Mechanics of low-angle extensional shear zones at the brittle-ductile transition

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Abstract

The main objective of this presentation is to show that the shear zones that ultimately lead to the formation of detachment planes at mid-crustal depths during post-orogenic extension are the results of strain localization. The destabilizing factor is the transformation of feldspar grain into weaker white mica. The prerequisite to that transformation is the fracturing of the feldspar grain. A constitutive model which capture those features is presented and constrained from field data before being applied to obtain the numerical solution of the localization problem.

1 INTRODUCTION

The two objectives of this presentation are first to study the origin of low-angle extensional shear zones at the brittle ductile transition of the extending continental crust and, second, to reconcile, tentatively, the apparent contradiction between their observed sub-horizontal orientation with the approximately +/- 45^o predicted by classical failure criteria for frictionless materials. Regional studies have shown with little ambiguity that normal faulting can occur indeed with a low original dip as in the Basin and Range province, the Woodlark Basin or the Aegean region. This normal faulting nevertheless contradicts Andersonian mechanics and question the overall mechanical behaviour of the continental crust and its state of stress. To explain the rotation of the principal stress directions at mid-crustal depth, Melosh [1] considered the crust to be ductile and sustaining a combined simple shear and extension. The linear viscosity model used for that construction, however, cannot explain the trend towards failure which is assumed here to be initiated by localization.

Low-angle shear zones at the brittle-ductile transition are also evidenced by seismic profiles and micro-seismicity recorded in active regions. In the northern Aegean Sea, seismic profiles show shallow dipping reflectors in the downward prolongation of major normal faults [2]. The shallow-dipping detachment of the southern margin of the Gulf of Corinth proposed by Sorel [3] could root at depth in a seismically active decollement at the brittle-ductile transition. The destabilizing

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factor responsible for strain localization at mid-crustal depths and the low dip angle of these shear zones are two prerequisite questions to be addressed before discussing this micro-seismicity, as it will be done in this presentation.

2 MODEL PROBLEM AND MAIN RESULTS

At mid-crustal depths, reaction-softening due mostly to feldspar to mica reaction, is the major destabilizing factor responsible for strain localization. This phase transformation requires feldspar fracturing which is detected with the Mohr-Coulomb criterion. Gueydan et al. [4] have incorporated these features in a rheological model, which will be first discussed, for a mixture of three phases, feldspar, quartz and mica, undergoing dislocation creep at a common strain rate. The proposed constitutive material parameters are constrained by comparing the results of a 1D simple shear analysis of the lower crust with data obtained in the East Tenda Shear Zone, Alpine Corsica, France. It is shown that the formation of a horizontal shear zone at the brittle-ductile transition occurs after less than half a million years. Strain localization occurs only if the shearing velocity Vs is increased by at least a factor of five from the steady state value so that the equivalent shear stress becomes sufficiently large to permit the feldspar grain fracturing. The depth of the shear zone is mostly governed by the Mohr-Coulomb criterion used to detect this fracturing and by the time lapse during which the shearing velocity Vs is increased. The time required for the shear band to form depends on the reaction kinetics. Timing and depth are consistent with Pressure-Temperature constraints obtained in the field for the East Tenda Shear Zone.

The second part of this talk deals with the prototype of the extending continental crust which consists of ductile layers sustaining a flow which combines stretch and shear by applying appropriately the velocities Ve and Vs, respectively, at the boundaries. Starting from a simple shear steady state, the velocities are first increased with time and then kept constant defining a transient regime during which localization can develop. The 1-D and 2-D solutions of this thermo-mechanical boundary value problem are found by numerical means using the finite-element method implemented in the code SARPP [5]. A Lagrangian description of the deformation is adopted and the incompressibility constraint imposed by penalty so that the nodal unknowns are the displacement and the temperature. Note that the periodic boundary conditions are also enforced by penalty. The upper crust and the upper lithospheric mantle are discretized by two sets of 40x5 nine-noded Lagrangian elements for the 2-D analysis. The lower crust is partitioned into 40x 30 elements of the same type. This discretization, as well as the element type selected, was found to be sufficient to capture strain localization. The heat equation is solved throughout the whole structure with radiogenic heat production and shear heating contribution in the ductile crust corresponding to the conversion of mechanical work into heat. The boundary conditions for the thermal problem are the flux from the mantle set to 30 mW/m2, and the surface temperature kept to 300 K. Mechanical equilibrium and the heat equation are enforced in a staggered manner. Further information on the numerical scheme is found in [6].

The 1D finite element solutions of this combined flow, for which the localization has to remain in a flat region, show a depth partitioning in deformation mode between the mid-crust, mostly dominated by pure shear, and the deep crust, sustaining simple shearing. The velocities ratio Ve/Vs has to be as low as 0.001 for localization to take place at the depth of approximately 13 km which is the base of the reaction zone below which the feldspar-to-mica reaction is not activated. Strain localization does not propagate to greater depths because feldspar fracturing is not possible but can propagate laterally, leading to the formation of a periodic system of synthetic shear bands within half a million years, as it is revealed by the 2D solution, Figure 1. These results could explain the presence of a flat weakened zone at the brittle-ductile transition of the extending continental crust without contradicting classical local failure criteria. Indeed, these criteria predictions are

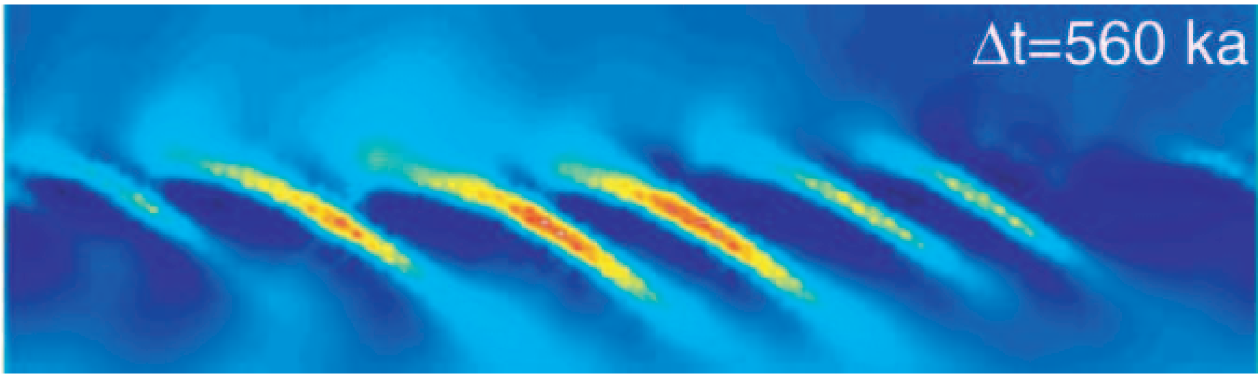

Figure 1: Isocontours of equivalent strain rate (over one order of magnitude) over a length of 20 km and the depth ranging from 10 to 15 km [7]. Note that the dip of the shear bands is consistent with the combined extension and shear loading but are found in a horizontal shear zone where the feldspar to mica reaction took place and has weakened the rock.

found to be consistent with the orientation of the shear bands which define the internal structure of the flat weakened zone. Finally, the stress state within the weakened zone is examined in details to shed light on potential micro-earthquakes and local fluids migration.

References

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