical mineral, using piezometer equations. In this way, the temperature and stress conditions are known for the change from aseismic to seismic deformation in the so-called "seismogenic zone", because dynamic recrystallization is persistent until the rocks start to fracture. In addition, plastic deformation during postseismic creep is part of the seismic cycle. Hence, stresses from piezometers characterize not only the plas-

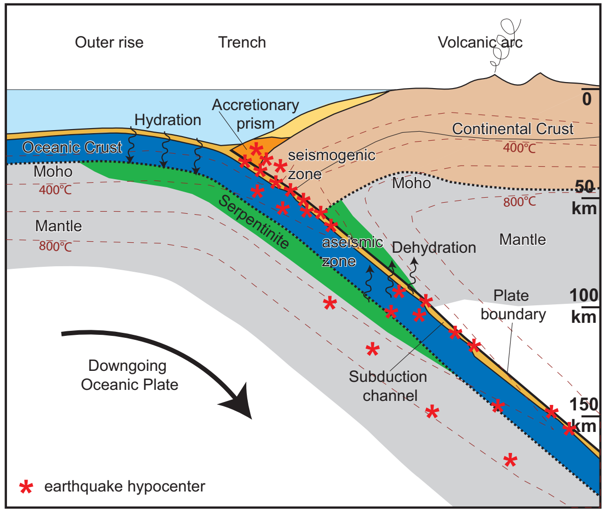

Figure 2: Schematic cross section through a subduction zone (e.g. Chile) displaying sediment transport into accretionary prism and subduction channel. The occurrence of seismic and aseismic deformation and the intensity of earthquakes are controlled by tectonic stresses.

tic deformation, but also represent minimum estimates of the stresses required for fracturing and generation of earthquakes.

Numerous studies have attempted to experimentally calibrate piezometer equations for the most important minerals: quartz, olivine, calcite, and feldspar, along with theoretically derived piezometer equations. These have been applied by hundreds of researchers working on shear zones worldwide for the past 40 years. One quite obvious microstructural feature, however, has largely been neglected: that new grain formation and growth by dynamic recrystallization is not a single process, but the result of different interacting processes. In quartz, for example, three characteristic mechanisms can be determined based on the interaction of three basic processes. Because recrystallization in nature is very slow, it is impossible to reproduce the full range of dynamic recrystallization mechanisms in laboratory experiments. Crucial information has to come from quartz microstructures found in natural shear zones. While a qualitative description of microstructural changes is quite straightforward (Fig. 1), related quantitative parameter changes are yet to be defined. Global analyses on the size-frequency distribution of dynamically recrystallized materials are completely lacking. This prompted a group of researchers from IFM-GEOMAR and Brown University (USA) to undertake the first systematic investigation of recrystallized grain size distributions of quartz by analyzing the data of 555 samples from 31 studies on shear zones worldwide. In our statistical analysis we discovered a remarkable grouping in recrystallized grain size distribution, which is directly correlated to the three different recrystallization mechanisms (Fig. 1). The observed discontinuous distribution calls for distinct piezometer calibrations for different recrystallization mechanisms of quartz. This forces a reassessment of stress estimates published so far. As recrystallization mechanisms in other minerals controlling the plastic behavior of rocks, metals and ceramics, and also in water ice, are very similar to quartz, our findings will change the general understanding on dynamic recrystallization processes and the related stresses.

The rheology of quartz is not only important for intracrustal shear zones, but also for plastic flow and stress in subduction zones, in the buried rocks filling the so-called subduction channel (Fig. 2). Deep seismic imaging indicates that in addition to downgoing mantle lithosphere and oceanic crust, continental slivers and marine sediments are transported deep into the Earth´s mantle. In most of these materials quartz is the mineral defining the plastic behavior of the whole rock. In the rare cases where such rocks were later exhumed by tectonic processes (e.g. in the Alps or the Norwegian Caledonides), stress estimates provide crucial information on the physics of subduction processes. Experimental data show that quartz can suffer dramatic strain-hardening by small parameter changes, e.g. strain rate increase due to more localized deformation or dehydration at high pressures. This in turn forms mechanical asperities near the deep end of the seismogenic zone or deeper in the subduction channel where earthquakes are generated. Hence, the new findings on recrystallized grain size distribution of quartz allow for a better understanding of the plastic to brittle transition and thus earthquake nucleation in the subduction channels at convergent plate boundaries.

Reference

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