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Lithosphere rheology and dynamics: interplays between models and data (Stephan Mueller Medal Lecture)

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Our vision of the mechanisms of lithosphere dynamics and mantle-lithosphere interactions becomes less and less blurred. Yet, many key questions remain open due to the (principally) insufficient observational and experimental constraints. For instance, the effective rheological parameters are still poorly known, and the respective roles of the mantle and lithosphere in tectonic and geodynamic processes are not sufficiently well understood, specifically in terms of their inferences for the dynamic topography, collision processes and continental breakup, formation of passive continental margins, feedbacks between tectonic and surface processes, formation of large-scale faults, intraplate seismicity, survival and destruction of cratons. For continents and continental margins, the uncertainties of the data are especially considerable due to the complex structure and history of continental plates. For example, in one continental rheology model, dubbed "jelly sandwich", the strength mainly resides in crust and mantle, while in the alternative models the mantle is weak and the strength is limited to the upper crust. In this context, thermo-mechanical multi-physical numerical modelling has become an essential tool for studying complex lithosphere-scale processes, for testing, validating and verifying rheological, geodynamic and geological concepts and, moreover, for providing stronger constraints on … the data itself. State-of-the-art models account for rheological and mineralogical structure of the lithosphere, phase changes and fluid circulation, and implement high resolution calculations, so that their outputs can be directly matched with multi-disciplinary geological and geophysical observations. I here will review the advances in understanding the lithosphere rheology and mechanics and its interactions of the lithosphere with the mantle, first, by discussing the constraints from rock mechanics, elastic thickness, earthquake data and long-term observations and, second, by examining the physical plausibility of various rheological assumptions within numerical models. For the latter, I present the results of thermo-mechanical numerical experiments aimed at testing the possible tectonic and geodynamic implications of different rheological assumptions in a number of geodynamic settings. In particular, we show, on the basis of the numerical experiments, that even if there is certainly no single rheology model for continents, the "jelly sandwich" concept with "dry" olivine flow law and ductile lower crust seem to represent better the long term behavior of the lithosphere in most geodynamic scenarios. I then discuss the results of recent numerical models of mantle-lithosphere interactions. In particular, we show that the dynamic topography is strongly reduced and modulated due to the complex mechanical response of the continental crust, while, in presence of active mantle upwellings, even very weak far-field forces are both sufficient and necessary for initiation of localized continental breakup , narrow rifting or for formation of mega-scale strike-slip faults. These findings demonstrate the dominant role of the thermos-rheological structure of the continental crust and of the far-field stress/velocity conditions and intra-plate stresses in controlling surface and lithospheric dynamics during mantle-lithosphere interactions.