well as the detachment zone. These features are consistent with the N-S extensional regime still prevailing in the Southern Aegean region.

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Alpine structures and their evolution: numerical modeling and natural examples

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Recent geophysical investigations have highlighted the crustal structure of the Swiss Alps: a bivergent orogen, in which upper crustal units were stacked northwards and southwards above an asymmetric subduction geometry involving lithospheric mantle and lower continental crust. Numerical dynamic modeling explains how upper crustal material from thinned crustal sections can be subducted to greater depths, whereas in normal crustal sections the upper crust detaches from the lower crust and becomes accreted to the upper plate.

A simple conceptual model for modes of accretion, erosion and subduction at convergent margins can be described in terms of the mass flux among four components: the accretionary wedge (pro-wedge); plug uplift; retro-wedge; and the subduction zone, the latter consisting of a conduit of slowly-deforming material and a rapidly-deformed subduction channel. The subduction conduit widens or narrows in response to flexural loading of the downgoing plate and the relative fluxes of tectonic erosion, accretion and underplating. Crustal-scale models span a continuum of behaviour from single-vergence, with development of a landward dipping (pro-)shear zone, to double-vergence with formation of a seaward dipping (retro-)shear zone. Results show that single-vergent deformation occurs whenever the mass flux lost by subduction is equal to or greater than incoming mass flux. This mode can develop dynamically by flexural compensation and/or subduction retreat.

The combined action of pro-shear (nappe stacking) and retro-shear (back-thrusting) uplifts a plug between the two shear zones. Subsequent focusing of shear along the retro-shear zone results in rotation of the plug and overlying units, leading to crustal-scale backfolds. Heterogeneities in the pro-crust focus shear and lead to the development of “nappe structures“. Accretion of small continental terranes within a model subduction zone can cause crustal-scale fold nappes and shear zones to develop, with accompanying tectonic underplating and/or frontal accretion. In the case of the Swiss Alps, the entrance of the European margin into the Alpine subduction zone triggered back-thrusting along the Insubric Line and the adjacent units ultimately leading to the development of a bivergent thrust belt. Underplating and plug-uplift between pro- and retro-shear accompanied by erosion led to the exhumation of high-grade rocks in the core of the orogen. The model experiments predict features relevant to Alpine dynamics, including (1) similar crustal thicknesses and exhumation patterns, (2) continued accretion and subduction of upper crustal fragments allowing high-pressure metamorphic conditions, (3) tilting and exhumation of lower crust when a midcrustal weak zone is present, and (4) “shunting“ of material across the strong lower crustal wedge of the upper plate.

Experiments concentrating on nappe-scale structures suggest that the formation of detachment folds require a high thickness ratio between detachment horizon and the competent unit above. Imbricate thrust sheets evolve in the case where the detachment horizon is thin. Lateral heterogeneities in the cover sediments control the nappe internal structures. For example, discontinuities such as present in passive margin sequences are preferential sites for the nucleation of folds and thrust faults.

Morphogenesis: interaction between crustal and surface processes

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Morphogenesis at convergent plate boundaries reflects material fluxes at the surface and in subsurface. The fate of material entering a convergent margin is many-sided. In the simplest cases it gets subducted into the mantle, or accreted to the margin. Accretion leads to the formation of an orogenic wedge, the growth of which implies internal deformation and the creation of an elevated area (surface uplift), which in turn triggers denudation. Thus, material formerly accreted is subject to erosion and may reenter the convergent margin. Loading of the convergent margin by the growing wedge flexes the subducting plate. This process may lead to the subduction of formerly accreted material (by subduction erosion) and – in order to maintain the wedge's critical taper – to further surface uplift and erosion.

In the case of the Swiss Alps, morphogenesis resulted from a continent-continent collision which occurred in the past ca. 40 Ma. This collision led to the exhumation of high grade metamorphic rocks in the Lepontine area where denudation removed some 25 km of the nappe pile. Further north, denudation removed about 10 – 15 km of section following surface uplift owing to crustal scale folding and thrust faulting associated with the Aar massif. The large scale 1st order geomorphic characteristics of this chain include two water divides and two belts of high elevations. On an erodibility map these areas of high elevation correlate to bedrock types with low erodibility (granitic rocks).

Numerical surface process modeling was carried out to examine the coupling between surface and deep processes. Surface processes include fluviatile and hill slope diffusive mass transfer. Deep processes are modeled with tectonic forcing as deduced from the crustal evolution of the Swiss Alps. This includes two uplift maxima: an earlier uplift in the model-Lepontine area which is followed by uplift of a model-Aar massif. A model-crust with rocks of homogeneous erodibility, subjected to such an Alpine-type tectonic forcing, results in a drainage pattern dominated by very stable rivers insensitive to changes in uplift rates. These rivers maintain their course perpendicular to the orogen axis almost irrespective of changes in uplift rates or erosional parameters. A natural analog of such a behavior can be found in the Coast Range of British Columbia.

If a highly erodible unit, intended to represent a 2 km thick nappe stack of sedimentary rocks sandwiched between crystalline basement, is included in the model, the drainage pattern undergoes a profound change. Instead of incising the later forming northern model-Aar massif uplift, axial rivers get captured by headward erosion of longitudinal rivers developing along the highly erodible units. The defeat of these axial rivers is held responsible for the creation of the secondary water divide and the ensuing migration of the main water divide away from the maximum uplift of the model-Lepontine area.

Applied to the Swiss Alps the model results suggest that the primary signature of the collision, a nappe stack composed of rocks of very different erodibilities, together with the late-collisional uplift played an important role in the reorganization of the Miocene drainage pattern with axial rivers to the longitudinal rivers flowing today. In their lower course, rivers are more sensitive to tectonic uplift. An example can be found in the ancestral Aar river, which was deviated and forced around the uplifting Jura Mountains in Mio-/Pliocene times.

Ti-releasing reactions within biotites: the step from a magmatic precursor to a metamorphic biotite. SEM, TEM and electron microprobe investigations on biotites from the Kellerjochgneiss (Northern Zillertal, Tyrol, Eastern Alps)

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Petrological investigations of the Austroalpine Kellerjochgneiss show a pervasive low-T/high(?)-P metamorphic overprint, which can be attributed to the Eo-Alpine orogeny. Thermobarometric calculations yield pressures ranging from 5.5 to 10.5 kbar and temperatures ranging from 380 to 430°C. Pre-metamorphic minerals present are K-feldspar and albite porphyroblasts and biotite porphyroblasts, which now contain abundant Ti-phases which form grid-like structures (sagenite grid). The Eo-Alpine mineral assemblage is: muscovite + biotite (Ti-poor) + albite + chlorite + quartz ± stilpnomelane.

Investigations with the polarizing microscope, SEM (scanning electron microscope), TEM (transmission electron microscope) and the electron microprobe are conducted on samples from the Kellerjochgneiss and the adjacent, strongly deformed Stengelgneiss. The Ti-phases occuring within or in the vicinity of biotite are rutile, ilmenite and titanite. The presence of titanite also indicates possible reactions involving the addition of Ca by a fluid or through adjacent phases such as plagioclase and/or clinozoisite. The textural investigations of the exsolutions down to the Å-scale within the biotites should help to identify the possible reactions leading to the formation of the Ti-phases within the biotites as well as to identify possible chemical protolith domains within the biotites and determine their compositions.

Textural investigations of biotites with the polarizing microscope, SEM and microprobe show abundant Ti-phases occurring within the biotite porphyroblasts. Most biotites contain rutile needles which occur as sagenite grids. Electron microprobe analysis yields high Ti-contents of biotites of up to 5 wt% TiO_2 due to contamination of the analysis by rutile needles, whereas