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Strength of the lithosphere: long-term effects of short-term melt-induced weakening

Taras Gerya
ETH-Zurich, Institute of Geophysics, Department of Earth Sciences, Zurich, Switzerland (taras.gerya@erdw.ethz.ch)

Long-term strength of the lithosphere is often assumed to be equivalent to its volume-time-averaged deviatoric stress level. However, this definition is only correct for a homogeneous visco-elastic material, in which no localized (in both space and/or time) weakening processes occur. In all other cases the long-term material strength should be defined as an average amount of work needed to produce a unit of irreversible (i.e. inelastic) deformation. This defines strength as a ratio of the integral (through volume and time) mechanical energy dissipation to the integral strain, which in turn makes strength to be a strain-averaged rather than volume-time-averaged quantity (Gerya et al., 2015). As the result, paradoxical behavior can occur when long-term strength of the lithosphere can be significantly lower than its average long-term deviatoric stress level. Such behavior is in particular intrinsic for fluid- or melt-bearing visco-elasto-plasic mantle and crustal rocks showing various strain localization phenomena. Melt-induced weakening can play critical role for enabling lithospheric deformation in the areas of intense mantle-derived magmatism, such as mid-ocean ridges, rift zones and hot spots. It implies significant reduction in the long-term brittle strength of the deforming lithosphere subjected to frequent melt percolation episodes. Such weakening corresponds to conditions when shear stress reaches the tensile yield strength of rocks at nearly equal melt and solid matrix pressures. The dominant features of melt transport in this regime are planar, sharply localized zones (dykes) in which melt is transported though the lithosphere from the source region. Mechanical energy dissipation balance shows that the long-term effective strength of the melt-weakened lithosphere is mainly defined by the ratio between melt pressure and lithostatic pressure along dykes during short dyke emplacement episodes, which control most of the lithospheric deformation and mechanical energy dissipation. We quantified the range of expected values of the lithospheric strength by performing 2D numerical hydro-mechanical experiments on melt-bearing rock deformation as well as seismo-mechanical experiments on long-term lithospheric deformation assisted by frequent short-term dyke propagation episodes. These numerical experiments shows that the long-term lithospheric strength in the areas of intense magmatism can be as low as few MPa and is critically dependent on the availability of melt for enabling frequent episodes of dyke propagation through the lithosphere. Short-lived visco-plastic deformation is localized along propagating weak dykes whereas bulk of the lithosphere only deforms elastically and is subjected to large deviatoric stresses. The experiments suggest that it is not the high strength of the elastically deforming strong lithospheric blocks but the low strength of visco-plastically deforming dykes that define the long-term effective strength of the lithosphere. Thus, the low long-term strength of the melt-weakened lithosphere could be associated with high volume-averaged deviatoric stress level for this lithosphere. Possible geodynamic implications of melt-induced weakening for modern and early Earth tectonic processes are discussed.

Gerya, T.V., Stern, R.J., Baes, M., Sobolev, S., Whattam, S.A. (2015) Plate tectonics on the Earth triggered by plume-induced subduction initiation. Nature, 527, 221-225.