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Viscosity structure in the lithosphere inferred from observed post-seismic deformation

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Satellite-based geodetic observations (GPS and/or InSAR) can provide precise constraints on the mechanisms that drive stress-relaxation following an earthquake [e.g., Hager et al., Annu. Rev. Earth Planet. Sci., 19, 351, 1991; Massonnet & Feigl, Rev. Geophys., 36, 441, 1998]. Among several post-seismic deformation mechanisms, visco-elastic relaxation may be the dominant component of long period and long wavelength deformations observed following earthquakes. The choice of rheological model is important if these deformation fields are to be modelled. Several transient rheological models have been proposed to explain observed post-seismic deformation, which appears to require greater viscosities as deformation progresses [e.g., Freed & Burgmann, Nature, 30, 548, 2004; Ryder et al., GJI, 169, 1009, 2007; Hearn et al., JGR, 114, B08405, 2009]. Alternatively, the variation of viscosity with depth may be important in explaining observed post-seismic displacement rates [e.g., Hetland & Hager, GJI, 166, 277, 2006; Riva & Govers, GJI, 174, 614, 2009].

In this study, we examine the effects of depth-dependent viscosity in the lithosphere to infer how the signature of viscous relaxation can be distinguished in the surface displacement data. Using a parallelized 3-D finite element code, oregano_ve, we solve the linear Maxwell visco-elastic response to a strike-slip fault in a rectangular block, assuming a viscosity beneath the faulted elastic layer which decreases exponentially with depth. Slip on a strike-slip fault is implemented using the split node method [Melosh & Raefsky, BSSA, 71, 1391,1981]. We compare the surface displacement histories predicted for the post-seismic viscous relaxation of a uniform viscosity (UNV) model and depth-dependent viscosity (DDV) models at different points on the surface.

Our numerical experiments show that a UNV model can well approximate DDV model behaviour, but the apparent UNV viscosity which best fits a DDV displacement history depends on distance from the fault; smaller viscosities are required at greater distances from the fault. The differences between UNV and DDV displacement histories also depend on distance from the fault. In the near-field, where elastic stress is greater, the UNV prediction can approximately mimic the DDV prediction. On the other hand, in the far-field where elastic stress is less, the mismatch can be significantly greater; the DDV model predicts a relaxation mode in which greater viscosities are inferred in later phases. The model behaviour described in this study demonstrates an important signature of DDV structure in the far-field, and suggests that the signature of other relaxation mechanisms such as aseismic-slip and/or poroelastic relaxation would possibly be captured from the mismatch in the near-field.

In this study, we also attempt to apply the model to the InSAR dataset of Ryder et al. [GJI, 169, 1009, 2007], obtained following the 1997 Manyi (Tibet) earthquake. The preliminary result of the DDV structure in the crust shows that effective elastic layer thickness is greater than depth extent of the fault. Furthermore, it is implied that horizontal variation of viscosity (smaller viscosities in the near-field) and/or relaxation mechanisms other than viscous creep in the near-field are also required to explain observed post-seismic displacement patterns. Thus, the geodetic data are not always explained only in terms of the DDV structure, but the DDV model predictions provide an important opportunity to discuss the effective elastic layer thickness in relation to the slip distribution on the fault, which offers a key to understanding of the stress-accumulation in the earthquake cycle, and the necessity of other relaxation mechanisms in the systematic way.