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Non-lithostatic pressure and its causes by thermal, hydrological, mechanical and chemical processes

Stefan Markus Schmalholz, Evangelos Moulas, Yuri Podladchikov, and Annelore Bessat
University of Lausanne, Institut de sciences de la Terre, Lausanne, Switzerland (stefan.schmalholz@unil.ch)

Many geologists and petrologists assume for geodynamic interpretations that pressure in the Earth in depths greater than a few kilometers is lithostatic because differential stresses would relax by viscous flow on long time scales (> 1 to 10 Ma). However, it is well known that the existence of oceans and continents and the associated bimodal distribution of topography and crustal thickness is decisive evidence that pressure in continental and oceanic plates is not lithostatic over geological time scales because otherwise continents would have flown apart and covered everywhere the denser oceanic rocks resulting in a vertically-only density stratification with lightest material on top and heaviest material at the bottom. Force balance calculations show that the average differential stress across a 35 km thick continent must be ca. 80 MPa so that the continent does not flow apart. Similar force balance calculations for the India-Himalaya-Tibet system even indicate that ca. 100 MPa differential stress in average across a 100 km thick lithosphere is required to maintain the Tibetan plateau for a duration of ca. 10 Ma. Furthermore, plate tectonic features such as lithospheric flexure around subduction zones and seamounts indicate locally maximum differential stresses of up to 1 GPa. In addition to these large scale features there are also mineral-scale observations indicating significant non-lithostatic pressure. For example, the existence of exhumed coesite in garnet indicates deviations of the lithostatic pressure of more than 1 GPa in order to maintain the high pressure in the coesite within the garnet during its exhumation to the surface.

There are many more thermal-hydrological-mechanical-chemical (THMC) processes and observations indicating significant (> 100 MPa) differential stress, and hence, non-lithostatic pressure. Here, we (i) present an overview and classification of processes causing non-lithostatic pressure on all geological spatial and temporal scales, (ii) provide estimates for the magnitude of non-lithostatic pressure and (iii) present natural examples and residual stress estimates from Raman spectrometry and high-resolution electron backscatter diffraction (HR-EBSD). Generally, non-lithostatic pressure can be caused by (i) mechanically-driven processes, such as applied tectonic stress or burial of rocks with heterogeneous bulk moduli, (ii) thermally-driven processes, such as temperature increase due to shear heating or magmatic intrusions, and (iii) hydrologically-chemically-driven processes, such as dehydration reactions or compositional changes by solid-state diffusion. These processes can be alternatively classified into processes for which the deformation is either dominated by near-incompressible or compressible deformation. A formidable challenge for future research is to quantify non-lithostatic pressure in rock caused by THMC processes, understand its impact on tectono-metamorphic processes and to obtain more natural and experimental evidence.