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Structural style of inversion of rifts and passive margins: feedback between mountain building and surface processes

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Abstract: Inversion of sedimentary basins and passive margins at various stages of their evolution is modelled with thermo-mechanical viscous-plastic finite element techniques. We focus on two aspects of the inversion and collision process: 1) the role of the strength of the lower crust on the style of inversion, and 2) feedback relations of surface processes with the tectonic deformation and their control on the style of lithosphere inversion. The model involves a 35 km thick crustal layer and a 125 km length lithosphere. All materials follow frictional-plastic strain softening, or thermally activated viscous flow laws. The model is thermally coupled and the thermal evolution is calculated. During a first phase, the model is extended to form a rift basin. The rift basin or passive margin geometry is then used as initial condition for a phase of lithosphere scale inversion and collision. Using a prior rift or passive margin formation phase allows examining the role of pre-existing heterogeneity on the style of inversion and continental collision. We examine the effect of very simple end member surface process models on the style of mountain building: 1) no erosion and no sedimentation, 2) no erosion and complete sedimentation, and 3) complete erosion and complete sedimentation. Very contrasting behavior is observed for these end-member variations in surface process model.

Keywords: mechanical modelling, lithosphere inversion, strain localization.

While there is significant progress in understanding first order controls on styles of rifting and passive margin formation, still relatively little is known about factors that control the structural style of inversion of these structures. Especially the importance of structural weaknesses formed during earlier rifting vs. new formed structures both at crustal and lithospheric scale, and the role of mass redistribution by surface processes and their relative importance are not very well understood.

Much recent work has been devoted to understanding the coupling and feedbacks between tectonics, surface processes, and climate and many of the fundamental relationships in this dynamic system have been identified (e.g. Beaumont *et al.*, 2000b; Roe *et al.*, 2006). Crustal and lithospheric tectonics while fundamentally driven by mantle dynamics (Fig. 1, link 1) and modified by inheritance (Fig. 1, link 2) is also strongly linked to the atmosphere-hydrosphere system through erosional forcing. Tectonic processes change the elevation of the earth primarily through the isostatic response to crustal thickening or thinning. Increasing relief at multiple scales enhances fluvial erosion and transport (Fig. 1, link 4) and also tends to increase orographically localized precipitation (Fig. 1, link 3), which can result in orographic denudation. Climate and denudation are linked through orographic forcing of precipitation, through glaciation and, on a global scale, by changing precipitation patterns (Fig. 1, link 5). The primary feedbacks of surface processes on tectonics result from redistribution of mass causing variations in gravitational stresses that can enhance or inhibit deformation, and from the influence of exhumation on the thermal structure and, hence, rheological properties of the crust and lithosphere (Fig. 1, link 6) (Beaumont *et al.*, 1992; Willett, 1999; Braun, 2006).

Recent advances in both tectonic and surface process modelling allow quantitative investigation of these fundamental relationships (Beaumont *et al.*, 1992; 2000b; Willett, 1999; Stolar *et al.*, 2006). This has greatly increased the predictive power of such models and their ability to reproduce geological observations. It has, for instance, been demonstrated that the large-scale geometry of an orogen depends on the dominant wind direction (Beaumont *et al.*, 1992; Willett, 1999). Studies linking critical wedge dynamics and surface processes on the scale of the whole orogen have established how overall wedge geometry is related to surface process efficiency (Stolar *et al.*, 2006; Roe *et al.*, 2006).

However, a number of first-order questions and challenges remain: 1) the coupling and feedbacks on the scale of individual structures have not been assessed, 2) most coupled tectonic (TM)-surface process models (SPM) consider only 2D tectonic deformation (e.g. Beaumont *et al.*, 2000b); investigating coupled 3D TM's and plan view SPM's is necessary, 3) perhaps the greatest difficulty is the range of spatial and temporal scales involved, through which the interaction evolves. Improvements need to be made to include better physically based components with appropriately scaled model parameters that allow correct integration of the non-linear SPM components on the required model time resolution (e.g. Braun, 2006).

Continental rift zones and passive margins exhibit a range of structural styles from non-volcanic to volcanic and from narrow to wide margins (Louden and Chian, 1999; Whitmarsh *et al.*, 2001). The factors controlling these styles or rift modes are, although still subject of active research, reasonably well understood (Braun and Beaumont, 1987; Bassi *et al.*, 1993; Buck, 1991; Huismans and Beaumont, 2002; Lavier and Manatschal, 2006; Huismans and Beaumont, 2007). The major remaining challenges are 3D aspects of rifting and passive margin formation.

Factors controlling tectonic inversion of rift zones and passive margins are, however, less well constrained. Both local inherited weaknesses and regional inherited crust and mantle lithosphere structure are believed to contribute to the structural style of inversion. However, it is still unclear in which extent structural inheritance plays a role during inversion tectonics. Regional inherited factors contributing to the structural style of inversion include variations 1) in crustal and lithospheric thickness, 2) in composition (e.g. wet vs. dry, felsic or mafic rheologies), and 3) in thermal structure that affects the lateral and vertical strength distribution. Specifically the time since rifting, the spatial variation and amount of crustal and mantle lithosphere thinning, and potential melting of middle/lower crust and mantle during the extensional phase will determine the response of the lithospheric system to inversion.

The strength of inherited faults and shear zones is not well constrained. Major faults and shear zones show repeated reactivation through time (Holdsworth, 2004) which suggests these structures are weak. The processes leading to the implied weakening are, however, not well understood and are strongly debated (Scholz, 2000; Zoback, 2000). Proposed weakening mechanisms include 1) alteration of feldspar rich rocks into mica rich aggregates with lower frictional and ductile strength, 2) cohesion loss, 3) grain size reduction leading to viscous weakening, 4) serpentin-

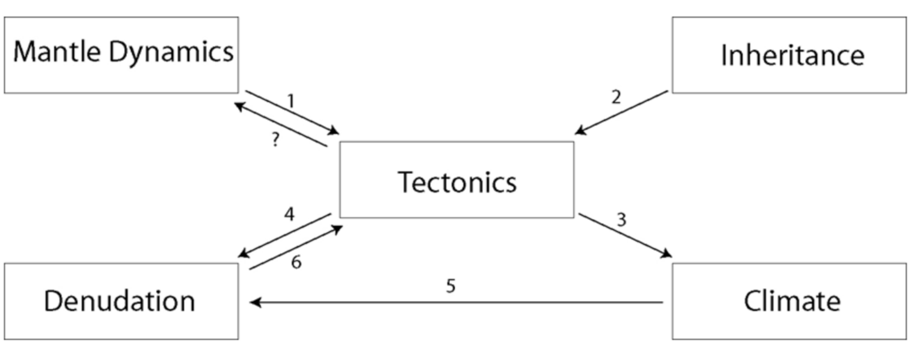

Figure 1. Primary feedback relationships between Tectonics, Mantle Dynamics, Inheritance, Denudational processes, and Climate.

isation of mantle rocks lowering frictional strength; or dynamic effects such as 5) fluctuations of fluid pressure and mineralization in fault gauges, 6) shear heating and formation of melt leading to catastrophic fault failure, and 7) shear heating during viscous deformation leading to thermal runaway on shear zones. Studying the role of inherited large fault structures during inversion tectonics may shed light on the temporal and spatial variation of the strength of large faults.

The Pyrenean-Cantabrian mountain belt is a very well studied example of an inverted rift basin and passive margin. Deep seismic crustal cross sections constrain crustal structure from east to west, pre-inversion and inversion structures have been mapped in great detail, and a large geochronological data base provides constraints on exhumation history (e.g. Choukroune and ECORS Team, 1989; Muñoz, 1992; Fitzgerald *et al.*, 1999; Vergés *et al.*, 2002). Formation of the pre-Pyrenean rift zone occurred during a series of rift events in the Triassic and Late Jurassic, culminating in close to crustal separation in the Late Cretaceous with the final rift stages developing synchronously with early Bay of Biscay opening. Crustal scale restoration (Vergés *et al.*, 2002) constrains the end Cretaceous crustal structure for cross sections in the eastern, central and western Pyrenees.

The Pyrenean-Cantabrian mountain belt was formed by inversion of this rift basin, partly continental, partly oceanic. The surface expression of this inversion is a 150 km wide collision zone flanked by thin-skinned fold and thrust belts and associated foreland basins. The mountain belt is characterised by decreasing amounts of shortening (120-170 km) and exhumation going from east to west. Exhumation of the orogen is asymmetric with greater and younger exhumation on the southern side. Erosion of the core of the Pyrenees evolved from a broad region of unroofing from 60-40 Ma, followed by a progressive southward shift with high erosion rates between 36-20 Ma in the south and low erosion rates on the northern side of the orogen. Erosion and exhumation localized in the core of the Pyrenean belt around 20 Ma (Beaumont *et al.*, 2000a; Sinclair *et al.*, 2005). During the post-orogenic evolution erosional processes have created a peneplain (Babault *et al.*, 2005), which origin remains controversial (Gibson *et al.*, 2007). The change from planation to fluvial incision during Pliocene times is attributed to capture, climate change and neotectonic uplift. The three major fluvial systems are characterized by terraces, which formed in response to the post-orogenic tectonic evolution and the dynamics of climate. The Cantabrian Mountains constitute the western prolongation of the Pyrenees. This part of the system was uplifted as a consequence of the inversion of the Mesozoic passive margin in the southern part of the Bay of Biscay.

Moderate inversion, good preservation of both pre- and syn-orogenic strata, and good constraints on crust and lithospheric structure make the Pyrenean-Cantabrian Mountains belt an excellent example to study rift and inversion tectonics, orogenic processes and post-orogenic uplift and their relation to inheritance and climate-driven surface processes. The exceptional preservation of syn-orogenic strata in the Pyrenees allows reconstructing shortening rates since early stages of collision and constrains the geometry through intermediate stages (Muñoz, 1992; Vergés *et al.*, 2002).

Lithosphere scale inversion of passive margins

In previous works we focused on the dynamic evolution of sedimentary basins and passive margins and their inversion (Huismans and Beaumont, 2002, 2003, 2007, *in preparation*; Huismans *et al.*, 2005) which indicated that surface processes can strongly impact the style of deformation (Huismans and Beaumont, 2002; Buiter *et al.*, 2004).

Here we present preliminary forward dynamic models of inversion of passive margins at various stages of their evolution. The numerical model involves a 35 km thick crustal layer and a 125 km length lithosphere. All materials follow frictional-plastic strain softening, or thermally activated viscous flow laws. The model is thermally coupled and the thermal evolution is calculated. Extensional or contractional boundary velocities are applied at the sides of the model lithosphere (Fig. 2a). During the first phase the model is extended to form a rift basin (Fig. 2b). The rift basin or passive margin geometry is then used as initial condition for a phase of lithosphere scale inversion and collision. Using a prior rift or passive margin formation phase allows for realistic ‘oceanic’ subduction before continental collision. Henceforth, the effect of simple end member surface processes on inversion style and mountain building is illustrated in generic models. End-member surface process models include 1) no erosion and no sedimentation, 2) complete erosion and no sedimentation, 3) no erosion and complete sedimentation, and 4) complete erosion and complete sedimentation.

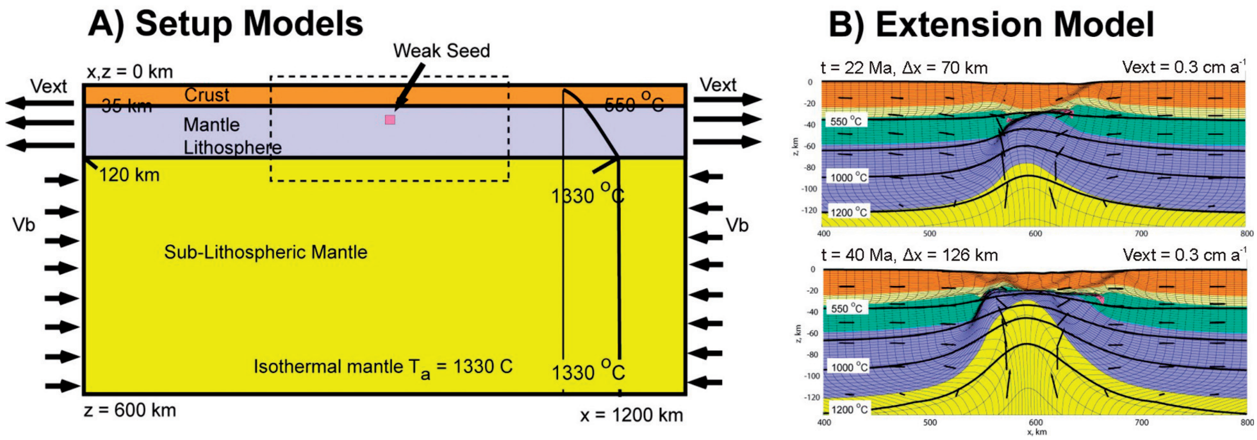

Figure 2. Numerical setup and modelling Approach. (A) Model geometry showing crust and mantle lithosphere layer thicknesses, the weak seed, and the velocity boundary conditions. Extension or shortening is driven by velocity boundary conditions and seeded by a small plastic weak region. The model has a free top surface and the other boundaries have zero tangential stress (free slip). Whether material deforms plastically or viscously depends on the ambient conditions. At yield flow is plastic, below yield deformation is viscous. The initial temperature field is laterally uniform, and increases with depth from the surface, T_0 = 0 °C, to base of crust, T_m = 550 °C, following a geotherm for uniform crustal heat production, A = 0.8 μW m^{-3} and a basal heat flux, q_m = 20 mW m^{-2}. The temperature increases linearly with depth in the mantle lithosphere and the sub-lithospheric mantle is isothermal at T_a = 1330 °C. For more details on modelling method see Huismans and Beaumont (2003), (B) zoom in on model results as outlined in box in model setup. Extensional model run close to breakup. The extensional models are used as starting configuration for lithosphere scale inversion models.

Preliminary forward dynamic models illustrate the first order control of inheritance and surface processes on styles of passive margin inversion (Fig. 3). Forward dynamic models are inverted after an initial rift phase (Fig. 3a). The model results show strongly contrasting styles of inversion tectonics. In the case without surface processes (Fig. 3b) initial deformation occurs on rift related crustal border faults and shear zones in the mantle lithosphere, after which the 'orogenic wedge' grows by outward propagation of new formed thrust structures. The case of highly efficient erosion (all topography is removed, figure 3D) shows a significantly different style of inversion with most deformation localized in a very narrow region.

TopoEurope project PYRTEC: Pyrenean inversion tectonics, surface processes and climate

A large interdisciplinary project submitted to the ESF Eurocores program TopoEurope, "*Spatial and temporal coupling between tectonics and surface processes during lithosphere inversion of the Pyrenean-Cantabrian mountain belt*", will study factors that control the structural style of inversion in the Pyrenean-Cantabrian mountain belt. Project partners include academic institutions in Norway, Spain, France, Netherlands, and the United Kingdom. The project will study the importance of structural weaknesses formed during earlier rifting vs. new formed contractional structures both at crustal and lithospheric scale, and the role of mass redistribution by surface processes and their relative importance. The Pyrenean-Cantabrian mountain belt and associated structures in the Bay of Biscay is one of the best candidates to study feedback relations between tectonic inversion, inherited structures, and surface processes as: 1) inversion is moderate and the pre-orogenic rift/passive margin structure can be very well constrained, 2) excellent geological and geophysical data-bases constrain present day crustal structure, inversion tectonics, foreland basin architecture, and exhumation history, and 3) the belt shows remarkable along-strike variations in the amount of convergence and style of deformation, providing different scenarios to study the feedback relations between tectonic inversion, structural inheritance and surface processes.

To understand the fundamental coupling between tectonic and surface processes it is essential to integrate data constraints on deep structure, tectonic evolution, exhumation and deposition, with quantitative coupled tectonic and surface process models. A strongly interdisciplinary approach, coupling observational studies and theoretical modelling, will provide the conditions to significantly enhance our understanding of the coupling and feedback between large scale deformation, surface process response, and structural inheritance during inversion tectonics in general and the Pyrenean mountain belt in particular. The project will use state-of-the-art large deformation

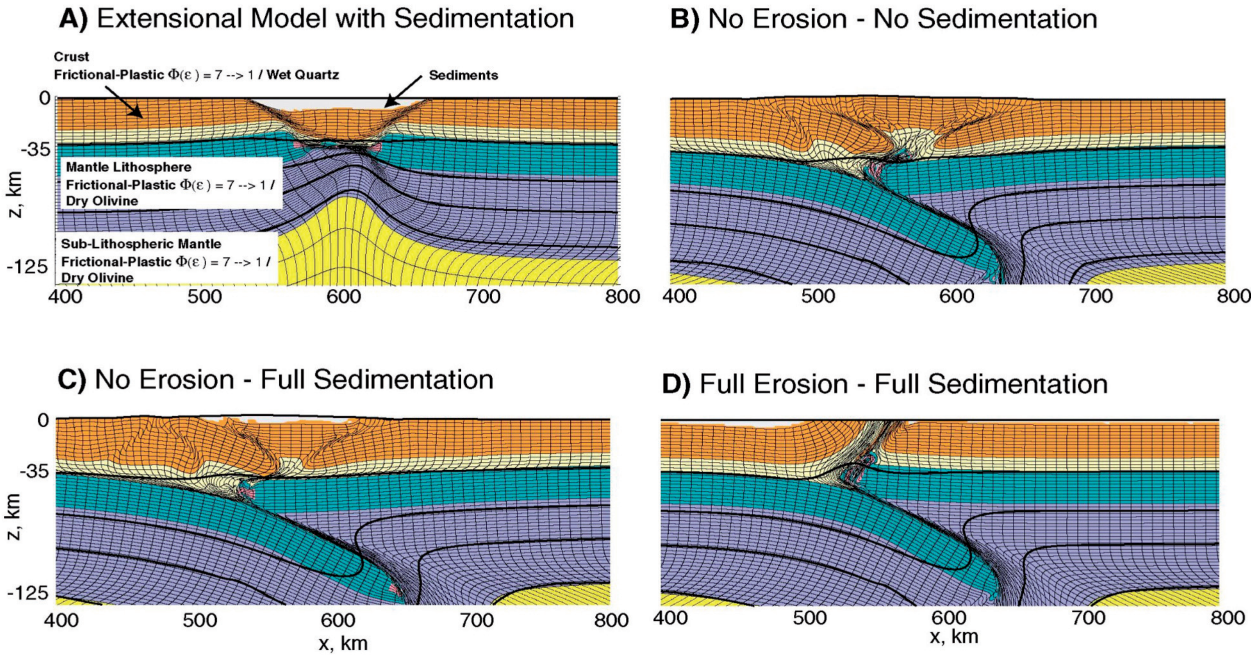

Figure 3. Effect of simple end-member surface processes during lithosphere scale inversion. (A) Forward extensional model, (B) inversion with no erosion-no sedimentation. Note outward migration of thrusts into foreland, (C) inversion with no erosion-full sedimentation. Note sediments in core of the inverted zone, (D) inversion with full erosion-full sedimentation. Note strong localized deformation in central zone. (Huismans and Beaumont, *in preparation*).

analogue, numerical, and surface process modelling techniques to develop novel insights on the tectonic and surface process controls on inversion tectonics.

Conclusions

The model results indicate that the efficiency of surface process models to remove and distribute mass in the system forms a strong control on the overall style of inversion and collision. Without erosion or sedimentation deformation migrates outward into the foreland after an initial phase of orogenic growth. In the end-member case where erosion removes all topography, deformation is localized in the core of the orogen with strong asymmetric exhumation.

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