Role of lithospheric-scale geological heterogeneity in continental lithosphere dynamics

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Starting from our analysis of the Alpine orogen in 4D-MB (Spooner et al. 2022), we analysed how the Alps compare to other parts of the Alpine-Himalayan collision zone (AHCZ). We find that all orogens in the AHCZ exhibit characteristic diffused seismicity compared to the intraplate regions (Storchak et al. 2013). Interestingly, they also show a thicker-than-average silica-rich upper crust and total crustal thickness, while their lithosphere thickness has been shown to be similar to that of stable continental interiors (e.g., Tibet, Zagros Priestley et al. 2018). These observations provide a metric for the lithospheric-scale geological inheritance, the role of which we aim to understand in continental lithosphere dynamics over geologic timescales. We use data-driven modelling to compute the present-day thermomechanical state of the AHCZ lithosphere (Cacace & Scheck-Wenderoth 2016). To do so, we first compute 3D steady-state temperature distribution in the AHCZ considering variations in the crustal layers from published models with representative radiogenic heat production and thermal properties. The temperature boundary condition is fixed at the surface to 15^{o}C and at the base of the model (200 km) is derived from the conversion of seismic tomography models. We then compute the differential stress distribution for the AHCZ using equilibrium 3D temperature distribution and laboratory-derived rheological properties representative for each layer in the model.

Our results (Kumar et al. 2023) indicate the existence of a critical crustal thickness, which is thermodynamically controlled by the internal energy and chemical composition of the crust. The value of this critical crustal thickness matches the global average of continental crust thickness. Orogenic lithospheres with thicknesses above this critical value possess higher potential energy and are weakened by the internal energy from heat-producing elements, whereas continental intraplate regions with thicknesses close to the critical crustal thickness are stronger. Weaker orogenic lithospheres deform via dissipating this energy in a diffused deformation mode, leading to zones of deformation in contrast to focused deformation at the plate boundaries.

The observed crustal differentiation in the AHCZ could be understood as perturbations to the critical crustal thickness caused by plate-boundary forces. The dynamic evolution of these perturbations (Houseman & Houseman 2010) indicates that the critical crustal thickness is a stable fixed-point attractor in the evolutionary phase space of the continental lithosphere. The exact characteristics of the evolutionary path depend on the amplitude of perturbations, the source of the initial driving energy, and the relaxation time scale of the active dissipative process (thermal diffusion and/or viscous deformation). Typical ranges of thermal properties and viscosities of the continental lithosphere suggest that the thermal diffusion always lags the viscous relaxation giving rise to a thermodynamic feedback loop between thermal and mechanical relaxation of the out-of-balance energy in the orogenic lithosphere. Exponentially growing energy states, leading to runaway extension are efficiently dampened by enhanced dissipation from radioactive heat sources. This eventually drives orogens with their thickened radiogenic crust towards a final equilibrium state.

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