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Quartz Rheology and Short-time-scale Crustal Instabilities

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Abstract—We present numerical results of thermal-mechanical feedback in crustal quartz rheology and contrast this behavior to the vastly different character of an olivine mantle. In the numerical experiments quartz is found to have a very strong tendency for short-time-scale instabilities, while our numerical experiments show that olivine has a decisive tendency for a stable thermally lubricated slip. At the same time, olivine can also go through a transitional period of creep bursts, which are physically caused by multiple interacting ductile faults at various length and time scales which collocate quickly into a major shear zone. Since olivine has this strong propensity to self organize in a large apparently stable fault system, it lacks the dynamics of interacting ductile faults evident in other minerals. Quartz behaves totally different and keeps its jerky slip behavior for prolonged deformation. An example is shown here in which a 30×50 km piece of a wet quarzitic crust is extended for about 2 Ma. The associated total displacement field clearly shows the unstable slipping events, which have a characteristic time frame of one to several years, In contrast, olivine is very stable and has a much longer time scale for thermal instability of 100 kyrs.

Key words: Quartz, rheology, slow earthquake, thermal-mechanical mode, instability.

1. Introduction

Up to now, most previous work on thermo-mechanical feedback has been focussed on the olivine rheology, characteristic of the mantle (Regenauer-Lieb and Yuen, 2000, 2003, 2004) yet the influence of crustal rheology on the dynamics has not been explored. Yuen and Schubert (1979) have shown that, for the dynamics of large ice masses, the activation energy plays an important role in the shear-heating instabilities of ice sheet dynamics, cast within the framework of a one-dimensional model. There an activation energy contrast of a factor of 4 was examined. It is well known (Evans and Kohlstedt, 1995) that the activation energies for quartz are considerably smaller than those for olivine, therefore, we will now explore the differences in the rheologic paths taken between olivine and quartz. This issue is

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especially critical in time scales, as what YUEN and SCHUBERT (1979) found for ice-sheet dynamics. Our objective in this work is to compare the dynamical behavior in the instabilities between quartz and olivine. Of particular importance is the difference in the time scales of the instabilities, which would have strong implications for earthquakes with a long time scale, such as the recent Sumatran event, whose source spectrum does not saturate at low frequencies (STEIN and OKAL, 2005). This implies that the physics of the process is governed by slow slip not detectable from surface waves (ISHII *et al.,* 2005; KRUGER and OHRNBERGER, 2005; NI *et al.,* 2005) but rather bears the characteristics of a slow earthquake.

First, we will discuss the pioneering experiments carried out by EVANS (1984) on quartz. In particular, their experiments revealed a sharp difference in the yield strength between quartz and olivine. Then we will display the differences in the numerical results of the two-dimensional numerical models. We will discuss the ramifications of our work for earthquake instabilities in the final section of this paper.

2. *Quartz Indents like a Glassy Polymer*

Experiments on the indentation hardness of quartz by EVANS (1984) revealed remarkable material properties of quartz. The hardness of quartz $H = C\,\tau_y$ is a function of the differential yield stress τ_y, the angle of the indenter with the test surface β, and the Young's modulus E

$$C = \frac{2}{3}\left[1 + \ln\left(\frac{1}{3}\frac{E}{\tau_y}\tan\beta\right)\right]. \tag{1}$$

C varies between 3 and 1 depending on whether E/τ_y is of the order of 10^2–10^3 or larger (e.g., most metals), or of the order of 10 (e.g., low-temperature, glassy polymers, glass), respectively (JOHNSON, 1970; TABOR, 1970, 1996). If the hardness and the elastic modulus are known at a given temperature the constraint factor C and the yield stress can be computed (EVANS and GOETZE, 1979; JOHNSON, 1970). The hardness data for quartz suggest that at temperatures below 600°C, the ratio of Young's modulus to the yield is very low, probably less than 25. Therefore, Evans concluded that the hardness behavior of quartz is more akin to that of a highly elastic material, such as a polymer, than to that of a metal.

On the other hand, olivine shows a totally different behavior more akin to metal. This notion is true for the fast laboratory time and space scale, where quartz behaves more like a glassy polymer. However, can this important material property also survive for longer time scales where viscous creep is certainly more significant? We have re-interpreted the original data of Brian Evans and co-workers and cast it into a finite-element thermo-mechanical analysis (ABAQUS/STANDARD, 2000) to pose the important question whether Evans ideas concerning the importance of elastic deformation for quartz also holds true for the geological time scale. If so, this observation would have important implications for the emergence of a short-time-scale seismic response out of a smooth long-term geological loading rate.

3. Thermal-mechanical Equations

We give here a summary of the equations based on thermal-mechanical coupling, which forms the basis of our work (e.g., REGENAUER-LIEB and YUEN, 2004). Based on the energy conservation principle, NEMAT-NASSER (1982) has shown that for an elastoplastic body the rate of deformation, decomposes additively as:

$$\dot{\varepsilon}_{ij}^{tot} = \dot{\varepsilon}_{ij}^{el} + \dot{\varepsilon}_{ij}^{pl} \tag{2}$$

for finite elastic (*el*) and plastic (*pl*) rate of deformation, provided that the strain increments are defined with respect to the same reference configuration and that the overall elastic strain remains small compared to the plastic strain. We extend this solid thermodynamic approach and consider thermal expansion, appearing as part of the elastic strain rate (*el*) and viscous creep (*cr*) components, i.e.,

$$\dot{\varepsilon}_{ij}^{tot} = \dot{\varepsilon}_{ij}^{el} + \dot{\varepsilon}_{ij}^{pl} + \dot{\varepsilon}_{ij}^{cr}. \tag{3}$$

For the elastic component, which is important for short time scales, we assume isotropic hypo-elasticity, and objective stress rates. Special care is exercised in the integration of rate constitutive equations to preserve objectivity. Hypo-elasticity is limited to small elastic strains (but large rotations) implying that elastic strain (but not rotations) remain small compared to their viscous or plastic counterparts. This assumption is valid for most geological materials, such as quartz and olivine; the two materials on which we will focus in this study.

Polymers (e.g., rubber) can exhibit significant elastic and plastic deformation of comparable magnitude and the computationally more expensive additive hyper-elastic approach is warranted which is in itself objective. In our mathematical treatment we note that, although quartz is stated to behave like a polymer in the laboratory experiments, hypo-elasticity is sufficiently accurate to describe the flux of the thermodynamic potentials (e.g., Helmholtz free energy). In this context we emphasize that Evans analogy between quartz and glassy polymers is only meant to describe the characteristics of the yield phenomenon underlying the indentation experiments at low temperatures. More precisely, the stress-strain characteristics of quartz is akin to polymers below the glass transition temperature. For such conditions the classical theory of elasticity assumes small elastic strain (hypo-elasticity) which is an adequate mathematical simplification for glassy polymers and for rocks. However, polymers above the glass transition temperatures are in a leathery or rubbery state. The latter transitions are clearly peculiarities in polymers that have not been observed in rocks.

However, the magnitude of visco-plastic strain can reach significantly much larger quantities than the elastic strain (≫1000%). For the viscous part we assume that the viscosity is made up of a combination of power law and Peierls Stress contribution, each with their lumped instantaneous nonlinear viscosity η and for the plastic deformation we assume von Mises plasticity, with a pressure (p) dependent and a temperature (T) yield stress τ (see the Appendix) combined within the visco-plastic flow rule thus

$$\dot{\varepsilon}_{ij} = \frac{1+v}{E}\dot{\tilde{\sigma}}'_{ij} + \frac{v}{E}\dot{p} + \alpha \dot{T}_{\text{equ}}\delta_{ij} + \frac{1}{2\eta}\sigma'_{ij} + \dot{\varepsilon}^{pl}\frac{\sigma'_{ij}}{2\tau}, \tag{4}$$

where the Young's modulus is E and the Poisson ratio is v. The objective co-rotational stress rate is $\dot{\tilde{\sigma}}_{ij}$. The prime symbol denotes the deviator of each tensor and the over-dot its substantial derivative with respect to time. The pressure p is defined as the trace of the stress tensor divided by 3 and the plastic strain rate by its second invariant. The third term in the equation (4) spells out the thermal-elastic strain through thermal expansion α where δ_{ij} is the Kronecker delta.

We solve the fully coupled mass conservation, momentum equation and energy equations within a Lagrangian framework. The classical equation for mass conservation of compressible media is

$$\frac{\partial \rho}{\partial t} + \rho \nabla \cdot \mathbf{u} = 0, \tag{5}$$

where ρ is the density and $\mathbf{u}$ the local material velocity.

The momentum equation for an infinitesimally small volume element dV is:

$$\nabla \cdot \sigma_{ij} + \mathbf{f} = 0, \tag{6}$$

where $\mathbf{f}$ is the body force and the first term describes the surface tractions. The set of basic thermal-mechanical equations is closed by the energy equation

$$\rho\, C_p \dot{T} = \chi \sigma'_{ij} : \dot{\varepsilon}_{ij} + \alpha \delta T_{\text{equ}}\, \dot{p} - \rho\, C_p \kappa\, \nabla^2 T, \tag{7}$$

where again the over-dot denotes the Lagrangian (substantive) time-derivative, and c_p the specific heat. The first term on the right describes the shear-heating term, χ is the dimensionless shear-heating efficiency (1 for full efficiency) and this coefficient χ depends on the microstructure of the polycrystalline material (BERCOVICI and RICARD, 2003). The second term on the right is the isentropic work term, where α is the thermal expansivity which multiplied by the adiabatic temperature change δT_{equ} describes the recoverable elastic volume change.

Further details on the numerical solution technique (REGENAUER-LIEB and YUEN, 2004), our novel approach for calculating shear zones (REGENAUER-LIEB and

YUEN, 2003) and further details on the simple, but unified brittle-ductile model setup (REGENAUER-LIEB *et al.*, 2005) can be found elsewhere. We use high resolution calculations with a local resolution of 300 m $\times$ 300 m and a total initial spatial grid of 30 $\times$ 50 km.

The heart of our numerical approach lies in the energy equation that is solved in a fully coupled way with the displacement equation using a solver for highly nonlinear systems (ABAQUS/STANDARD, 2000). The novelty of our approach thus lies in abandoning empirical constitutive theories for faulting and abstaining from *ad hoc* weakening laws. We solve instead the energy equation including thermal-elastic feedback and shear-heating terms to provide a self-consistent framework for the nucleation, weakening and persistence of shear zones. We calculate here, for the first time, the dissipative structures developing in a quartz dominated crust in extension. Quarzite flow law is taken to be representative for a granitic composition where two types of perturbations are included. First, completely random heterogeneities are the presence of other minerals in the granite (e.g., feldspar crystals). These are mimicked by random nodal (5°C) thermal perturbations applied at the start of the model triggering a white noise of thermal stresses. Another set of sinusoidal perturbations is superposed with 5°C amplitude and a 10-km long wavelength in order to give the model some short wavelength structure. The motivations for these mild perturbations are aimed at mimicking some structure, which should be inherited from previous buckling or necking modes of the upper crustal units.

Another motivation for the short wavelength perturbation is to test for the influence of the model boundary which cannot be avoided. Since periodic boundary conditions are taken with respect to vertical displacement on the left and right side of the model. In a foregoing study (REGENAUER-LIEB *et al.*, 2005), we have varied the amplitude and wavelength of the short wavelength perturbations and find a perturbation independent pattern that emerges upon subjecting the model to pure shear horizontal extension. This pattern appears to be independent of the sinusoidal perturbations and we find a thermodynamically inspired criterion for the nucleation of listric faults, which is reported elsewhere (REGENAUER-LIEB *et al.*, 2005). This pattern is apparently due to decoupling above a maximum dissipation, subhorizontal layer marking the rheological transition from a brittle p-dependent to a ductile T-dependent localization phenomenon. We call this layer the brittle-ductile transition in a granitic crust.

We use here exactly the same setup and compare for the purpose of clarity the results to a virtual crust of the same dimensions and temperature profile but composed of the main mechanical constituent olivine. This crust is labeled "oceanic crust," bearing in mind that the temperature profile would be different for a real oceanic crust and the lower part of the crust would in fact be the mantle. We discuss the surprising difference in the mechanical behavior, in particular, the tendency for short time-scale instabilities.

4. Quartz versus Olivine

Indentation experiments on olivine (EVANS and GOETZE, 1979) and quartz (EVANS, 1984) suggest that quartz yields when it has stored a substantial amount of elastic energy. It is thus best compared to a polymer. On the other hand, olivine does not store elastic energy efficiently and fails in smooth manner. Its mechanical behavior is better compared to a metal. This could have strong implication for the genesis of and interpretation of earthquakes. It is surprising that these important implications have never been seriously investigated as a potential explanation for the apparent absence of earthquakes in the mantle part of the continental lithosphere. Instead theories where the continental mantle is assumed to be anomalously weak have been favored (JACKSON, 2002). This implies that the continental mantle is rather hot and/or anomalously wet. The absence and presence of earthquakes could have a simple mechanical reason, if one extrapolates the mechanical data by Brian Evans (EVANS, 1984).

However, there remains the open question, whether the laboratory results can be extrapolated to geological conditions. For this extrapolation the Peierls stress quantifies the stress required for the first dislocations to move (see Appendix). The data suggest that quartz has an anomalously high Peierls stress τ_y , which implies that the ratio of Youngs modulus over yield stress E/τ_y could be even lower than suggested by Evans. However, a high intracrystalline threshold for plasticity may have quite the opposite effect at lower temperatures. The material may fail by brittle mechanism or deform by a phase transition. It is well known that materials with a very high Peierls stress like silicon (higher than the ideal strength) can undergo a phase transition when deformed under low temperatures (GALANOV *et al.*, 2003). Thus a lattice instability may actually precede dislocation mobility at low temperatures and accommodate deformation (ROUNDY and COHEN, 2001). If water is available alpha quartz may for instance transform into amorphous silica (DI TORO *et al.*, 2004) thus allowing creep at considerably lower shear stress than extrapolated with the formulation in the Appendix. From the Appendix, we can see that the yield stress of alpha quartz is 1.1 kbar at 500 K. It is thus lower than the brittle failure stress but still possibly higher than the phase transition stress. In order to test Evans contention on the quartz-olivine difference for geological strain rates we use an order of magnitude lower stress for the onset of creep, thus allowing power-law creep, to dissipate elastic energy above an initial strain rate of 10^{-16} s^{-1} or an associated initial yield stress of 110 bar. Thus we assess the difference with the highest permissible E/τ_y for quartz but we leave the olivine rheology untouched, thus narrowing the differences between quartz and olivine.

We perform extension experiments with a homogeneous quartz rheology "granitic" crust (30-km thick to the basic symmetry plane, a steady-state initial geotherm with a 10-km thick radiogenic layer producing 40 mWm^{-2} radiogenic heat, and a bottom heat flow at 30 km depth of 30 mWm^{-2}) thus we obtain a surface heat flow of 70 mWm^{-2} and compare the extension results to the same thickness and temperature crust made of homogeneous olivine (200 ppm H/Si) labeled "oceanic" crust. The extension velocity is fixed at 1 cm/yr in both cases. The boundary conditions are perfectly symmetrical extension in x direction and there is a half symmetry in the z direction, i.e., the top is a free surface but the bottom is a zero vertical flow plane although free to glide in a horizontal plane. The motivation for using a fully symmetric setup is to test for the phenomenon of symmetry breaking on random thermal perturbations that have been inserted at the start of the model.

Recent work by B. Kaus (KAUS and PODLADCHIKOV, 2004) in his thesis has identified four different thermal feedback modes based on a single inclusion. These are listed as viscous, static-plastic, plastic and thermal runaway. Our solution has multiple inclusions and we cannot interpret the results in terms of a classical domain map. However, we link single inclusion and multiple inclusion studies by discussing the results in terms of a matrix problem in which we explore the potential for exciting multiple global eigenmodes in space and time (REGENAUER-LIEB and YUEN, 2000, 2004).

We have presented an indirect approach to the formation of shear zones, where a perfectly homogeneous olivine or quartz slab is slightly modified with initial thermal imperfections. During subsequent extension a smoothly varying deformation field gives way to one involving highly localized deformation. We interpret the results using the definition of the classical direct approach (RIKS, 1984). The localization phenomenon is there seen as a bifurcation phenomenon in which the velocity field aborts the continuous branch and takes a new discontinuous path. The problem may then be understood as a numerical solution to a nonlinear matrix problem where the tangential stiffness matrix K is a function of the nodal displacements D and we look for d the unknown increment of nodal displacement leading to bifurcation.

$$K_{(D)}d = F \tag{8}$$

This tangential stiffness is equal to a residual nodal force F. If the determinant of the stiffness matrix becomes zero a bifurcation is detected. The corresponding eigenvectors of $K_{(D)}$ are associated with zero eigenvalues. We may define this nodal displacement as the bifurcation eigenmode(s).

In our analysis we encounter two basically different bifurcation phenomena which can be attributed to two different families of elasto-visco-plastic eigenmodes of the system. One in which the shear zone nucleates on thermal perturbations in the ductile field, and the second which is fully associated with elasto-plastic (brittle, *pressure-dependent*) displacements.

The perturbations are exciting initial short wavelength shear zones which at 17 ka are present in both rheologies (Fig. 1). These coincide with the two left lateral and right lateral 45° shear characteristics (slip lines) of an ideal rigid-plastic body. After

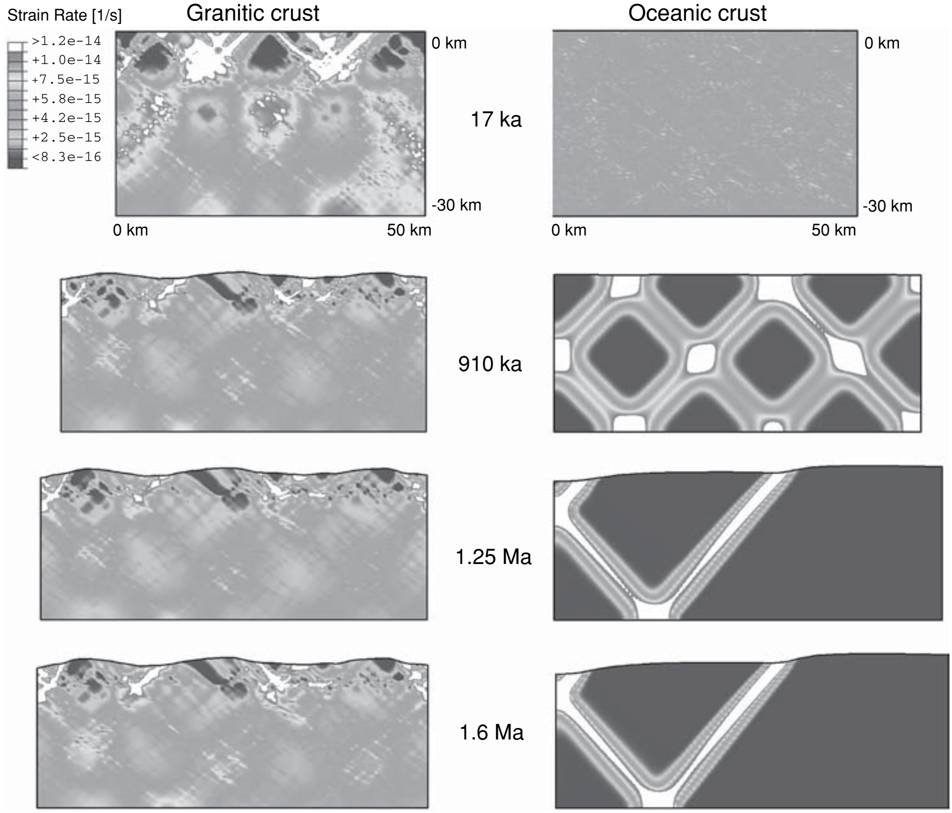

Figure 1
Synchronous time slices of identical (70 mW/m^2 surface heat flow) extending (1 cm/a) slabs consisting of quartz and olivine rheology, here called granitic and oceanic crust showing strain rate maps. The transition from pressure sensitive to T sensitive creep occurs when the T-dependent flow law produces a shear stress that is equal to the lithostatic stress. The left panels show the persistence of highly dynamic solutions in the strain rate map [up to 10^{-12} s^{-1}] of the 30 × 50 km crust while the right panels show relatively stable deformation [order of 10^{-14} s^{-1}] of the same olivine crust, respectively. The prominent subhorizontal decoupling zone at the brittle-ductile transitions in the left panels - see marker grid in the corresponding Figure 2 (ROSENBAUM *et al.,* 2005) - is completely missing in the olivine case.

17 ka there is, however, a significant departure from the ideal rigid-plastic solution in the quartz rheology, only. Quartz displays—owing to a mismatch of brittle and ductile localization mechanism as well as a maximum dissipation at a decoupling interface (Figs. 2 and 3)—shear localization at the surface that peters out with depth into a prominent listric fault system with extremely high strain (> 7000%). The color scale in the strain rate plot in Fig. 1 has been clipped (white) to show the tendency for the characteristics to turn around towards the subhorizontal decoupling layer. However, such listric faulting is better seen in the strain plots on a marker grid shown

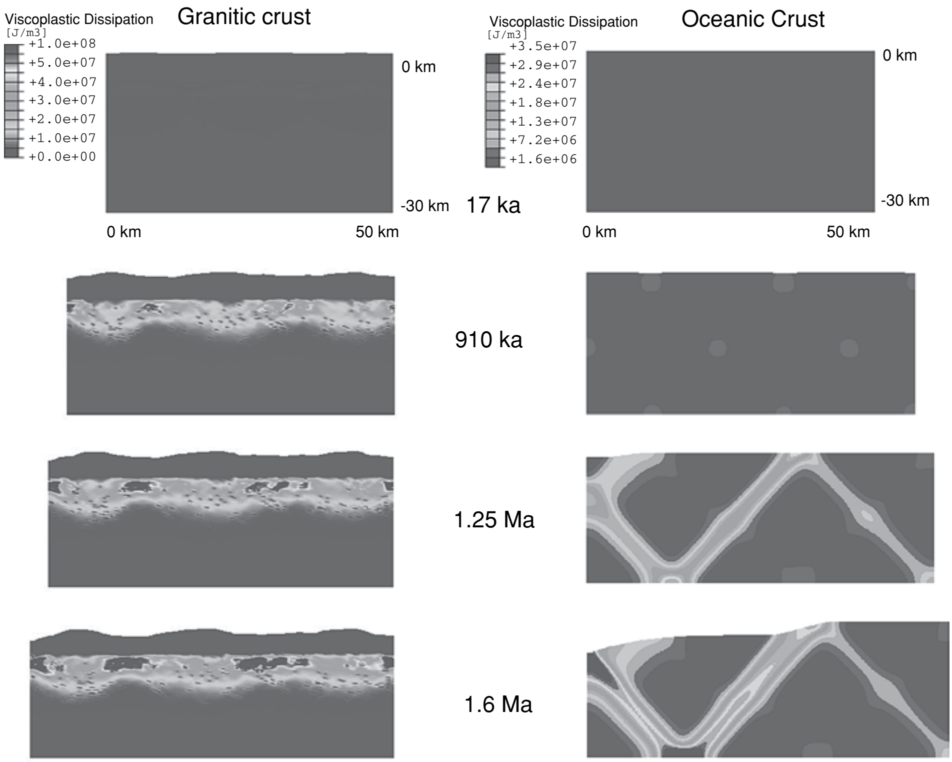

Figure 2

Time slices of the visco-plastic dissipation (shear heating) corresponding to the sequence shown in Figure 1. Comparing the left panel with Figure 1 one can see that even a weak shear heating (light blue patches @ 17 ka) has a strong effect on producing the weak detachment and localizing the faults. Shear heating on detachments intensifies with time and produces a low viscosity zone at the strongest part of the quartz plate (REGENAUER-LIEB *et al.*, 2005). For the olivine the low viscosity zone develops as well. It is fully developed as a crust cutting oblique fault at 1.6 Ma. However, in spite of the higher activation energy of olivine, shear heating is lower by a factor of 3 than in the equivalent red patches in the quartz detachments. This is due to the fact that for the olivine case the oblique low viscosity zone traverses the entire crust.

elsewhere (Fig. 2, in ROSENBAUM *et al.*, 2005). The brittle-ductile decoupling surface in the quartz slab leads to a clear separation of pressure (elasto-plastic) and temperature-dependent (elasto-visco-plastic) eigenmodes operating simultaneously in three different depth levels.

The olivine slab, on the contrary, can keep the ideal plastic characteristics and develops them further into long wavelength features through thermal-mechanical weakening on the largest elasto-visco-plastic (*temperature-dependent*) eigenmode of the system. This governs the entire model absorbing the shorter wavelength shear bands. The olivine slab appears to lack the brittle elasto-plastic (*pressure-dependent*) eigenmode.

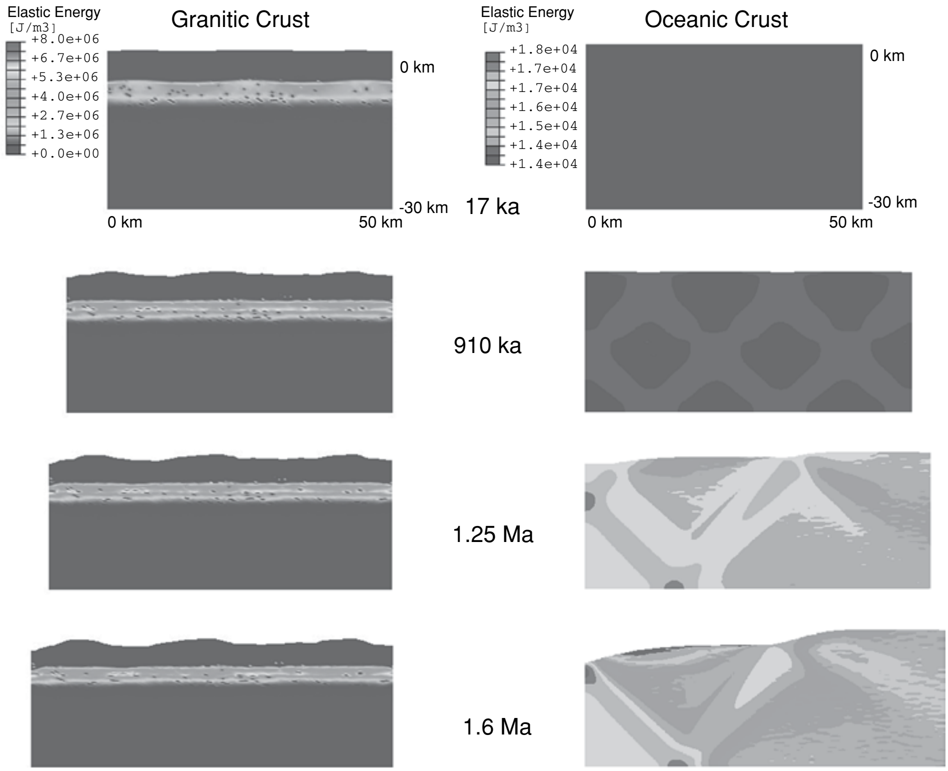

Figure 3
Stored elastic energy for the equivalent time slices in Figures 1 and 2. Quartz develops a strong elastic core and stores most of its energy in a thin band near the detachments while the olivine plate ruptures entirely and has high elastic energy around the shear zones. Note that the elastic energy in shear zones for the olivine plate is close to two orders of magnitude smaller than for the equivalent quartz detachment. It follows that quartz has a strong propensity toward seismic instabilities, while olivine prefers to creep.

The richness of the quartz simulation leads to a chaotic fast time-scale feature only observed in the quartz rheology, thus Quartz has a very strong tendency for short-time-scale instabilities. These instabilities are shown in a log-log plot of maximum model displacement versus time in Figure 4. Olivine has a preference towards stable slip enhanced by thermal-mechanical feedback, although olivine can also go through several transitional periods of creep bursts with a much slower time constant. These are caused by multiple interacting faults shown in Figure 1.

5. Summary and Discussion

Since olivine has a strong propensity to self-organize in a large apparently stable fault system (Regenauer-Lieb and Yuen, 2004), it lacks the dynamics of interacting

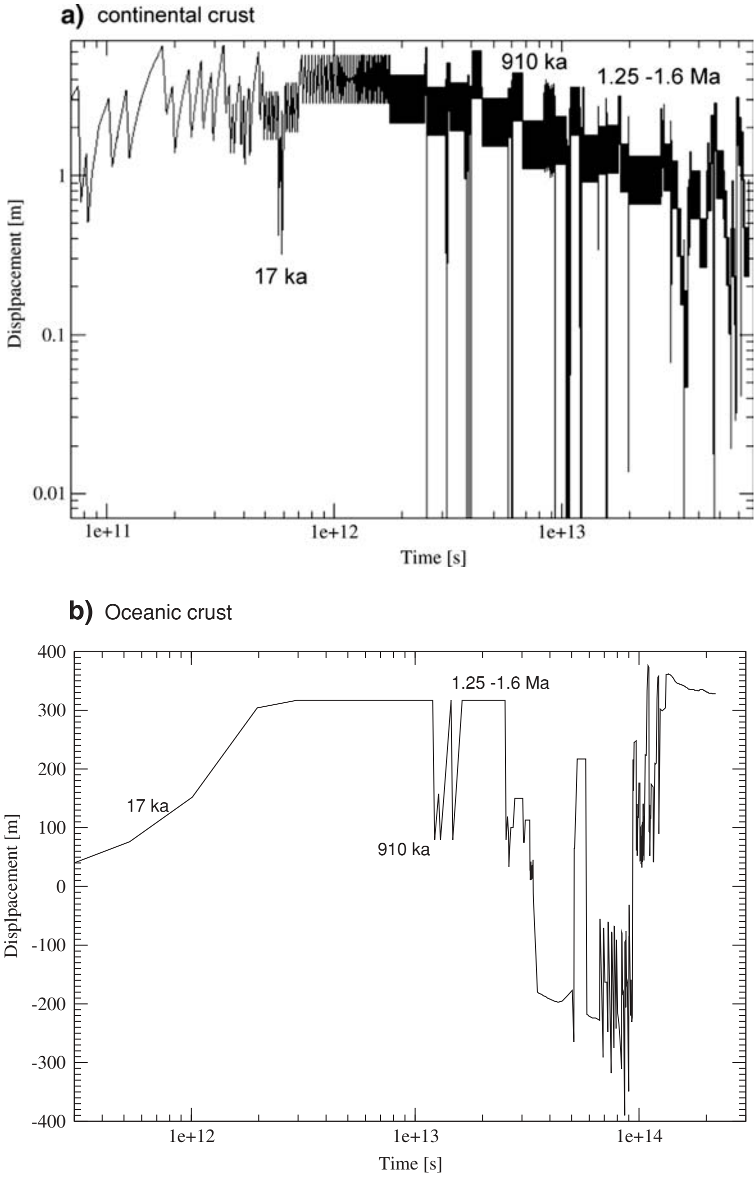

Figure 4
This figure shows the maximum model displacement for a stable time step, thus giving an indication of the convergence of the coupled momentum and energy equations. a) In a granitic crust we note individual creep bursts with a frequency larger than a single day (around 10^5 s), characteristic creep burst of a year interval prevail, above 1e + 12 s the noise on the displacement time series amplifies around a distinct power-law trend. b) The same mode with an olivine crust produces relatively stable deformation with instabilities that are two to three orders of magnitude slower than for quartz.

ductile faults evident in other minerals. Quartz behaves totally different and retains its jerky slip behavior for prolonged deformation. An example has been discussed here in which a 30×50 km piece of a wet granitic crust is extended for about 2 Ma. For quartz the associated total displacement field clearly shows the unstable slipping events which have a characteristic time frame of one to several years. The same olivine slab on the other hand is very stable and has a characteristic thermal-mechanical instability time frame of 100 kyrs. The vast difference in thermal-mechanical behavior hinges on two main thermal-mechanical differences.

- Olivine has an activation enthalpy of around 500 kJ/mol while quartz has an activation enthalpy of only around 134 kJ/mol. This results in stronger weakening through thermal-mechanical instabilities for olivine than for quartz, which in turn implies extreme localization and selection of single master faults, which does not interact with other faults. Hence, olivine lacks seismicity induced by thermal-mechanical feedback. However, as the activation energy or the yield stress increases or the Young's modulus is reduced, the vigor of the instability decreases until a lower limit.
- Quartz has a considerably lower ratio of yield stress over Young's modulus. Therefore quartz is closer to the optimum for shear heating feedback through multiple interacting instabilities than olivine. In effect, micro-indentation experiments have shown that quartz deforms like a polymer while olivine deforms like a metal (EVANS, 1984). Hence, this can explain the jerky creep phenomenon observed in quartz.

Here, we have compared only two specific materials olivine and quartz. We have also explored key parameter ranges, varying elastic modulus, activation energy and yield stress over several orders of magnitude. This analysis prompts us to qualify quartz as a material that is marked by prominent short-time-scale feedback processes. We have discussed that the results indicate at least two different families of eigenmodes, which for the case of quartz appear to communicate in a flip-flop manner along the major subhorizontal detachment on top of the maximum dissipation layer in Figure 2. We find indications of a power-law time series (Fig. 4). The analysis of this phenomenon clearly calls for an extended analysis for fractal space-time evolutions. Calculations are very time-consuming and we therefore refrain from discussing our parameter runs here, which are far from comprehensive. A different model setup is required. We are now investigating this phenomenon more closely by characterizing only the behavior of the critical layer.

We conclude by also encouraging more laboratory experiments on the low stress, low temperature end of the Peierl's stress mechanism in quartz, which needs to be clearly looked at to understand the mechanism for ductile instabilities. An additional interesting phenomenon that may boost the tendency of quartz for creating earthquakes is phase transitions and associated changes in elastic modulus. Apart from results for dry silicon, no experimental data exist for the low temperature regime of alpha quartz since the pioneering experiments performed by Brian Evans in

1984. Upon reinterpreting the original data we find that the classical Vickers indentation experiment is not suited to deliver reliable estimates of the Peierls stress, based on the elasto-plastic contact theory of Johnson (JOHNSON, 1970) which has recently been improved by accounting for phase transitions (GALANOV *et al.*, 2003). New experiments need to be designed (GOLDSBY *et al.*, 2004). A potential avenue for directly deriving micro-mechanical data is for instance given by a quantitative comparison of atomic force microscopy (AFM) indents with fully coupled finite element (FEM) and molecular dynamics (MD) calculations.

Using a simple generic setup in extension we have conducted numerical experiments in order to compare the fundamental behavior of quartz versus olivine. The motivation for this study was based on the surprising difference of the two materials in laboratory indentation experiments. Since under laboratory conditions quartz behaves much like a polymer and olivine much like a metal, we expect fundamental differences in terms of creep instabilities at crustal scale and geological conditions. The focus of the paper was hence to assess whether quartz according to its low yield stress/Youngs modulus ratio, may contribute at crustal scale to fast ductile slip events. Unexpected short-term instabilities were obtained and followed to a single day at which stage we stopped the calculations because we did not consider inertial terms in our formulation. Our models were initially not geared at specific earthquake simulations, but they nevertheless suggest that seismic instabilities may be triggered by such creep events. We suggest that this important phenomenon is a possible source for slow earthquakes.

Our simplified crustal setup has produced quartz slip events with a typical time period of a year. Although this is still outside the realm of slow earthquakes (e.g., SACKS *et al.*, 1978), more realistic boundary conditions may lead to shorter time-scale instabilities. Slow earthquakes with time scales of days to weeks, such as the recent Sumatran event in December, 2004, may be more common than previously thought (www.eri.u-tokyo.ac.jp).

Fully coupled thermal-mechanical deformation can lead to counterintuitive results. An example is the paradoxical observation of lack of earthquakes in the continental mantle. Although crustal rocks are generally softer than the mantle, earthquakes seem to occur only just above the Moho and not below (JACKSON, 2002; MAGGI *et al.*, 2000). The paradox may be resolved by considering the stabilizing effect of olivine described in this paper. Another puzzling aspect is that olivine has the tendency to develop a weak and aseismic, ductile master fault cross-cutting the lithosphere (REGENAUER-LIEB and YUEN, 2000). We show here a comparison for the same models discussed before (Fig. 5). We show here the elastic stress of the 1 Ma case of Figure 5. This figure illustrates the counterintuitive phenomenon that the strongest material is becoming the weakest material through the effect of deformation.

For an interpretation of Figure 5 it is useful to note that the shear stress maps the elastic energy (Fig. 3) and also the dissipation (Fig. 2). Thermal-mechanical

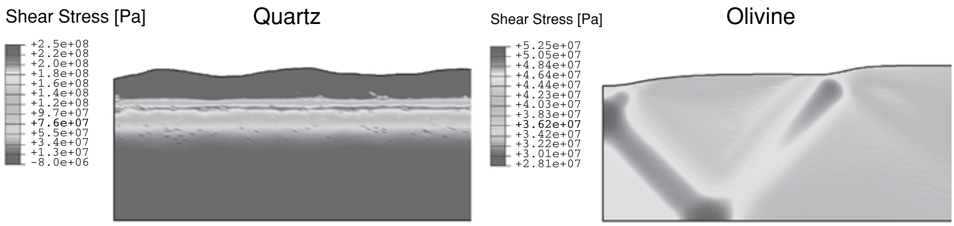

Figure 5

Second invariant of the deviatoric stress tensor after 1 Ma of extension. As expected from the jelly cake rheology, the granitic crust (Quartz rheology) has initially (not shown) substantially lower strength than the oceanic (olivine). However, after thermal-mechanical feedback the situation shown here is quite the opposite. Quartz is stronger (peak stress 2.5 kbar) than olivine (peak stress 525 bars). Quartz also has a significantly higher tendency for instabilities which potentially turn seismic.

weakening is hence highest in areas with high shear-stress/dissipation potential. Olivine can be seen to create a weak crustal cross-cutting fault, while quartz weakens on a subhorizontal layer. Through thermal-mechanical feedback the ''strong'' olivine crust (Kohlstedt *et al.*, 1995) becomes weaker than the same crust composed of ''weak'' quartz rheology (Fig. 5).

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Appendix

Temperature-sensitive Yield Stress

Following the work of Wang and Shimamoto (Wang, 1996; Wang and Shimamoto, 1994) there exists in the low dislocation density, low stress regime a threshold-like phenomenon, which is linked to a lower yield stress phenomenon. A visco-plastic rheology threshold appears associated with the activation of dislocations at low stress. This logic implies that, in addition to the well-known Peierls mechanism as a stress delimiter at high stress (Ashby and Verall, 1977; Kameyama *et al.*, 1999), there also exists a low stress delimiter (KOCKS, 1987; KOCKS *et al.*, 1975) attributed to the Peierls mechanism (REGENAUER-LIEB *et al.*, 2001). This mechanism assists and inhibits power-law creep. It is hence important for the capacity of low temperature material to store elastic energy before the onset of creep. Hence we also expect significant impact for lithosphere or crustal behavior.

The low stress-yield stress can be derived by two independent theoretical considerations. One approach requires knowledge of the activation enthalpy; a characteristic strain for the onset of creep and knowledge of the thermally influenced lattice vibration (KOCKS, 1987; KOCKS *et al.*, 1975). This approach has been applied for olivine rheology (e.g., BRANLUND *et al.*, 2001; REGENAUER-LIEB and YUEN, 1998, 2000) and has recently been discussed in full details (REGENAUER-LIEB *et al.*, 2004). The necessary data can be obtained from Vickers indentation experiments and extrapolated from the high stress experiments of the Peierls mechanism. The required material constants for low temperature have, however, only been derived with confidence for olivine indents.

We have attempted to derive the Peierls stress flow law from the quartz indentation data (EVANS, 1984) using the same approach as proposed for the olivine case (EVANS and GOETZE, 1979). We find that we cannot use the elastic contact formulae because of the polymer-like behavior of quartz. Nano-mechanical constants cannot be derived for quartz because the indentation formula combines a rigid-plastic assumption with an elastic approach. The low ratio of elastic modulus over yield stress invalidates the basic assumption of infinite rigidity, i.e., insignificant elastic strain upon yield. Elastic strain plays a considerably larger role in quartz than in olivine.

Additional aspects for failure of deriving the Peierls stress flow law may be deformational processes other than those accommodated by dislocations, such as solid-solid phase transformations, flash heating under the indenter and surface energy effects. These phenomena are currently being assessed (DI TORO *et al.*, 2004; DIETERICH and KILGORE, 1996; GALANOV *et al.*, 2003; GOLDSBY *et al.*, 2004; ROUNDY and COHEN, 2001), but it is premature to use nano-indents for the estimation of the Peierls stress. An experimental technique, which is very well suited for the low stress branch of the Peierls mechanism has been devised (WANG, 1996; WANG and SHIMAMOTO, 1994) but this experiment cannot be performed for the low temperatures of alpha quartz. A classical Bingham-type rheology was found for low stress—high temperature deformation. This implies no creep (just elastic deformation) before the onset of yield and then Newtonian creep (Harper-Dorn creep) finally assisting the onset of the classical power-law creep for higher stress. For simplicity we just use a lower threshold stress for power creep (equation A3) of 110 bar, without incorporating the Peierls stress mechanism.

The ideal Peierls stress can also be calculated theoretically from WANG (1996) and WANG and SHIMAMOTO (1994) and the experiments and the theory are compared in Table 1.

Table 1

Predicted and observed Peierls stress for Olivine and Quartz rheology (WANG, 1996; WANG and SHIMAMOTO, 1994)

	Material	T [K]	ν	d/b	$\tau_{\text{Peierls } (T)}$	$\tau_{\text{Peierls } (T)}$	$\tau_{\text{Peierls } (T=0)}$
		Temperature Experiment	Poissons Ratio	Unit cell-burgers ratio	Peierls Stress Experiment	Peierls Stress Predicted	Peierls Stress Predicted
Mg2SiO4	Forsterite	1823	0.24	0.635	1.85E+07	6.43E+07	4.21E+08
$(MgFe)_2SiO_4$	Olivine	1673	0.25	0.714	2.07E+07	3.24E+07	2.12E+08
SiO_2	Quartz (beta)	1073	0.25	0.55	5.24E+07	8.25E+07	5.40E+08
SiO_2	Quartz (alpha)		0.17	0.55		1.06E+08	7.61E+08

$$\tau_{\text{Peierls } (T=0)} = \mu \frac{1}{1-v} \exp\left(-\frac{d}{b}\frac{2\pi}{1-v}\right) \tag{A1}$$

where the parameters are explained and given in Table 1 and the elastic shear modulus μ is of the order of 40 GPa for quartz and 60 GPa for olivine for the temperatures of the experiment.

The temperature sensitivity of the Peierls lower yield stress phenomenon can be approximated by a linear relation (WANG, 1996).

$$\tau_{\text{Peierls } (T)} = \frac{\tau_{\text{Peierls } (T=0)} T_m}{13T}, \tag{A2}$$

where T_m is the melting point temperature.

Power-law Creep

For calculating viscous strain rates we only use power-law creep.

$$\dot{\varepsilon}^{cr}_{ij} = A\sigma'_{ij}\, J_2^{n-1} \exp\left(-\frac{H^{\text{Power}}}{RT}\right). \tag{A3}$$

We use a flow law of wet quartzite where 0.4% wt water has been added in a sealed capsule (KRONENBERG and TULLIS, 1984). The material constant $A = 3.98\ 10^{-21}\ \mathrm{Pa}^{-n}\mathrm{s}^{-1}$, the activation enthalpy is $H^{\text{Power}} = 134$ kJ/mol and $n = 2.6$. Material constants for the wet (200 ppm H/Si) olivine power-law rheology are listed in REGENAUER-LIEB *et al.*, (2001).

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