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Orogenesis and Subduction in Analogue Models

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Summary

Orogenesis is often the result of a collision between tectonic plates. The evolution and large-scale geometry of mountain belts vary, and is mainly governed by interplay between several geodynamic conditions and processes. Important parameters during orogenesis are for instance the total amount of plate convergence, and the relative motion as well as the velocity of the colliding plates. In addition, rheological conditions, referring to the strength of the plates and the evolving orogen, play an important role during orogenesis as they are strongly dependent on composition, pressure, and temperature.

The response of a tectonic plate (lithosphere) during collision is by thickening, folding, or subduction. Oceanic lithosphere easily subducts, while continental lithosphere mostly thickens or folds. Geophysical research on the deep subsurface of mountain chains has shown that thickening and subduction can also coincide. In this scenario, the mantle lithosphere undergoes subduction; meanwhile the crust is scraped off and thickens into a wedge geometry (orogenic wedge). Since orogenesis is a very slow process, and the deep sub-surface is inaccessible to direct observations, insights on the interaction between mantle subduction and crustal thickening are so far limited. A better understanding of continental collision zones demands for an integrated approach involving geological and geophysical interpretations as well as a combination of several modelling techniques.

The aim of this thesis is to investigate the mechanical interaction between continental mantle lithosphere subduction and mountain building. With the use of analogue modelling, the favorable mechanical boundary conditions for subduction of the continental mantle lithosphere are first determined. Subsequently, the consequences of these boundary conditions on the development of the overlying orogen are studied in more detail. Emphasis is put on the large-scale geometric similarities between the model results and mountain ranges worldwide.

Throughout this thesis, the evolution of the Alps is an important theme. Therefore the tectonics of the Alps has been investigated in detail, and includes several interesting along-strike variations. On a relative short distance these variations comprise the total width of the orogenic wedge, the timing and vergence of nappe stacking, and the amount of exhumed high-grade metamorphic rocks. At a deeper level, recent geophysical studies have revealed a lateral subduction polarity change, indicating southward subduction of the European mantle lithosphere below the Western- and Central Alps, but northward subduction of the Adriatic mantle lithosphere below the Eastern Alps. This research elaborates on a possible correlation between this “subduction-flip” and the crustal variations observed at shallower depths. First, we investigate if a lateral change in subduction polarity has an imprint on the overlying crustal architecture. Second, if this is the case, we discuss whether certain crustal structures within the Alps can be interpreted in the context of a subduction polarity change at depth. A combination of lithosphere- and crustal-scale analogue modelling together with a detailed field study has been used to address these questions.

Based on the regional distribution of cooling ages throughout the Eastern Alps, insights can be gained on the exhumation history of the orogen. In this context, Chapter 2 presents a compilation of geochronological data, which documents the post-collisional cooling history of the Eastern Alps. The cooling ages were derived from Rb/Sr and Ar/Ar isotope ratios, and zircon or apatite fission tracks. The results portray cooling restricted to the Tauern Window during the early Miocene, followed by regional exhumation during the late to middle Miocene. Exhumation of the Tauern Window occurred relatively fast, and was coincided by normal displacements along both the Brenner- and Katschberg faults, as well as erosion in response to large-scale folding. This indicates a strong interplay between N-S shortening and E-W extension during exhumation of the TW.

The first series of analogue models, presented in Chapter 3, provide insights on the mechanical boundary conditions allowing for subduction of the continental mantle lithosphere. It turns out that the geometry and the rheology of the plate boundary play important roles. A 45° dipping plate boundary and the presence of a weak lubricator are needed to initiate subduction. It also appears that the mantle lithosphere only subducts if it is able to decouple from the overlying crust. With ongoing subduction, deformation of the crust remains localized close to the plate boundary. Only if subduction hampers, for instance by consumption of a lubricator or by limitation of crust-mantle decoupling, both plates begin to deform internally.

In the presented analogue models, decoupling between the crust and the mantle lithosphere occurs along rheological boundaries. Hence, the use of a weak lower crust promotes decoupling. However, the experiments presented in Chapters 4 show that varying the rheological stratigraphy of the lithosphere may also have consequences for the build-up of an orogen. The presence of a decoupling horizon in the lower plate results namely in widening of the orogenic wedge towards the foreland. On the other hand, limiting the decoupling horizon to the plate boundary will produce a relative narrow wedge. In addition, the above experiments emphasize the role of the degree of decoupling on the total amount of subduction of mantle lithosphere, the initiation of retro-shears, and the evolving topography of the orogen.

Within Chapter 5, a second, more advanced, series of analogue experiments shows that a lateral transition of subduction polarity can have a strong influence on the geometry of the orogen. This influence is in particular underlain by a lateral interaction between the adjacent domains of opposing subduction polarity. At mantle depth, interaction between the subduction domains results in the development of a transition zone, in where the amount of subduction is limited, while the upper plates bend down significantly. Hence, within the transition zone, the colliding mantle structure appears symmetric. As a result, the lower crust thickens, the orogenic wedge widens towards both plates, and topography is low. The width of the transition zone is governed by the degree of decoupling between the subduction domains. Lateral decoupling reduces interaction, while strong coupling leads to a relative wide transition zone with a clear surface expression.

The outcome of the field study on the kinematics of the Passeier- and Jaufen fault system is treated in Chapter 6. Field data interpretations indicate that these faults do not form a single fault system. The Jaufen fault underwent a ductile- and a brittle deformation phase, while the Passeier fault solely went through a stage of brittle deformation. Additionally, a tensor analysis in combination with crustal-scale analogue experiments indicates that the formation of the Passeier line can be directly related to the South Alpine indenter

geometry. This interpretation has implications for a suggested connection between the much larger Giudicarie- and Brenner faults. Although these faults may still be considered as expressions of the lateral subduction flip, a kinematic connection between these faults cannot be supported.