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Formation of orogenic wedges and tectonic nappes during continental collision

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The concept of an orogenic wedge has been applied to explain the tectonic evolution of many orogens worldwide. Orogenic wedges are characterized by (1) a first-order shear zone which underthrusts the mantle lithosphere and lower crust beneath the adjacent mantle lithosphere and (2) a sequence of second-order shear zones which form tectonic nappes mainly in the upper crust. Shear zone and tectonic nappe formation in a deforming lithosphere is, however, incompletely understood.

We perform two dimensional thermo-mechanical numerical simulations of lithospheric shortening to study shear zone and tectonic nappe formation, and associated nappe stacking and orogenic wedge formation. The only initial perturbation in the model lithosphere is a different temperature at the left (1300 °C) and right (1400 °C) half of the model bottom. The simulations show the self-consistent and spontaneous formation of first- and second-order shear zones which result from a conversion of mechanical work into heat and the associated thermal softening due to temperature-dependent viscosity. The shear zone thickness is physics-controlled, hence mesh-insensitive, and numerically resolved in the simulations. The numerically calculated differential stress (30 – 260 MPa), temperature (280 – 380 °C) and strain rate (10-13 s-1) inside ductile crustal shear zones agree with corresponding estimates for natural shear zones. This agreement between modelled differential stress, temperature and strain rate with corresponding natural estimates supports previous results which indicate that thermal softening is a controlling softening mechanism for natural shear zone formation. Temperature increase inside crustal shear zones is ca. 100 °C. The tectonic overpressure inside upper crustal shear zones is up to 250 MPa and can be twice the value of the corresponding deviatoric stress.

Lateral spacing of upper crustal shear zones is controlled by the depth of the upper/lower crust boundary which acts as mechanical detachment level. Modelled upper crustal shear zones are typically active between 1 and 4 My and their spacing is approximately 50 km. Surface processes such as sedimentation and erosion influence orientation, spacing and activity time of shear zones but do not impact the fundamental process of shear zone formation and propagation.

Simulations produce both singly-vergent and doubly-vergent wedges. Topographic uplift rates are controlled by the applied bulk shortening rate whereby slower shortening rates cause smaller uplift rates. The results could explain thick-skinned tectonics and basement cored uplift in natural orogens such as the Laramide orogen, Taiwan or the Shillong plateau associated with the Himalaya. The modelled, subsequent ductile shear zone formation could also explain the evolution of the Greater Himalayan Sequence. Furthermore, the modelled surface uplift and subsidence associated with crustal shear zones could explain major consecutive thrusting events and related sedimentation during the formation of the Helvetic nappe system in Western Switzerland.