Climatic and tectonic controls on river incision and Quaternary terrace staircase formation in the Pyrenees

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10 Summaries

10.1. English summary

This study investigates the coupling of earth surface processes, climate, and tectonics, particularly focussing on fluvial incision and sediment routing in the river systems of the Pyrenees. Extensive terrace staircases in the foreland domains formed in the deeply entrenched valleys of the transverse river network of the Pyrenees. The paired (bilateral) terrace staircases in the southern Pyrenees foreland (i.e. Ebro basin) show striking similarities between the major southern Pyrenean tributary rivers as to the number and elevation of individual terrace levels and the inferred long-term (Quaternary) incision magnitudes. The amplitudes of valley entrenchment are consistent in northern Pyrenean rivers but valley cross-sections disclose asymmetric staircase geometries and non-uniform terrace extent and preservation. Aiming at unravelling the drivers of fluvial valley entrenchment and terrace staircase formation in the Pyrenees two major river systems have been investigated (i) the prominent Segre River in the southeastern Pyrenees and (ii) the Garonne River which drains large parts of the central northern Pyrenees.

Terrace staircases are composed of successions of abandoned river floodplains separated by incision scarps that result from alternating periods of extensive floodplain aggradation during cold-climate periods and phases of vertical and lateral erosion associated with climatic transitions (e.g., Vandenberghe, 2001, 2008). Such climate-triggered terrace formation is superimposed on a long-term incision trend by a river that is stream-power controlled and determined by the base level position of the fluvial network (e.g., Whipple and Tucker, 1999; Blum and Törnqvist, 2000). Long-term river incision is commonly a response to base level lowering or catchment scale uplift (Merritts et al., 1994; Maddy et al., 2001) and, hence, can only be evaluated considering the specific climatic, tectonic and base level setting of a drainage network.

At first, numerous sediment outcrops were investigated for (post)depositional structures and deformations. Major terrace levels were sampled for exposure dating via ^{10}Be cosmogenic nuclides. Field-based geomorphological mapping was combined with GIS-based DEM and stream profile analyses. In a second step, results were integrated in a numerical landscape evolution model (TISC; Garcia-Castellanos et al., 2003) that was used to assess the relative impacts of Quaternary climate change, tectonic uplift, lithospheric flexural isostasy, and differential bedrock erodibility on stream (terrace) profile development in the southern Pyrenean drainage system.

Results indicate relatively synchronous formation of the foreland terrace staircases in relation to Pleistocene glacial–interglacial climatic cycles in the Pyrenean headwaters. Accordingly, major alluvial terrace levels were formed by extensive floodplain aggradation during maximum extents of (valley) glaciers during cold-climate periods. The extensive (i.e. braided) river floodplains were abandoned during cold-warm climate transitions when rivers adapted single-channel drainage patterns and progressively incised the underlying substratum. Longitudinal terrace correlations in both northern and southern Pyrenean rivers show overall (semi)parallel terrace profiles, arguing for similar measures of gradual base-level lowering or continuous uplift of the foreland basins (and the Pyrenees) during Quaternary times.

In the Garonne, exposure dating and morphogenetic correlations across the glaciofluvial interface indicate major terrace complex development in response to successive Pleistocene glaciations in the Pyrenees (e.g., MIS 6, 4, 2), implicating that large incision scarps relate to major (glacial-interglacial) climatic transitions. The individual levels of a terrace complex are separated by smaller incision scarps that reflect less pronounced intra-glacial climatic fluctuations. Outcrop investigations in the Garonne revealed intense sediment weathering and large sediment fluxes in the northern Pyrenees resulting from persistently (sub)humid climatic conditions and powerful compound ice tongues that descended to the northern Pyrenees piedmont (e.g., Calvet, 2004).

In the Segre River extensive (cold-climate) floodplains aggraded during Marine Isotope Stage 8 (or 7), MIS 6, MIS 4, and MIS 2, but exposure ages indicate that also during warmer isotope stages with sufficient climate variability prominent terrace levels may be formed (e.g., cold stages of MIS 5). Local deformation of alluvial deposits is caused by faulting, folding, and halokinesis. Anomalies in gravel thicknesses along the Segre middle–upper reaches probably relate to local subsidence and/or sediment pulses in response to glacial outwash phases or temporary blockage of the river course.

Using a stream-power based numerical model (*TISC*) - which involves diffusive and linear surface runoff, lithospheric flexure, tectonic uplift, and runoff and sea-level fluctuations - different climatic, tectonic, and base level scenarios were tested regarding fluvial incision and terrace staircase formation in the southern Pyrenees and Ebro foreland basin. Model results show that only a scenario involving continuous Quaternary uplift and climate variability (i.e. sea-level and runoff fluctuations) generates (semi)parallel terrace profiles and realistic Middle–Late Pleistocene incision magnitudes that are in agreement with both the terrace staircase geometries in major southern Pyrenean tributary rivers (e.g., Segre, Gállego) and also the incision history inferred from the Ebro basin outlet. Based on the Ebro model, the Pyrenees and their foreland basins experience continuous (Quaternary) uplift, also providing a mechanism for staircase entrenchment in northern Pyrenean rivers (e.g., Garonne).

Based on the numerical model (*TISC*), sea-level fluctuations mainly affect the lower reaches of the Ebro network and are not a potential control of incision in the tributaries of the Pyrenees (e.g., Segre River). A large base level drop at the Ebro basin outlet, for instance caused by a (Pliocene) uplift event affecting the Catalan coastal ranges (e.g., Janssen et al., 1993), causes a rapid erosion wave along the Ebro drainage network that results in divergent terrace profiles and minor Middle–Late Pleistocene incision magnitudes. This profile development is not compatible with the (semi)parallel terrace staircases in the Ebro basin (e.g., Segre). The model also indicates that (glacial–interglacial) runoff and sea-level fluctuations cause variable incision magnitudes along the longitudinal stream profiles, with maxima occurring during periods of the highest discharge (runoff).

Lithospheric flexure is negligible in response to erosion along the main channels of the drainage network (i.e. because of little sediment volumes eroded per unit time). Isostatic rebound of the lithosphere intensifies once erosion propagates across the tributary and headwater catchments and affects the hinterland domains of the drainage network. Long-term erosional rebound of the lithosphere is uniform in the model, having an overall longitudinal gradient, perpendicular to the axis of the Pyrenees. Hence, lithospheric isostatic flexure can neither explain the different valley geometries on the northern Pyrenees piedmont nor it provides a mechanism for the asymmetric (west-lateral) terrace staircase in the (middle) Garonne that indicates a progressive eastward migration of this river during Quaternary times, probably in response to a latitudinal gradient in uplift.

Ongoing tectonic uplift in the Pyrenees region could result from lithospheric compression in response to (slow) plate convergence between Iberia and Europe, causing lithospheric folding, crustal shortening in the foreland areas, and regional isostatic rebound to erosion (Cloetingh et al., 2002; Vergés et al., 2002; Vernant et al., 2013). Alternative uplift mechanisms relate to (i) small-scale mantle convection (*dynamic topography*, Faccenna and Becker, 2010) and (ii) lithospheric unflexing due to slab detachment, convective removal, or post-orogenic heating of the lithospheric root underlying the Pyrenees (Desegaulx et al., 1991; Cloetingh, 2004; Gunnel et al., 2008; Roure, 2008; Duretz et al., 2011; cf. Baran et al., 2014). Providing further evidence for external forcing by uplift, forward model scenarios show that the present Ebro foreland drainage system is actively incising and not in (gradient) equilibrium.