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Cenozoic relief formation and mountain uplift: from the Alps towards a global perspective

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Based on the sediment budget of the Eastern, Swiss and Western Alps the regional tectonic evolution is identified as the dominant factor of erosion and uplift from the Oligocene to the late Miocene. Since the late Pliocene (2.7 Ma), regional and global climate change became the dominant factor of erosion due to cyclic glaciations.

The early post-collisional history of the Alps is characterized by doubling of sediment discharge rates around 30 Ma, attributed to isostatic and thermal of the lithosphere related to crustal thickening and slab breakoff. Until terminal Miocene time, the sediment discharge rates in the Alps varied during short-lived phases. An increase at 23-21 Ma and 18-16.4 Ma was succeeded by a decrease at 20.5-18 Ma and 16.5-13 Ma, respectively.

An important, still ongoing period of uplift, as reflected by rapidly increasing sediment discharge rates, started in terminal Miocene time in the Swiss and Western Alps and affected the Eastern Alps 1 to 2 Myrs later. The so far unknown, exact timing hinges on the stratigraphic resolution of early Pliocene deposits of the Rhone fan as the volumetrically most important sink of the Alps, and a change of the heavy mineral composition in the middle Pliocene in this fan, reflecting the catchment reorganistion of the Rhone river. The reason for terminal Miocene to Early Pliocene onset of uplift is not clear, but deep-seated lithospheric processes appear to be likely.

If various types of data from the Tethyan mountain belt in the prolongation of Alps, which constrain exhumation or erosion, show major pulses of uplift around 17, 10, 5, and 2.7 Ma. Whereas until $\sim$1992 only indirect evidence of surface uplift has been available, new methods developing since then claim, e.g., to reflect elevation-dependent paleo-pressure of gas in basalt vesicles or paleo-elevation of precipitation as reflected by oxygen isotope composition of fossils and caliche crusts. Evidence from large plateaus, which are driven up solely by tectonic forces, indicates earlier uplift, e.g. for parts of the Tibetan plateau, than previously assumed. The southern and central parts of the Tibetan plateau attained modern elevation before middle Miocene times, the southern part possibly even in Oligocene times. Since the late Miocene, at latest, the Tibetan plateau only grows laterally by uplift of crustal segments in the N and NE, and by extrusion to the E and SE. Similar observations are reported from the Altiplano in South America, which appears to have reached modern elevation during the early Miocene. North of the Altiplano, younger uplift is also observed. In North America, late Cenozoic uplift appears to have rejuvenated the Laramide orogen which had formed a high mountain belt in Early Cenozoic times and declined for tens of million years. Young uplift is inferred along the western cordillera of North America. However, time constraints for surface uplift of individual narrow Alpine-type mountain ranges remain vague, due to lack of applicable methods for direct measurements.

Increasing mountain glaciations since the late Pliocene (2.7 Ma) and potentially increasing zonal wind speed of the westerlies, forcing orographic precipitation, accelerated valley erosion. Thus, increase of local relief and isostatically forced peak uplift is partly and even largely driven by climate. Importance of positive feedback of climate and uplift since then masks or superimposes evidence of tectonically forced uplift. Presently available data indicate that Neogene mountain uplift in global scale is caused by tectonic activity in changing segments of both the Tethyan and the circum-Pacific arc, not forced by climate change prior to 2.7 Ma. Nevertheless, the causal role of climate change for global late Miocene to Middle Pliocene uplift of Alpine-type mountain chains remains controversial.