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Late-stage orogenic processes: How to link surface motion with distinct lithospheric processes

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There is still a lack of knowledge of surface expression caused by deep-seated lithospheric processes, and how such processes could be distinguished from other, e.g. climate-induced, surface processes like denudation. Surface expressions of deep-seated lithospheric processes in convergent settings are expected to have been long-lived and to show large wave-length structures creating a dynamic topography (Wortel and Spakman, 2000; Cloetingh and Ziegler, 2007). Resulting continent-continent collisional orogens are bivergent, and the principal vergency of collisional orogens is controlled by the previous subduction of oceanic lithosphere (Beaumont et al., 1996). A number of tectonic processes are shown to be active during late orogenic phases and these processes particularly result in specific patterns of surface uplift and denudation of the evolving orogens as well as subsidence in the associated foreland basin. A number of these processes are not fully understood. Late-stage orogenic processes include, among others, slab break-off, slab delamination respectively of lithospheric roots, back-thrusting, tectonic indentation and consequent orogen-parallel lateral extrusion and formation of Subduction-Transform Edge Propagator (STEP) faults acting on the subducting lithosphere (Molnar and Tapponnier, 1975; Wortel and Spakman, 2000; Ratschbacher et al., 1991; Govers and Wortel, 2005). Here, we discuss these processes mainly in terms of their near-surface geological expressions within the orogen and the associated foreland basins, and how these processes could be distinguished by such geological features. We also show distinct theoretical models applied to the arcuate Alpine-Balkan-Carpathian-Dinaric system, which is driven by the oblique convergence of Africa-Europe.

Slab-break-off results in lateral orogen-parallel migration of sharp subsidence in a linear belt in front of the slab window, coupled subsidence and subsequent uplift/basin inversion of peripheral foreland basins, linear orogen-parallel migration of sudden uplift of central portions of the orogen and magmatism during slab-tearing. In contrast, slab delamination results in widespread uplift/basin inversion and also widespread surface uplift and magmatism (e.g., Platt et al., 2003).

Subduction-Transform Edge Propagator faults (STEP faults; Govers and Wortel, 2005) also induce lateral orogen-parallel migration of sharp subsidence in a linear belt in front of the lateral slab window (tip of STEP fault), uplift/basin inversion, laterally linear, orogen-parallel migration of sudden uplift and magmatism during slab-tearing. Subsidence could be induced by back-arc extension after retreat and passage of the orogenic wedge.

Intraplate back-thrusting/orogenic shortening results in a continuous signal of subsidence by growing orogenic load, growth structures at the orogen-facing basin margin, lateral migration in the case of transpressive (oblique) shortening and continuous surface and rock uplift in the orogenic wedge with a lateral gradient across the orogenic wedge.

Tectonic indentation and lateral extrusion is a consequence of rheological contrast and the shape of the weak orogen and involved rigid plates as well as of the orientation of convergence (Molnar and Tapponnier, 1975; Ratschbacher et al., 2001). It results in a similar, but continuous signal during back-thrusting/orogenic shortening in the orogen and subsidence in the foreland by growing orogenic load, growth structures at the orogen-facing basin margin and lateral migration in the case of transpressive shortening. Partitioning of deformation and surface uplift in the extrusion wedge and indentor is common. The extrusion wedge often shows a lateral gradient in surface motion, strong surface/rock uplift at the tip of the indentor, increasing subsidence further away in the extrusion wedge. In contrast, the indentor itself displays little surface uplift.

Consequently, the most distinct effects between various late-stage orogenic processes are temporal-spatial variations of vertical surface motion, kinematics and magmatism. A close inspection of the models shows that

only a combination of observations in the foreland basin and within the orogenic wedge is distinctive for specific models, and solutions are not necessarily unique. However, lateral migration of magmatism and subsidence in the foreland basin and lateral migration of surface uplift are distinct for slab break-off and STEP faults, whereby the proposed migration direction is opposite. Consequently, a combination of various methods, e.g. low-temperature geochronology, kinematic studies and dating of volcanic rocks, is needed to distinguish between tectonic processes in question.

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