The "Brittle - Ductile Transition" in the KTB Borehole - a tentative prognosis.

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Abstract

The state of stress and the rheological behavior of the continental crust as a function of depth are predicted by extrapolation of laboratory data (GOETZE & EVANS 1979, BRACE & KOHLSTEDT 1980). One of the most prominent tasks in the KTB project is to test the validity of these concepts, and in particular to penetrate the transitional range between brittle upper and ductile deeper crust. The actual processes and conditions in this transition zone are hardly predictable and require direct analysis under natural conditions. Measurements of the state of stress (see ZOBACK et al. 1993) and the temperature as a function of depth are to be correlated with the microstructural record of "quenched" samples; the microstructure reflects the activated processes. Due to the low average bulk strain rate in the intraplate anorogenic setting of the KTB the actual relations are expected to differ from those commonly observed in exhumed orogenic belts. Here, the transitional range may be penetrated in a shallower level at lower temperatures than the commonly invoked 300 °C.

Introduction

The state of stress in the Earth's crust and the rheological behavior of rocks under natural conditions are still poorly constrained despite their fundamental significance. To gain a deeper insight into these properties, beyond the crustal depth commonly accessible for direct observation, is one of the central tasks in the KTB project.

In the upper crust, under low temperatures and pressures, strength is limited by brittle failure and friction controlled sliding. In the deeper levels of the crust, under elevated pressures and temperatures, the strength is governed by creep, i.e. plastic flow with a very low strain rate. Currently, predictions of the state of stress and the rheological behavior in the crust as a function of depth rely on the extrapolation of laboratory data, as first proposed by GOETZE & EVANS (1979) and BRACE & KOHLSTEDT (1980). This prediction is visualized in the form of a strength envelope (differential stress vs. depth).

As a first approximation, frictional resistance appears to be independent of rock type (BYERLEE 1978) and increases linearly with pressure; the influence of temperature is negligible. Apart from uncertainty concerning the pore fluid pressure at depth, which effectively controls brittle failure and frictional sliding, this part of the approach is straightforward. Stress measurements in the KTB borehole down to a depth of 6000 m support the validity of the concept (ZOBACK et al. 1993)

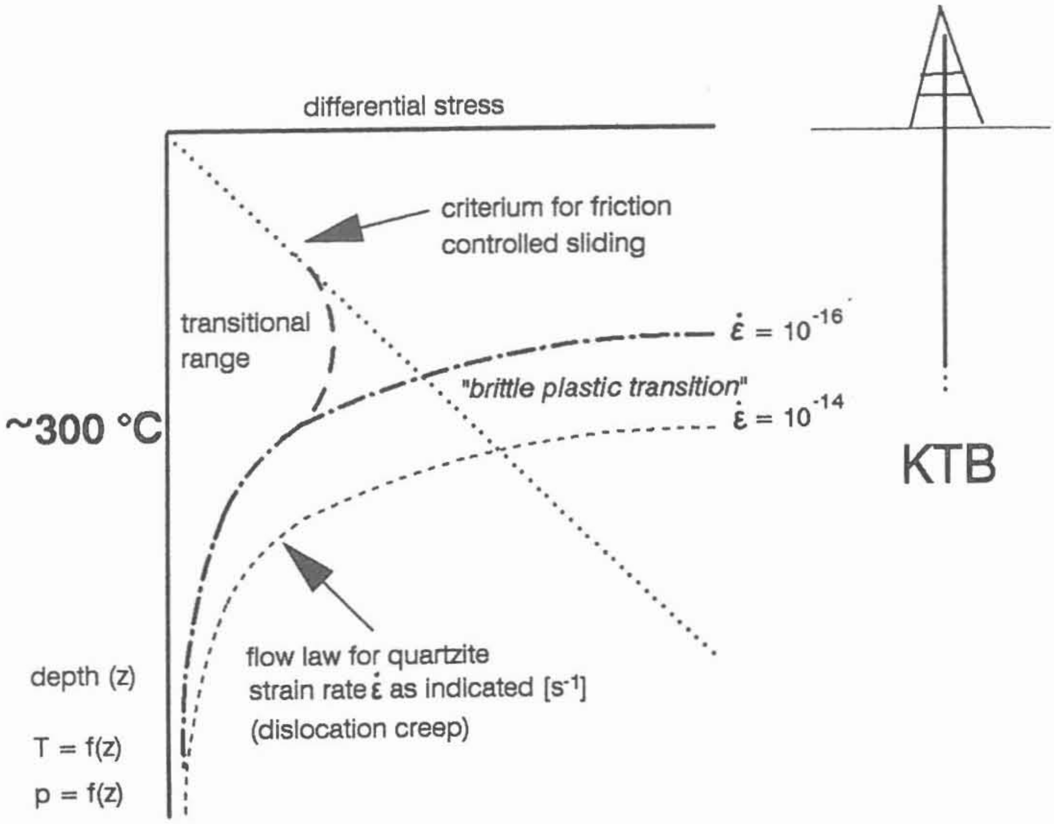


Fig. 1: Schematic diagram illustrating the predicted strength of the continental crust as a function of depth, the "brittle plastic transition", and the position of the KTB. See text for discussion.

Stress during plastic flow, on the contrary, is a function of temperature and strain rate. In contrast to brittle failure and friction it is virtually independent of pressure under crustal conditions, but strongly dependent on type of material. Due to the low natural strain rates, all laboratory data must be extrapolated over 8 to 12 orders of magnitude. Furthermore, there are a number of different deformation regimes, each governed by a dominating deformation mechanism and described by a constitutive equation for steady state flow. At present, most experimentally derived flow laws cover the regime of dislocation creep (e.g. CARTER & TSENN 1987), referred to as power law creep according to the form of the mechanical equation of state. The basic mechanism is dislocation glide, accompanied by climb-controlled recovery and/or dynamic recrystallization. Other deformation regimes relevant to natural rock deformation (e.g. dissolution precipitation creep, diffusional creep) are hardly accessible on laboratory time scales. In a polyphase material, and virtually all natural rocks are polyphase, the situation is much more complex and in addition to the deformation regime relevant for each component, the share and spatial distribution of the minerals must be considered (e.g. HANDY 1990). Altogether, it becomes very clear from this yet uncomplete account of problems that predictions for the lower part of the crust require extensive simplifications and are based on a bundle of assumptions.

In models predicting the strength of the continental crust generally flow laws derived for quartzite are applied. As a first approximation, this simplification seems to be reasonable since microfabrics in many metamorphic rocks show that quartz is the weak phase and controls rheology. The microfabrics created in deformation experiments are similar to those observed in nature, and the derived flow laws - despite significant variance in the low stress region and still unresolved problems with respect to the influence of water - invariably predict the steep increase in the steady state flow stress for a strain rate of 10^{-14} s^{-1} at a temperature close to 300 °C (e.g. PATERSON & LUAN 1990). This finding is consistent with observations in naturally deformed rocks, where the correlation between microstructure and thermobarometric results indicates that steady state dislocation creep is operative at temperatures above about 300 °C, but not below, as first noted by VOLL (1976). In fact, the microstructural record of natural rocks strongly supports that the extrapolation of laboratory data to natural strain rates yields reasonable results. In the case of quartz, this is furthermore supported by the correlation between heat flow and depth of seismic activity in the continental crust (e.g. CHEN & MOLNAR 1983), which also predicts the transition to aseismic flow at a depth roughly corresponding to the position of the 300 °C isotherm.

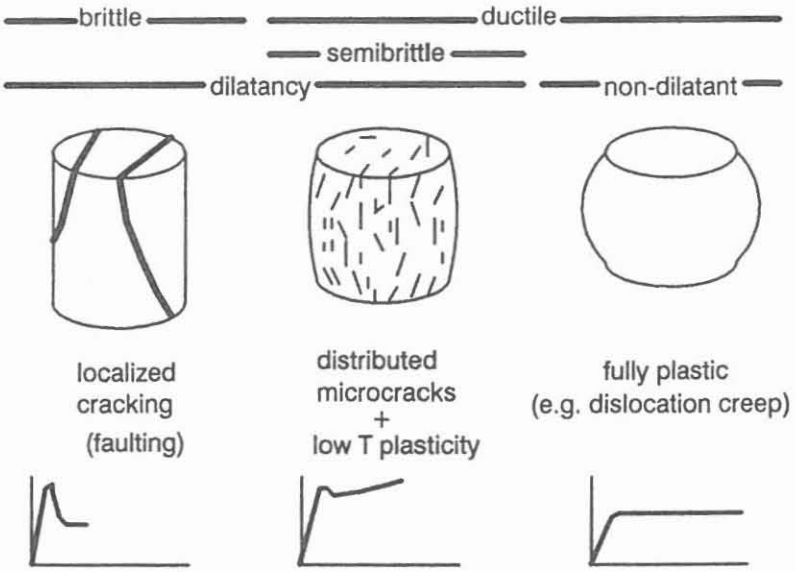


Fig. 2: The phenomenology of the brittle-plastic transition, modified after EVANS et al. (1990)

Nature and experiment:

Consequently, the mechanical behavior of continental crust is modeled combining the criterium for frictional sliding and a flow law for steady state dislocation creep of quartzite. The intersection of the two curves marks what is generally referred to as the "brittle - ductile transition" (fig. 1) or - strictly speeking (see RUTTER 1986) - the "brittle - plastic transition" (for definitions see fig. 2). In fact, this transition cannot be sharp, as suggested by the simple diagram, but must constitute a broad range. This is inherent to the following facts:

- various deformation mechanisms can be activated in each mineral phase
- natural rocks are polyphase materials
- activation of dislocation glide depends on orientation of the crystal
- the stress field is inhomogeneous also on a microscopic scale
- pore geometry and pore fluid pressure strongly influence mechanical behavior
- assumption of steady state flow, with a constant strain rate across the rheological transition zone, is not justified; the actual relations must be considered in terms of an interplay between rate of loading and rate of relaxation.

Experimental studies of the "brittle - plastic transition" (e.g. EVANS et al. 1990) in rocks show that the transitional range can be described as follows. On the low temperature, low pressure side there is a transition from localized brittle failure along macroscopic cracks (brittle s.s.) to distributed failure by microcracking (macroscopic ductile). In this range crystal plastic deformation by dislocation glide on favourably oriented glide planes, or twinning, starts to contribute to deformation. This field has been termed semibrittle (fig. 2). The contribution of crystalline plasticity increases with increasing pressure and temperature. On the high temperature, high pressure side the contribution of microcracking vanishes and deformation proceeds essentially by dislocation creep. This is the semibrittle - plastic transition. Dislocation creep is non-dilative and insensitive to pressure. Using a natural quartzite as starting material these transitions have been studied experimentally by HIRTH & TULLIS (1994).

In addition to the specific properties of natural polyphase rocks, the role of deformation mechanisms other than dislocation creep must be considered for evaluation of the "brittle - plastic transition" as a rheological transition zone on the crustal scale. The design of the high strain rate laboratory experiments is inappropriate to model these processes.

The brittle - plastic transition in the KTB:

The KTB project provides the first opportunity to study the microfabrics of rock samples immediately gained from deeper levels of the continental crust with ambient temperatures between 250 and 300 °C. These samples are unmodified by any processes commonly occurring during slow natural exhumation. Their microfabrics, which have developed in time scales on the order of 10^6 Ma, reflect the actual processes proceeding as a function of the prevailing conditions. The ambient temperature to which the sample was exposed over geologic times is readily determined; the slow cooling history is well constrained by fission track data related to depth (see WAGNER et al., this volume). Measuring the state of stress (ZOBACK et al. 1993) and the pore fluid pressure needs advanced technology and careful evaluation. Correlation of the microstructural record with the actual boundary conditions is equivalent to the study of a "quenched" sample after a natural strain rate experiment.

When designing experiments and analytical studies, which are to be performed in the KTB drillhole and on the recovered samples in the near future, the following conditions must be born in mind:

First, the average bulk strain rate in the intraplate, anorogenic crustal setting drilled by the KTB must be very low. The order of 10^{-16} s^{-1} may be a reasonable estimate. This has the following implications:

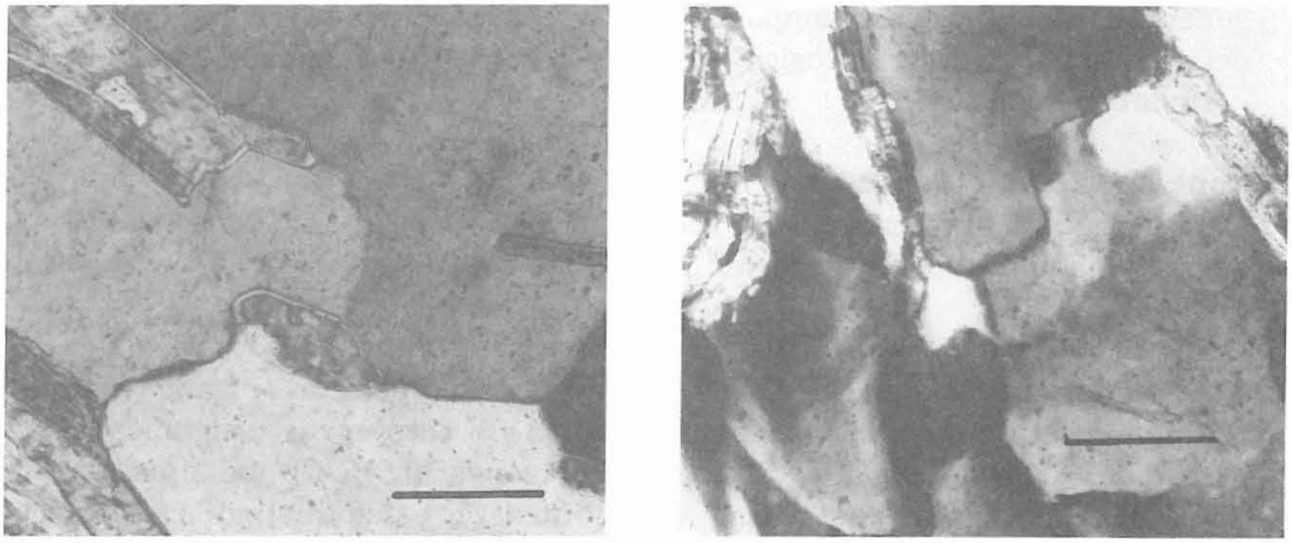
(i) As predicted by the available flow laws, dislocation creep in quartz could be an effective relaxation mechanism already at comparatively low temperatures. Based on the flow law proposed by PATERSON & LUAN (1990), creep with a strain rate of 10^{-16} s^{-1} would reqire a differential stress of about 30 MPa at a temperature of 250 °C and 10 MPa at 300 °C. According to these considerations the differential stress at 8500 m depth (T around 250°C) must be already lower than the differential stress measured at a depth of 6000 m (ZOBACK et al. 1993), which exceeds a minimum of 55 MPa, and is possibly as high as about 100 MPa. Thus, the "brittle - plastic" transition zone should already be penetrated at the current depth of 8729 m (July 1994) and temperatures close to 260 °C.

(ii) Other deformation mechanisms apart from dislocation creep are expected to be effective in relaxation. This holds particularly true for dissolution precipitation creep (generally referred to as pressure solution), which is effective in polyphase materials at comparatively low temperatures and low differential stress (RUTTER 1983), in the presence of an aqueous fluid phase. In fact, microfabrics in KTB-samples indicate that this process has been effective, and the presence of a free aqueous fluid phase has been documented. Hence, constitutive equations for dislocation creep are not necessarily relevant to predict the position of the transitional range between brittle failure and "plastic" flow in such a tectonic setting.

Second, the crust drilled by the KTB is in a state of slow exhumation and cooling. The consequence is that the microstructural record suffers from multiple overprinting. It may be difficult or impossible to distinguish microstructural features acquired during an earlier increment of deformation at still somewhat higher temperature from those adjusted during - say - a quasi stationary process over the last 10^5 to 10^6 years. The inferred slow strain rate implies a low rate of microstructural readjustment. The microstructural interpretation of the KTB samples in terms of relaxation mechanisms activated as a function of temperature must therefore rather rely on observation which feature becomes systematically absent with increasing temperature. In this respect, microcracks may be of limited value due to the influence of pore fluid pressure on brittle failure. The most prospective approach seems to be the study of the dislocation microstructure in quartz. This is even possible in very small samples from cuttings. The dislocation microstructure (visible in TEM) is thought to adjust readily, as compared to microstructures observed on the microscopic scale. It reflects the rate of recovery, governed by dislocation climb, which is the rate controlling step in dislocation creep. Since the rate of this thermally activated process increases exponentially with temperature, drastic changes can be expected over small depth intervals. Finally, the free dislocation density can be correlated with the actual state of stress in order to test experimentally calibrated paleopiezometers (for discussion see POIRIER 1985).

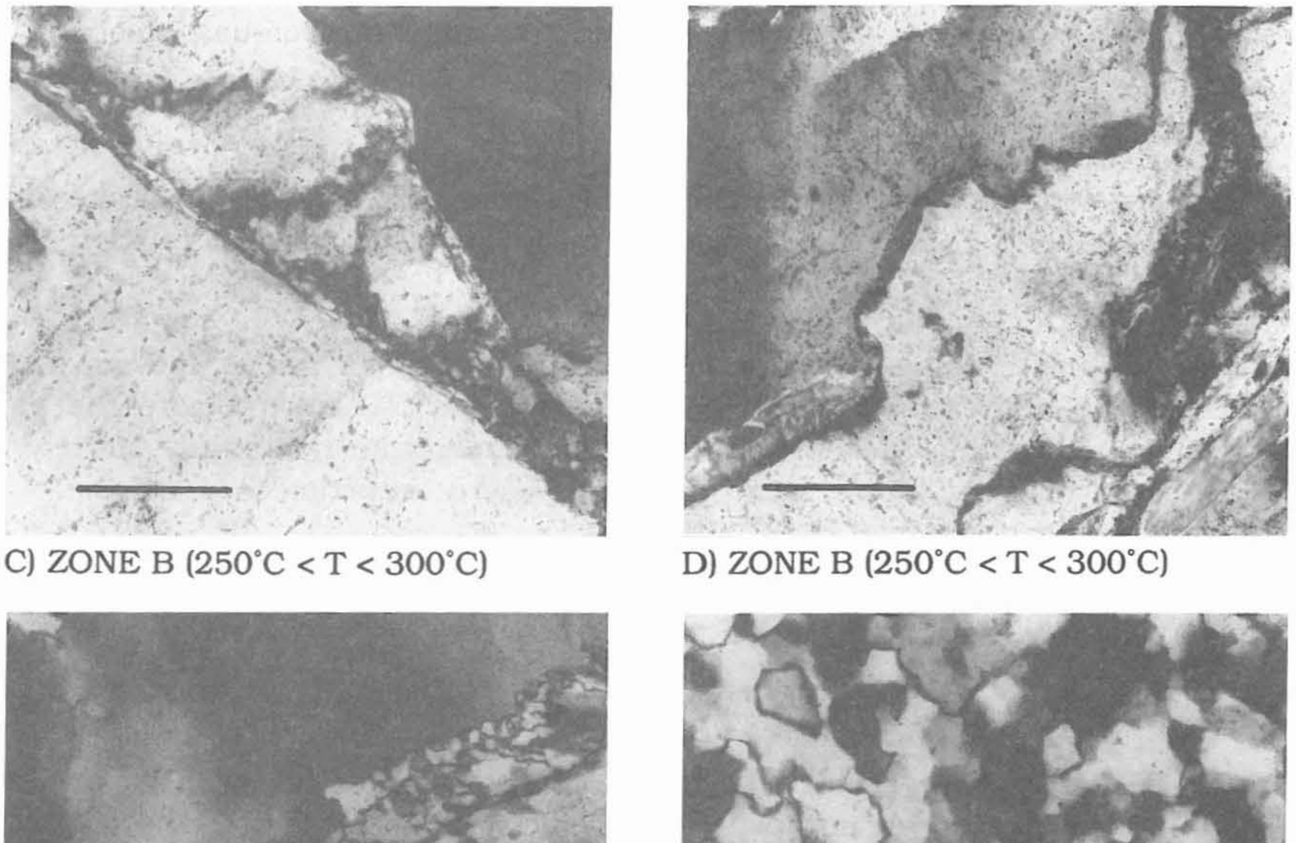
A natural example for illustration:

For the purpose of illustration, the change in the microstructural record of quartz across a fossil brittle plastic transition zone is shown in fig. 3. The example is from the Eastern Alps and will be described elsewhere in detail. There, the ambient temperatures during a specific stage of intense deformation show a marked gradient in the present level of erosion, which is revealed by the regional pattern of mica cooling ages and fission track data. In zone A, ambient temperatures were above the closure temperature for fission tracks in apatite, but below that for fission tracks in zircon. In zone B temperatures exceeded the closure temperature for fission tracks in zircon, but remained below that for the Rb-Sr and K-Ar systems of biotite. In zone C temperatures exceeded the closure temperature of biotite, but remained below that for the K-Ar system of white mica. The microstructural record correlates with the age pattern. Based on the



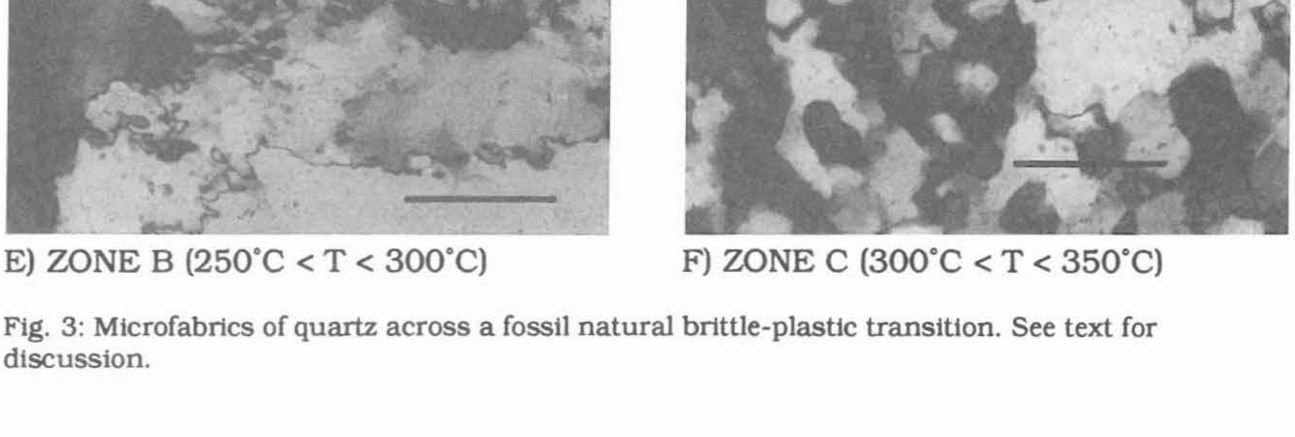
A) ZONE A (120°C < T < 250°C)

B) ZONE B (250°C < T < 300°C)



C) ZONE B (250°C < T < 300°C)

D) ZONE B (250°C < T < 300°C)



E) ZONE B (250°C < T < 300°C)

F) ZONE C (300°C < T < 350°C)

Fig. 3: Microfabrics of quartz across a fossil natural brittle-plastic transition. See text for discussion.

generally inferred closure temperatures, the temperatures prevailing during deformation and the rheological behavior recorded by microstructure are correlated as follows:

Zone A (120 °C < T < 250 °C):
Deformation highly localized; the volume of rock between fault zones shows virtually no microstructural record (fig. 3 A).

Zone B (250 °C < T < 300 °C):
Deformation distributed. Dislocation glide (low temperature plasticity) is the dominant deformation mechanism (fig. 3 B); recovery is insignificant. Additionally, formation of cataclastic shear zones (fig. 3 C) and pressure solution (fig. 3 D, stylolites) contributed to deformation. Healed microcracks marked by fluid inclusions are very common. Close to the boundary with zone C the microstructure reveals dynamic recrystallization with a very small grain size (fig. 3 E); there, the transition to quasi steady state power law creep may be reached.

Zone C (300 °C < T < 350 °C):
Microstructures indicate pervasive dynamic recrystallization with moderate grain size (fig. 3 F). The microstructural record indicates that deformation took place essentially by dislocation creep.

Note that this example is from a *high strain rate orogenic setting* and may be quite different from what is to be expected in the KTB. Furthermore, the samples are not "quenched" and later low temperature non-steady state processes have left some microstructural record, superimposed on the features described above.

Conclusions:

The KTB allows to gain deep insight in the mechanical behavior of continental crust in an intraplate anorogenic tectonic setting, and to test the predictions based on extrapolation of laboratory data. The bulk strain rate, averaged over about 10^7 Ma, is expected to be two to three orders of magnitude lower than that commonly inferred for orogenic settings. On these high strain rate environments, particularly on shear zones, geologists have focussed up to now when studying microstructures and rheology. In the KTB, mechanisms like pressure solution are expected to contribute to stress relaxation. We also do not know much about stress history. It may be possible that this is not smooth over the long periods of very low average bulk strain rate, and that short periods of elevated stress and strain rate control some aspects of the microstructural record despite a very small contribution to bulk strain. Altogether, the KTB provides the unique and outstanding chance to correlate the microstructure of "quenched" samples, which reflect the operative mechanisms, with the actual conditions in terms of temperature, differential stress and pore fluid pressure.

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