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

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2014

citation for published version (APA)
Stange, K. M. (2014). *Climatic and tectonic controls on river incision and Quaternary terrace staircase formation in the Pyrenees*. [PhD-Thesis - Research and graduation internal, Vrije Universiteit Amsterdam].

6 Synthesis

6.1. Primary aims and general approach

Present-day river landscapes are the product of a long-term and ongoing morphological development, which is governed by erosion-deposition processes in fluvial systems. Fluvial erosion and sediment routing are a function of stream power and related morpho-hydrological parameters (e.g., slope, discharge, and sediment load; Whipple and Tucker, 1999; Blum and Törnqvist, 2000; Merritts, 2007) that are determined by the specific climatic and geomorphic setting of a drainage system. Fluvial landscapes around the globe comprise comparable drainage configurations (i.e. meandering, anastomosing, and braided river systems) and common morphological features such as staircases of fluvial terraces (e.g., Vandenberghe, 2001; Bridgland and Westaway, 2008; Gibbard and Lewin, 2009). This indicates that, despite the complexity of internal fluvial dynamics (e.g., Schumm and Parker, 1973; Vandenberghe, 1995; Tucker, 2004), river landscape development is subordinated to connatural fluvial mechanisms that are controlled by (globally) common climatic, tectonic, and base level parameters (e.g., Molnar and England, 1990; Bridgland, 2000; Vandenberghe, 2003; Bridgland and Westaway, 2008; Pazzaglia, 2013).

The debate on the relative impacts of climate and tectonics on fluvial landscape development has a long history and is still on-going (e.g., Molnar and England, 1990; Maddy, 1997; Van den Berg and Van Hoof, 2001; Van Balen et al., 2010; Stange et al., 2013a, b). It is known that the formation of fluvial terraces is related to climate change and associated variations in river discharge and sediment transport capacity (Tucker and Slingerland, 1997; Vandenberghe and Maddy, 2001; Cordier et al., 2006). Staircases of terraces develop in response to a combination of climate-controlled terrace formation superimposed on a long-term incision trend (Merritts et al., 1994; Maddy et al., 2001). Potential drivers of fluvial incision relate to tectonic uplift, lithospheric flexural isostasy, or the base level settings at the outlet of a drainage network (Blum and Törnqvist, 2000; Bogaart and Van Balen, 2000; Maddy et al., 2001; Tucker, 2004).

The structurally determined, transverse river network of the Pyrenees (Jones, 2002, 2004; Stange et al., 2013a, 2014a) features deeply incised valleys with extensive terrace staircases that are well-suited to investigate the (external) drivers of staircase formation and incision. This is because the fluvial systems of the Pyrenees show striking similarities in long-term incision magnitudes and terrace staircase development (Lewis et al., 2009; Stange et al., 2013b, 2014a) disregarding geomorphic and climatic differences associated with the structure and exposure of the mountain range (e.g., double-wedge asymmetry, orographic effect on precipitation; Lewis et al., 2000; Calvet, 2004; Lynn, 2005). Aiming at assessing the relevant (external) drivers for long-term incision and terrace staircase formation in the Pyrenees, we applied a range of geomorphological methods, including digital and field-based terrain analyses, longitudinal stream (and terrace) profile analyses, outcrop surveys on terrace and moraine deposits, terrace exposure dating via cosmogenic nuclides, morphogenetic correlations between the glacial and the proglacial fluvial systems, and integrated numerical landscape evolution modelling.

6.2. Pliocene–Quaternary drainage development in the Pyrenees

In the southern Pyrenean foreland (Ebro basin), extensive pedimentation surfaces witness extensive denudation of the Pyrenean piedmont and indicate a gentle, low gradient palaeo-topography at (or before) the Pliocene–Quaternary transition (Mensua and Ibañez, 1977; Peña, 1983; Rodríguez Vidal, 1986, Sancho, 1991). Initial fluvial entrenchment of the present Ebro drainage network started in the early Quaternary. Palaeomagnetic age constraints on the oldest (preserved) alluvial terrace levels (180–190 m a.f.; Lewis et al., 2009; Peña et al., 2011) indicate the onset of valley incision and terrace formation prior to the Matuyama-Brunhes magnetic reversal (i.e. > 780 ka, Cinca River; Sancho et al., 2007).

In the (northern) Aquitaine foreland basin, the (late) Pliocene is associated with the final stages of important fan accretion at the Pyrenean piedmont (Taillefer, 1951; Icole, 1974). The limited extent of the Pliocene fans and the lack of preserved alluvial deposits suggest that long-range sediment transport by the North Pyrenean Rivers was insignificant during Pliocene times (Dubreuilh et al., 1995). Presumably around the Pliocene–Pleistocene transition, these rivers gained importance and began to gradually incise their valleys, involving considerable initial drainage redirections along the foreland transition. Stratigraphic and morphogenetic constraints on the oldest Quaternary alluvial deposits (e.g., 180 m a.f., Garonne River, Cavaillé 1965; Icole, 1974; Hubschman, 1975c) suggest that the initial fluvial entrenchment of the northern foreland fans (i.e. 15–20 m, 180 m a.f.; Cavaillé 1965; Dubreuilh et al., 1995) is consistent with the Pliocene–Quaternary drainage history in the southern (Ebro) foreland basin.

During the Early–Middle Pleistocene, the fluvial systems of the Pyrenees continued to incise. Successions of (alluvial) terraces indicate a stepwise downcutting of the river valleys. Since approximately Middle Pleistocene times, vertical entrenchment of the valleys intensified and extensive terrace staircases developed in the foreland basins of the Pyrenees (Stange et al., 2013b). The Middle–Late Pleistocene incision magnitudes are relatively uniform across the Pyrenees (i.e. 120–100 m; e.g., Lewis et al., 2009; Stange et al., 2013a,b, 2014a,b), but staircase geometries disclose considerable differences: in the Ebro basin, terrace staircases are overall symmetric, including 4–10 (bilateral) terrace levels (e.g., Mensua and Ibañez, 1977; Peña 1983; Rodríguez Vidal, 1986; Sancho, 1991; Luque and Julià, 2007; Lewis et al., 2009; Stange et al., 2013a, 2014a). The North Pyrenean Rivers feature 4–9 terrace levels (e.g., Hubschman 1975a,b,e; Carozza and Delcaillau, 1999; Calvet et al., 2011, Lacan et al., 2012; Stange et al., 2014a), but valley geometries are diverse, comprising both symmetric terrace staircases (e.g., upper middle Garonne; Adour) and asymmetric, left- or right-lateral terrace staircases (e.g., Garonne, Ariège; Stange et al., 2014a). The heterogeneity of drainage modifications in the Aquitaine basin hints at regionally different tectonic (or climatic) forcing during Middle–Late Pleistocene times.

6.3. External controls on incision and terrace staircase formation

6.3.1. Climate

Fluvial terrace staircases witness a cyclic repetition of floodplain aggradation and incision that is related to fluctuations in sediment supply and discharge (Tucker and Slingerland, 1997; Hancock and Anderson, 2002; Tucker, 2004; Sklar and Dietrich, 2006) in response to climate change (Schumm, 1977; Bull, 1990; Vandenberghe, 2002, 2008; Bridgland and Westaway, 2008). A number of terrace series suggest that in Quaternary fluvial systems terrace formation is linked to Pleistocene glacial–interglacial climate cyclicity (e.g., Antoine, 1994; Kasse et al., 1995; Bridgland, 2000; Maddy et al., 2001; Cordier et al., 2006): aggradation of extensive floodplains is caused by excess supply in glacio-fluvial sediment during cold-climate periods (e.g., braided river systems; Vandenberghe, 2001). Fluvial incision (erosion) prevails during climatic transitions (e.g., higher flood frequencies, thawing permafrost; Bridgland, 2000; Cordier et al., 2006; Vandenberghe, 2008), but fluvial response to climate change may be delayed and non-linear (e.g., Schumm and Parker, 1973; Schumm, 1977; Vandenberghe, 1995; Tucker and Slingerland, 1997). We looked into these backgrounds by combining modelling, terrace exposure dating, and geomorphological research on two river systems in the Pyrenees, the Segre River in the southeastern Pyrenees, and the Garonne River in the central northern Pyrenees.

The glacio-fluvial systems in the Pyrenees feature widespread glacial morphology with numerous moraines denoting extensive (Middle–Late) Pleistocene glaciations (Calvet, 2004; Calvet et al., 2011) –but owed to persistent climatic differences glacier extents were non-uniform across the chain (Taillefer, 1969; Calvet, 1994, 2004; Garcia-Ruiz et al., 2003). In the northern Pyrenees (i.e. 75% of the previously glaciated domains; Taillefer, 1984; Calvet, 2004), valley glaciers descended as far as the northern piedmont (e.g., Hérail et al., 1987; Delmas et al., 2011). In the southern Pyrenees ice tongues were less powerful and remained restricted to the interior valleys of the mountain range (e.g., Sancho et al., 2004; Turu and Peña, 2006a,b; Lewis et al., 2009; Garcia-Ruiz et al., 2013; Stange et al., 2013a). Exposure dating on moraines across the Pyrenees indicates maximum ice extent during Marine Isotope Stage 6 (Lewis et al., 2009; Delmas et al., 2011; Garcia-Ruiz et al., 2011) while several glacier re-advances occurred during MIS 5–2 (Pallàs et al., 2006, 2010; Delmas et al., 2008, 2009), involving close to maximum ice extent during MIS 4 (Delmas et al., 2011; Stange et al., 2014a). MIS 3 was marked by unsteady, fluctuating ice fronts (Delmas et al., 2011). The last significant ice advance in the Pyrenees occurred during early MIS 2 and was thus not synchronous with the Last Glacial Maximum in northern Europe (Calvet et al., 2011; Delmas et al., 2011).

Previously established glacio-fluvial chronologies for the southern Pyrenean rivers (e.g., Valira-Segre, Cinca, Gállego; Peña, 1983; Turu and Peña, 2006a,b; Lewis et al., 2009) indicate a close link between terrace formation and glacier fluctuations in the Pyrenean headwaters. We tested this hypothesis with regard to the Segre River terrace staircase, using new exposure age constraints for its major terrace levels.

Segre River (southern Pyrenees)

The Segre terrace staircase consists of seven (semi)parallel terrace levels separated by incision scarps of 6–30 m (Stange et al., 2013a), comprising (cut-and-)fill-type terraces associated with the younger (lower) levels, and older strath-type bedrock terraces with 2–7 m thick alluvial cover. A cold-climate origin of the coarse alluvial gravel is denoted by sand-filled (braided) channels, backfilled periglacial soil cracks, and occasional angular, probably ice-rafted boulders (e.g., Stange et al., 2013a,b). Local anomalies in gravel thickness (e.g., > 15 m) along the upper and middle Segre hint at episodic sediment pulses from the Pyrenean headwaters (e.g., glacial outwash phases; Stange et al., 2013a).

Cosmogenic terrace exposure ages represent minimum estimates on the abandonment of a terrace as an active river floodplain (e.g., Carcaillet et al., 2009). Accordingly, exposure ages obtained from the high and middle terraces in the Segre reflect terrace abandonment and the onset of incision at the end of cold-climate phase MIS 5d and glacial stages MIS 4 and MIS 6 (Stange et al., 2013b). Hence, the Segre terrace chronology is in agreement with terrace aggradation during cold-climate periods and reinforced fluvial erosion (incision) in the course of cold–warm climate transitions (e.g., Cordier et al., 2006; Vandenberghe, 2008).

In the Segre, the onset of intensified valley entrenchment is associated with the abandonment of high terraces that are preserved on remnant hills along the lower reaches. Age constraints on these terraces indicate their development in relation to the maximum Pyrenean ice extent during MIS 6 (Calvet et al., 2011; Garcia-Ruiz et al., 2011). Exposure ages from the Noguera Ribagorzana River, however, suggest an earlier onset of valley entrenchment and staircase formation already during MIS 7–8 (202 ka the latest; Stange et al., 2013b). The Segre terrace chronology is relative consistent with other fluvial systems in the southern Pyrenees (e.g., Gállego, Cinca, Segre–Valira; Turu and Peña, 2006b; Lewis et al., 2009), and accordingly the lower terraces of the Segre were formed most likely in response to glacier fluctuations during MIS 3–2 (e.g., Peña et al, 2005; Lewis et al., 2009; García-Ruiz et al., 2013).

Garonne River (northern Pyrenees)

Staircase geometries in the Garonne include both symmetric (bilateral) terraces situated along-strike of the mountain front and an extensive left-lateral terrace staircase in the foreland (e.g., lower middle reaches; Stange et al., 2014a). Distinctive sediment weathering in combination with morphogenetic analyses have shown to be useful for longitudinal terrace correlations between the different staircase configurations (e.g., Cavaillé, 1965; Icole, 1974; Hubschman, 1975a-f). The staircases in the Garonne feature four major terrace complexes including eight (semi)parallel terrace levels and the present-day active floodplain (Stange et al., 2014a). The coarse alluvial gravels reach thicknesses of ≥ 15 m in the lower Garonne terraces, indicating significantly higher sediment fluxes than those associated with the alluvial terraces in the lower Segre. Extensive vertical incision scarps of > 15 m witness intense erosion following the aggradation of each terrace complex in the Garonne. The internal levels of a terrace complex are separated by small incision scarps (< 5 m). Sediment weathering and pebble alteration in the gravel bodies disclose considerable age differences between the major terrace complexes, but in successive individual terraces contrasts are not as pronounced, except for the extensive upper level in the lower terrace complex Q3 (Stange et al., 2014a).

Chronological constraints in the Garonne are based on morphogenetic relationships of fluvial terraces and moraines that are situated in the terminal glacial basin near to the foreland transition (e.g., Hubschman, 1975f; Hubschman et al., 1984; Andrieu, 1991; Stange et al., 2014a). In addition, new terrace exposure ages along with earlier ^{14}C dating of glacial lake sediments and floodplain loams (Rieucau, 1971; Andrieu, et al., 1993) enable to refine the previous terrace chronologies in the Garonne (e.g., Hubschman 1975a, 1984; Andrieu, 1991). The individual terraces of complex Q3 developed during stadials or cold stages of MIS 2 (e.g., Stange et al., 2014a). The extensive upper terrace of Q3 is associated with a previous ice advance (presumably during MIS 4) that reached similar ice-extent as the valley glaciers during MIS 2 (Stange et al., 2014a). The higher complex Q2 is probably associated with the Pyrenean glacial maximum (i.e. MIS 6; e.g., Lewis et al., 2009; Delmas et al., 2011; Garcia-Ruiz et al., 2013). The proposed glaciofluvial chronology suggests that large incision steps relate to major cold–warm–cold climatic transitions intermediate to successive Pleistocene glaciations, whereas small individual terrace scarps reflect minor (intra-glacial) climate fluctuations. Accordingly, terrace complex Q1 developed during a previous (Middle Pleistocene) glaciation, most likely during MIS 8.

The Garonne terrace chronology is in alignment with other glaciofluvial systems in the northern and southern Pyrenees (e.g., Lewis et al., 2009; Delmas et al., 2011; Lacan et al., 2012; Garcia-Ruiz et al., 2013; Stange et al., 2013b). It means a relatively synchronous terrace development across the Pyrenees in response to Pleistocene glacial–interglacial climate fluctuations, although the climatic asymmetry of the Pyrenees (Taillefer, 1969; Calvet, 2004) causes differences in sediment fluxes, weathering intensities, terrace preservation, and valley morphologies (e.g., asymmetric periglacial valleys; Taillefer, 1951).

Our observations confirm a climate-triggered terrace formation, but climate impact can neither explain the different terrace staircase geometries, nor does it provide a mechanism for the uniform Quaternary incision magnitudes in the northern and southern Pyrenees (e.g., Segre, Garonne; Stange et al., 2013a-c). In addition, numerical modelling including (only) climate variability (i.e. fluctuating sea-level and runoff; Stange et al., 2014b) predict a long-term decrease of incision magnitudes and downstream convergent terrace profiles in the Ebro tributary rivers (e.g., Segre). This is not consistent with the observed (semi)parallel terrace staircases in the southern Pyrenees foreland, which indicate that long-term fluvial incision is continuous and relatively uniform along the rivers in the Pyrenees.

6.3.2. Base level controls

The erosive power and sediment transport capacity of a river largely depends on discharge and stream gradient, the latter is determined by the drainage network base level (e.g., sea-level, main river junction; Bull, 1991). Fluvial erosion and sediment routing enables a river to approach an energy-efficient gradient equilibrium toward base level (e.g., Merritts et al., 1994; Whipple and Tucker, 1999; Sklar and Dietrich, 2001; Crosby and Whipple, 2006), which is established once a river neither aggrades nor incises (Leopold and Bull, 1979). Hence, the ongoing incision that is predicted by forward modelling of the Ebro drainage system indicates that at present the rivers of the Ebro drainage basin are not in equilibrium (Stange et al., 2014b). Because discharge decreases toward the headwaters, rivers commonly establish concave-up (semi)equilibrium profiles (Mackin, 1948; Bagnold, 1977; Sinha and Parker, 1996). Also in the Ebro model, Pyrenean Rivers established concave-up profiles, apart from some irregularities (i.e. profile knickpoints) along the intramountain (upper) reaches. The latter are related to the local discharge regime (e.g., Howard, 1994; Jones, 2002; Crosby and Whipple, 2006) and to (post)orogenic structures and bedrock erodibility (Jones, 1999, 2004; Stange et al., 2013a, 2014a). The flat, low-gradient profiles in the foreland reaches hint at close-to-equilibrium conditions and base level adjustment to the drainage outlets at the Atlantic Ocean for the Garonne (Stange et al., 2014a) and the Mediterranean Sea for the Ebro River (confirmed by the model experiments by Stange et al., 2014b).

The observed (semi)parallel river terrace profiles in the foreland of the Pyrenees disclose relative consistent longitudinal gradients, arguing for stable base level positions throughout the Quaternary period. The long-term valley entrenchment, however, argues for the converse, because channel incision is a river's attempt to reduce its gradient toward a lower base level position (Merritts et al., 1994). Hence, the deeply incised staircases with (semi)parallel terraces reflect progressive (Quaternary) base level lowering at the outlet of the drainage systems (Stange et al., 2013a).

Several base level scenarios have been tested regarding Quaternary stream profile development and sediment dynamics in the Ebro basin, including (i) a climate scenario with sea-level and runoff variability (e.g., Miller et al., 2005; Bartlein et al., 2011), (ii) a large initial base level drop owed to Pliocene uplift of the Catalan coastal ranges (CCR; e.g., Janssen et al., 1993; see also Bartrina et al., 1992; Cloetingh et al. 1992; Roca and Deseglaux, 1992), and (iii) progressive base level lowering resulting from continuous catchment-scale uplift.

In agreement with previous studies on coastal fluvial systems (e.g., Tebbens et al., 2000; Vis et al., 2008; Viveen et al., 2013), sea-level variability causes gradient adjustments along the Ebro fluvial network. The upstream propagation distance of sea-level effects (e.g., low-stand profile knickpoints) depends on a number of factors such as slope, bedrock erodibility, discharge and sediment supply (Whipple and Tucker, 1999; Blum and Törnqvist, 2000; Crosby and Whipple, 2006; Loget and Van den Driessche, 2009). Taking into account these parameters, the Ebro model predicts that sea-level variability primarily affects the lower–middle reaches of the Ebro network and cannot explain the (semi)parallel entrenchment in the Pyrenean tributaries (e.g., Segre River, Stange et al., 2014b).

Similar to other stream power based numerical models, the fundamental controls on knickpoint migration rates in the Ebro model are sediment supply and discharge (or catchment area), whereas bedrock erodibility is at most a secondary factor (e.g., Bishop, 2005; Crosby and Whipple, 2006; Finnegan, 2013). The model scenario including a large base level drop at the Ebro basin outlet around the Pliocene–Quaternary transition (i.e. previous Pliocene uplift; Janssen et al., 1993) shows that the lower erodibility of the Catalan coastal ranges (CCR) somewhat delays the headward propagation of incision, but the spatio-temporal effects are minimal and erosion rapidly migrates upstream along the Ebro fluvial network. The model results imply that previously invoked (lithologic or tectonic) knickpoint retention in the CCR (e.g., Stange et al., 2013a) is not a potential base level mechanism for the gradual and uniform entrenchment of the Ebro drainage system during the Quaternary. In addition, the stream profile development in succession to Pliocene uplift in the CCR (e.g., Janssen et al., 1993) discloses instantaneous downcutting of the main river Ebro stream profile, entailing a rapid base level lowering at the tributary junctions, which in turn results in downstream divergent profiles in the lower–middle tributary rivers (e.g., Segre; Stange et al., 2014b). This terrace geometry is not consistent with the (semi)parallel terrace staircases in the Pyrenean tributary rivers.

Because the CCR has no potential as a long-lasting base level, the Mediterranean sea-level denotes the permanent base level of the exorheic Ebro drainage system. Hence, the only remaining mechanism for continuous base level lowering is uniform uplift of the fluvial drainage basin (e.g., Maddy, 1997; Maddy et al., 2001). We simulated continuous Quaternary uplift by a gradual sea-level drop at the Ebro basin outlet, starting from a reconstructed Ebro basin palaeo-topography at the Pliocene–Quaternary transition (e.g., Stange et al., 2014b). In this scenario (see below), climate-triggered sea-level fluctuations are superimposed on the long-term trend of relative base level lowering.

6.3.3. Tectonics

During the past two decades plenty of data have been gathered on Pliocene–Quaternary tectonic activity in N Iberia, including the Pyrenees–Cantabrian mountain chain and the Catalan coastal ranges (e.g., Masana, 1996; Goula, 1999; Vergés et al., 2002; Alvarez-Marrón, 2008; Chevrot et al., 2011; Lacan and Ortuño, 2012). Active fault scarps are reported from across the Pyrenees (e.g., Bourrouilh et al., 1995; Olivera et al., 2003; Alasset and Meghraoui, 2005; Ortuño et al., 2008), and also from the Catalan coastal region (e.g., Perea, 2006). Recent halokinetic uplift of anticlines along-strike of the northern and southern Pyrenean piedmont is evidenced in a number of Pyrenean streams by displaced alluvial terraces (e.g., Peña, 1983; Baize et al., 2002; Lucha et al., 2012; Stange et al. 2013b). Moreover, deformed alluvial deposits in the Têt River (Calvet, 1994; Carozza and Delcaillau, 1999), Segre River (Peña, 1983; Turu and Peña, 2006; Stange et al., 2013a,b), Adour River (Baize et al., 2002), Aspe River (Lacan et al., 2012), and Gave de Pau (Alasset and Meghraoui, 2005) bear witness to Quaternary tectonic activity. Estimations on Pliocene–Quaternary uplift rates in N Iberia are very heterogeneous, ranging from 0.01 to 0.5 mm y^{-1} (e.g., Olivera et al., 2003; Alasset and Meghraoui, 2005; Alvarez-Marrón et al., 2008; Ortuño et al., 2008; Lucha et al., 2012).

Assuming that incision magnitudes can be used as a proxy for uplift (e.g., Maddy, 1997; Van Balen et al., 2000, 2010; Busschers et al., 2007; Merritts, 2007; Rixhon et al., 2010), we estimated a low to moderate Quaternary uplift rate for the Ebro basin (i.e. 0.1 mm y^{-1}) on the basis of the Ebro basin pediments that are associated with the Pliocene–Quaternary transition (e.g., Mensua and Ibañez, 1977). The estimated uplift rate is in agreement with previous studies on tectonic activity and regional uplift across the CCR (e.g., 0.02–0.15 mm yr^{-1}; Perea et al., 2006, 2012; see also Masana, 1996; Ferrer et al., 1999).

Model results show that continuous Quaternary uplift triggers gradual incision across the Ebro drainage system. Although, the Middle–Late Pleistocene incision magnitudes in the Segre and Gállego are underestimated in the model (i.e. c. 70m), the predicted uniform valley entrenchment in the southern Pyrenean foreland is consistent with the observed (semi)parallel fluvial terrace profiles. Hence, continuous regional uplift in combination with climate variability can explain both gradual Quaternary valley entrenchment and Middle–Late Pleistocene terrace staircase formation in the foreland basins of the Pyrenees (Stange et al., 2014b). The causes for active uplift and the reactivation of Pyrenean structures could be linked to (ongoing) tectonic compression in response to (slow) plate convergence rates between Iberia and Europe, causing folding in the lithosphere (Cloetingh et al., 2002; Vergés et al., 2002), crustal shortening and isostatic rebound to erosion in the foreland basins (Vernant et al., 2013).

Based on our Ebro model, isostatic flexure of the lithosphere is negligible in response to (rapid) incision along the linear Ebro drainage network (i.e. because of little sediment volumes eroded per unit time). With time the flexural portions in fluvial downcutting increase, because erosion propagates across the numerous tributary and headwater catchments. The continuous source to sink sediment fluxes in the (Quaternary) model trigger relatively uniform isostatic erosional rebound in the Ebro foreland basin (c. 80 m along the Ebro River) and large-scale subsidence of the Ebro margin and Valencia trough (e.g., Farrán and Maldonado, 1990; Garcia-Castellanos et al., 2003; Stange et al., 2014b). Model results show that isostatic adjustments in the lithosphere may be ongoing, affecting also the northern Pyrenean foreland (Aquitaine basin). However, the predicted magnitudes of erosional rebound in the foreland basins of the Pyrenees do not compensate for the magnitudes of fluvial incision in the river valleys and thus argue for additional (tectonic) forcing. Potential mechanisms relate to tectonic uplift in response to (i) the effects lithospheric folding in Iberia (e.g., Cloetingh et al., 2002), (ii) ongoing (or recommencing) tectonic compression at the Iberia–Europe plate boundary in the Pyrenees (Vergés et al., 2002; Vernant et al., 2013), (iii) small-scale mantle convection (e.g., *dynamic topography*, Faccenna and Becker, 2010), and (vi) lithospheric unflexing due to slab detachment, convective removal, or post-orogenic heating of the lithospheric root beneath the orogen (Desegaulx et al., 1991; Cloetingh, 2004; Genser et al., 2007; Gunnel et al., 2008; Roure, 2008; Duretz et al., 2011).

In the northern Pyrenees piedmont, the continuous eastward migration of the Garonne (e.g., west-lateral terrace staircase) suggests a latitudinal gradient in uplift, with an uplift axis located beneath the Lannemezan molasse-fan (Stange et al., 2014a). Because model results indicate that erosional isostatic rebound of the lithosphere has an overall perpendicular gradient to the axis of the Pyrenees, the differential, partly opposite (Pliocene–Quaternary) valley asymmetries of adjacent rivers in the northern Pyrenean foreland argue for tectonic causes of uplift, probably in relation to lithospheric unflexing of the foreland basin (Desegaulx et al., 1991) and differential reactivation of pre-orogenic basement structures (e.g., Carbon et al., 1995) due to tectonic segmentation and lateral variations in rheological properties of the lithosphere (Garcia-Castellanos and Cloetingh, 2012).

6.4. Implications for future research

This research contributes to enhance the existing glaciofluvial chronologies in the Pyrenees and provides a better understanding of the potential (external) triggers for long-term fluvial entrenchment and terrace formation in the Pyrenees. Nevertheless, a number of issues remain to be resolved:

Extensive, cold-climate terrace aggradation is generally well established, but the timing and extent of fluvial erosion during climatic transitions needs better constraints. The Garonne holds an extensive, high-resolution terrace record with variable scarp heights, terrace extents, and valley geometries, which could be beneficial for further constraining fluvial sediment routing and excavation in response to climate-related multi-stage erosion phases. However, little (absolute) age constraints exist on incision and terrace staircase formation in the major foreland rivers of the northern Pyrenees.

Integrated terrace chronologies from different river valleys would also be advantageous for assessing the variable rates of Quaternary uplift and tilting of the northern Pyrenean piedmont and for confirming the (potentially) synchronous terrace development in the northern Pyrenees. In addition, exposure dating of the prominent higher terrace complex (Q2) in the Garonne could provide currently unavailable age constraints for the maximum ice extent in the northern Pyrenees.

In both foreland basins, the onset of valley entrenchment and early Quaternary drainage re-organisation (e.g., Garonne, Noguera Ribagorzana) is evidenced by fluvial morphology, but without additional age controls the timing and (potentially climatic) causes of enhanced vertical incision remain speculative. In the northern Pyrenees, the well-preserved morphology around the foreland outlet of the Neste River provides a good opportunity to investigate early Quaternary drainage (capture) mechanisms and to confirm the (presumably) Pliocene–Quaternary abandonment and fluvial disconnection of the extensive foreland fan of Lannemezan.

In the Ebro foreland basin, extensive pediments are probably associated with the Pliocene–Quaternary transition, but, as to the lack of chronological data, the onset of valley entrenchment (i.e. pediment abandonment) in relation to the Mid-Pleistocene climate transition remains an alternative. The Ebro basin pediments are probably very old, involving multi-phases of denudation, so that exposure sampling sites should be chosen carefully as for morphologically stable, inactive surfaces (e.g., flat, extensive isolated remnant hills), also considering the local erosion-burial history. Exposure dating on early Quaternary geomorphic units could also benefit from analyses of different cosmogenic nuclides – e.g., ^{21}Ne in addition to ^{26}Al and ^{10}Be. Applying different post-processing techniques (e.g., Monte Carlo, Profile rejuvenation) has shown to be useful for evaluating cosmogenic nuclide inheritance in depth-profiles.

It has been demonstrated that numerical modelling of different parameter scenarios enables to assess and quantify the external drivers of fluvial incision and to evaluate the impact of specific forcing factors on fluvial erosion, sediment routing, and stream profile development in fluvial systems. Model improvements include additional climate-related components (e.g., vegetation, permafrost, precipitation maps) and a better resolution of input data (e.g., DEM-grids, differential erodibilities, peak discharges). Although our model results seem to be valid and the Pyrenees region is affected by moderate but continuous Quaternary uplift, further research is needed on the rheological properties and processes in the mantle–lithosphere and their coupling with surface processes. We cannot exclude that uplift in the Ebro basin continued farther back in time, potentially shedding a new and different light on the long-term development of this foreland drainage basin. Based on our model, the low-gradient topography across the Ebro basin is not indicative for rapid base level lowering neither in relation to the Messinian salinity crisis nor in response to a sudden base level drop at the endo–exorheic transition.

This study has shown that combined numerical modelling, GIS- and field-based geomorphological research enables to evaluate fluvial system development and its relevant external drivers. Sediment investigations on site – e.g., regarding depositional processes and differential weathering – have proven to be useful for assessing the relation of terrace formation to specific environmental conditions, but absolute dating remains indispensable for solid terrace staircase chronologies. GIS-based analyses and modelling are essential tools for research on landscape dynamics and the coupling of earth surface processes. Because the validity of model results largely depends on the quality of input parameters, field-based studies will remain an essential part of geomorphological research, and owed to the number of parameters involved – e.g., climate, vegetation, hydrology, tectonics, and lithology – interdisciplinary geoscientific research becomes increasingly important (e.g., Alexander von Humboldt, c. 1821).

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8 List of figures

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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.

10.2. Samenvatting

Thesis titel: ***De invloed van klimaat en neotektoniek op fluviatiele insnijding en rivierterrasvorming in de Pyreneëen***

Dit onderzoek bestudeert de koppeling van oppervlakteprocessen, klimaat en tektoniek, met betrekking tot erosie en sedimenttransport in riviersystemen in de Pyreneeën. Het transversale riviernetwerk van de Pyreneeën bevat diep ingesneden dalen met uitgebreide terrasvlakken in de voorlandbekkens. De gepaarde (bilaterale) rivierterrassen in de voorlandbekkens van de zuidelijke Pyreneeën (b.v. het Ebro bekken) laten opvallende onderlinge overeenkomsten zien in het aantal en de hoogte van de individuele terrasniveaus en de daaruit afgeleide mate van insnijding op de lange termijn (Kwartair) van de belangrijkste zuid-Pyreneese zijrivieren. De hoogte van de dalwanden in de noord Pyreneese rivieren is consistent, maar de dwarsdoorsneden over de dalen laten asymmetrische terrasvormen en ongelijkmatige terrasverspreiding en -preservatie zien. Deze studie heeft ook tot doel het ontrafelen van de drijvende krachten achter de fluviatiele insnijding en terrasvorming in de Pyreneeën. Hiervoor zijn twee belangrijke riviersystemen bestudeerd, de prominente Segre rivier in het zuidoosten van de Pyreneen en de Garonne rivier die een groot deel van het centrale noorden in de Pyreneeën draineert.

Rivierterrasen zijn restanten van verlaten dalbodems ontstaan door insnijding. Ze zijn veroorzaakt door afwisselende periodes van dalbodemophoging door sedimentatie tijdens koudere periodes en fases van vertikale insnijding en laterale dalwanderosie tijdens klimaattransities (b.v. Vandenberghe, 2001, 2008). Naast deze door het klimaat gestuurde terrasvorming is een lange-termijn insnijdingstrend op te merken waarbij de energie gecontroleerd wordt door de afvoer en bepaald wordt door het basisniveau van het fluviatiele netwerk (bv. Whipple and Tucker, 1999; Blum and Törnqvist, 2000). Lange-termijn rivierinsnijding is een veelvoorkomende reactie op het verlagen van het basisniveau of de verhoging van het drainagebekken (Merritts et al., 1994; Maddy et al., 2001). Daardoor kan dit proces alleen beoordeeld worden met inachtneming van specificieke klimatologische, tektonische en basisniveau configuraties van het rivierbekken.

Met behulp van een combinatie van digitale en op veldwerk gebaseerde methodes zijn op de eerste plaats verscheidene sedimentaire ontsluitingen bestudeerd op (post)depositionele structuren en deformaties. Daarnaast zijn belangrijke terrasniveaus bemonsterd voor het dateren met behulp van ^{10}Be cosmogene nucliden. Op veldwerk gebaseerde geomorfologische karteringen zijn gecombineerd met op GIS gebaseerde DEM en stroomprofiel analyses. Tijdens een tweede stap zijn de resultaten geïntegreerd in een numeriek landschapsevolutiemodel (TISC; Garcia-Castellanos et al., 2003) dat is gebruikt om

de relatieve impact van kwartaire klimaatsverandering, tectonische opheffing, lithosferische flexurale isostasie en differentiële erodeerbaarheid van het gesteente terrasontwikkeling in de drainagesystemen van de zuidelijke Pyreneeën te bepalen.

Resultaten laten een relatief synchrone vorming van de terrasvlakken in het voorlandbekken zien in relatie tot Pleistocene glaciaal-interglaciaal cycli. Als gevolg hiervan zijn belangrijke alluviale terrasvlakken gevormd door dalbodemophoging tijdens maximale gletjeruitbreiding. De brede (b.v. vlechtende) dalbodems zijn verlaten tijdens de koud-warm klimaattransities omdat rivieren zich transformeerden naar een afvoer met één enkele stroombedding en zich insneden in het onderliggende substraat. Longitudinale terrascorrelaties in rivieren van zowel de noordelijke als de zuidelijke Pyreneeën laten (semi)parallelle terrasprofielen zien die duiden op een gelijkmatige verlaging van het basis niveau of een continue opheffing van het voorlandbekken (en de Pyreneeën) tijdens het Kwartair.

In de Garonne laten dateringen en morfogenetische correlaties met fluvioglaciale afzettingen zien dat belangrijke terrascomplexen gevormd zijn als reactie op de opeenvolgende glaciaties tijdens het Pleistoceen (b.v. tijdens MIS 6, 4 en 2). Dit impliceert grootschalige insnijding gerelateerd aan belangrijke (inter-glaciale) klimatologische transities. De individuele niveaus van de terrascomplexen zijn gescheiden door kleinschalige terrasresten die minder duidelijke intra-glaciale klimaatfluctuaties reflecteren. De bestudeerde ontsluitingen in de Garonne laten intense verwering van sedimenten en grote sedimentfluxen zien in de noordelijke Pyreneeën. Deze zijn veroorzaakt door aanhoudende (sub)humide klimaatsomstandigheden en krachtige gletsjhers die afdaalden tot aan het voorland van de noordelijke Pyreneeën (b.v. Calvet, 2004).

In de Segre rivier zijn dalbodems opgehoogd tijdens de glaciale fases MIS 8 (of 7), MIS 6, MIS 4 en MIS 2. Echter, de dateringen laten zien dat ook tijdens interglacialen met aanzienlijke interne klimaatswisselingen prominente terrasniveaus konden gevormd worden (b.v. tijdens de koudere fases van MIS 5). Lokale deformatie van alluviale afzettingen is veroorzaakt door breuken, plooien en halokinese. Anomalieën in de grinddikte in het midden- tot bovenstroomse bereik van de Segre zijn waarschijnlijk gerelateerd aan lokale verzakking en/of sedimentpulsen als reactie op de glaciale smelt fases of tijdelijke blokkades van de rivierstroming.

Door gebruik te maken van een numeriek model (*TISC*) – gebaseerd op berekening van de afvoerenergie en bevat aan de hand van erosieve oppervlakteprocessen, lithosferische isostasie, zeespiegel- en afvoerfluctuaties – zijn verschillende klimatologische, tektonische en baselevel scenarios getest om de meest relevante externe invloeden op fluviatiele insnijding en terrasvorming in het voorlandbekken van de zuidelijke Pyreneeën te bepalen. De resultaten van de berekeningen laten zien dat alleen het scenario met continue Kwartaire opheffing en klimaatvariabiliteit (zoals b.v. gereflecteerd in zeespiegelniveau en afvoerfluctuaties) de (semi)parallelle terrasprofielen en midden- tot laat-Pleistocene insnijding genereert zoals waargenomen in de dalen van de zuidelijke Pyreneeën (b.v. Segre, Gállego). Op basis van de modelresultaten ondervinden de Pyreneeën en de voorlandbekkens continue (Kwartaire) opheffing. Dit lverklaart ook de rivierinsnijding van de noord Pyreneese rivieren (b.v. Garonne).

Zeespiegelfluctuaties beïnvloeden hoofdzakelijk de benedenstroomse takken van het Ebro netwerk en zijn verder (b.v. in de Segre rivier) niet belangrijk volgens het numerieke model. Een aanzienlijke zeespiegeldaling bij de monding van het Ebrobekken, bijvoorbeeld veroorzaakt door een (Pliocene) opheffing voor de Catalaanse kust (b.v. Janssen et al., 1993), veroorzaakt een snelle erosiegolf langs het drainagenetwerk van de Ebro die resulteert in divergente terrasprofielen en kleinschalige midden- tot laat-Pleistocene incisie magnitudes. Deregelijke ontwikkeling komt niet overeen met de (semi)parallelle terrasvlakken in het Ebrobekken (b.v. Segre). Het numerieke model laat ook zien dat klimaatfluctuaties (b.v. met veranderingen van afvoer en zeeniveau op glaciaal-interglaciale schaal) leiden tot ongelijkmatige insnijding langs longitudinale rivierprofielen.

Flexuur treedt op als reactie op de erosie langs de hoofdgeulen van het drainagenetwerk. Maar, de invloed van flexuur is verwaarloosbaar door het lage sedimentvolume dat geërodeerd wordt per tijdseenheid. Maar lithosferische isostatische opheffing intensiveert als erosie voortschrijdt langs de zijrivieren. Lange-termijn isostatische opheffing door erosie is uniform in het model, waarbij een algemene longitudinale gradiënt haaks op de as van de Pyreneeën wordt gehanteerd. Hierdoor kan lithosferische isostasie niet de ongelijkmatige dalgeometrieën in de noordelijke Pyreneeën verklaren, noch een mechanisme vormen voor de asymmetrische (west-laterale) terrasvlakken van de Garonne welke gevormd zijn door de progressieve insnijding en oostwaartse migratie van de Garonne tijdens het Kwartair. Dit impliceert dus een latitudinale gradiënt in opheffing en dus tektonische forcering.

Aanhoudende tektonische obductie in de Pyreneeën kan veroorzaakt worden door lithosferische compressie als reactie op (langzame) convergentiesnelheid tussen Iberia en Europa, welke lithosferische plooiing en korst verkorting in het voorland veroorzaakt en regionale isostatische opheffing door erosie (Cloetingh et al., 2002; Vergés et al., 2002; Vernant et al., 2013). Dit bevestigt externe forcering door opheffing. De simulatiemodellen laent bovendien ook zien dat het huidige drainagesysteem in het Ebro voorland actief insnijdt en niet in evenwicht is.

ISBN: 978-94-6259-311-4