Geophysical Research Abstracts, Vol. 9, 05223, 2007
SRef-ID: 1607-7962/gra/EGU2007-A-05223

Brittle failure and short-term ductile deformation at 500˚C – the record of quartz veins beneath an exhumed low-angle normal fault

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The mechanics of low angle normal faults are poorly understood and the seismological record of fault activity at greater depths appears to be equivocal. Here we present the record of quartz veins in the exhumed footwall of a large low angle normal fault. These quartz veins, formed at temperatures of about 500˚C, indicate an event of brittle failure followed by an episode of ductile deformation, which we attribute to stress changes related to the earthquake cycle. Furthermore, a stage of very high permeability and fluid flow is implied. The peculiar record is found in an eclogite-amphibolite slice, about 200 m in length and 30 m in thickness, embedded in felsic gneisses on Rugsundøya Island in the Western Gneiss Region of Norway in the exhumed footwall block of a large low angle normal fault (LANF), the Nordfjord-Sogn Detachment Zone (NSDZ). Along the NSDZ, ultrahigh-pressure metamorphic rocks became exhumed from depths of about 100 km into the upper crust within a few million years. For analysis, the vein record is subdivided into three stages: (1) crack initiation, propagation, and arrest, (2) opening of fractures and precipitation of minerals from the fluid phase, (3) deformation of the vein. The Rugsundøya quartz veins originate from fractures, which crosscut all pre-existing structures and are oriented at a high angle to the foliation. Fracture branching is common. Both features indicate rapid crack propagation at high differential stress and consequently preclude quasi-static hydraulic fracturing at $p_{fluid} > \sigma_3$. The cracks were arrested within a few milliseconds after propagating over a distance on the order of 10^0 to 10^1 meters. Shape and aspect ratio of the veins indicate opening controlled by ductile deformation of the host rock, partly localized in shear zones. Shear zone formation to be coeval with opening of the fractures and vein

formation is demonstrated by the fact that the quartz veins nowhere cut through the shear zones, and that the shear zones nowhere deform the quartz veins. This indicates that both structures were formed simultaneously in a single stage of inhomogeneous deformation. The structures developed during ductile deformation were controlled by the cohesionless fissures and developing cavities, which were progressively sealed by quartz precipitated from the percolating fluid. In contrast, later deformation of the completely sealed veins is subordinate. Hence, the stage of considerable ductile deformation of the host rock was entirely concomitant with fluid flow and vein formation, and followed on quasi-instantaneous loading and brittle failure at temperatures near 500˚C, indicating a short-term, episodic process. The record is therefore interpreted to reflect co-seismic loading by stress-redistribution near a seismogenic fault (stage 1), followed by ductile deformation of a highly permeable crust with an initially high strain rate, referred to as postseismic creep (stage 2). All subsequent deformation of the completed veins (stage 3) is comparatively insignificant and has in part taken place at a later stage of exhumation and lower temperatures. If this is true, coseismic stress re-distribution in the middle crust at temperatures as high as 500˚C can lead to fracturing and subsequent rapid ductile deformation of the fractured rock during postseismic stress relaxation. Development of cavities controlled by ductile flow of the host rock occurs at a rate exceeding the rate of sealing, which implies a transient very high permeability. Identification of such record in exhumed rocks provides insight into details of distributed coseismic damage and postseismic creep at depth, which may become important for an improved understanding of the earthquake cycle and the inversion of geodetic data.