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Numerical Experiments on the Gravitational Instability of Continental Lithosphere

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The lithospheric mantle in continental regions is a part of the thermal boundary layer of the mantle convection system. This layer in general is intrinsically stable but, in cases where activated by tectonic deformation, it is subject to a gravitational instability which can remove all or part of the lithospheric mantle in the activated region and replace it with hot asthenenosphere. Some such mechanism has been implicated in regions as diverse as Tibet, Iran, the Altiplano, Pamir, New Zealand, western Mediterranean, and the western USA. The Southeast Carpathian region provides however one of the clearest examples of active mantle downwelling of the continental lithosphere: analysis of seismicity shows that seismically fast material in the upper 200 km beneath the Vrancea region of Romania is being stretched vertically; strains of order 100% requiring only a few million years. This deformation field is clearly not driven by surface convergence, because subduction ceased before 10 Ma and surface convergence since then has been minor under the persisting influence of the continuing collision between Adria and Europe. The depth distribution of deformation rate is explained, however, by rapidly developing gravitational instability. In the western USA, seismic, petrological, and sedimentological evidence have been cited in explaining the Isabella anomaly beneath the southwestern Sierra Nevada as a manifestation of mantle downwelling. In this case the downwelling occurs without seismic activity and the instability was possibly triggered by extension rather than convergence. Because this gravitational instability is inferred to develop quickly relative to the characteristic time scale of thermal diffusion it can be represented as a type of Rayleigh-Taylor instability. We have carried out numerical experiments which simulate the Rayleigh-Taylor instability using the Lagrangian-frame finite deformation programs basil (2D) and oregano (3D). The mantle downwelling, where inferred from observation, is typically localised rather than sheet-like, and the 3D capability is important in exploring the influence of laterally varying properties and non-Newtonian viscosity on the development of the instability. Using 3D calculations we show the effect of pre-existing structure in determining how and where lithospheric downwelling develops under the influence of a regional lithospheric stress field. With regional convergence, downwelling preferentially develops beneath a weak zone even if it strikes oblique to the direction of convergence. Along-strike localization of the downwelling mantle flow typically characterizes these experiments. In 3D these Lagrangian frame calculations are limited by the distortion of the tetrahedral finite element mesh, but in 2D we have implemented a dynamic mesh re-gridding scheme which enables deformation to be calculated for very large finite strains, at relatively high numerical resolution. Using these 2D calculations we investigate the extent to which lower crust may be entrained when downwelling occurs in the mantle, and how surface observations could be used to constrain the effective viscosity profile of the crust and lithospheric mantle. Spatial variation of effective viscosity (and, more generally, the type of constitutive relation) exert a dominant influence on the range of dynamical behaviours observed in our numerical experiments. The strong dependence of effective viscosity on temperature and composition (among other factors) thus can explain much of the highly variable response of the continental lithosphere observed in diverse tectonic situations.