Compressing a sheared and extended plate boundary: Modeling subduction in the Pyrenees

Ivar Midtkandal[1], Roy H. Gabrielsen[1], Jean-Pierre Brun[2] and Ritske Huismans[3]

1: University of Oslo, Norway
2: Université Rennes 1, Rennes France
3: University of Bergen, Norway

A series of laboratory experiments on lithosphere models made of layers of sand and silicone putty was performed to analyse the effects of crustal composition and the Iberian–European plate boundary geometry at the time of contractional onset of the Pyrenees. The current understanding of the deep structure of the Pyrenean–Cantabrian orogeny is that a north-dipping subduction took place in the eastern Pyrenees, whereas to the west, north of the Cantabrian, subduction is less well constrained. The transitional area near Pamplona in Spain is of particular interest, because a range of secondary structures should be expected to develop along this accommodation zone.

The lithospheric structure as incorporated in the design of the models was based on published ECORS profiles, published articles and geological maps. The models were built in a 42x45 cm container, as sand/silicon multilayers floating on a water solution of polytungstate, representing the asthenosphere. The polytungstate solution density is 2.41 kg/dm^3, which is denser than the lowermost silicone putty (1.6 kg/dm^3). Layers of sand and silicone putty were shaped to match the assumed initial lithospheric geometry and their relative strengths.

Figure 1 shows the initial model design. Above the polytungstate solution , a 1.0 cm thick layer of 1.6-kg/dm^3 silicone putty represents the ductile lithospheric mantle. The next layer consists of 0.5 cm thick layer of sand with a density of 1.6-kg/dm^3. In the “eastern” part of the model a 1.5 cm wide slot is removed and replaced with a mantle-type silicone putty to represent the mantle exhumation inherited from the extension of the Iberia northern margin prior to collision. This thin zone of ductile silicone putty acts as a weak line, from which structures developed and grew during shortening, allowing the Pyrenean subduction to develop. A 0.5 cm thick layer of silicone putty represents the lower crust with a 16° wedge originating from the model centre removed in the “western” part, where oceanic crust developed during opening of the Bay of Biscay. This wedge narrows into a 1.5 cm rectangle in the “eastern” half where extension produced less oceanic crust. The upper crust material consists of 1.0 cm sand with a density of 1.4-kg/dm^3. This layer does not cover the “oceanic” domain in the west. Along the margins where “continent” and “ocean” meet, a 2 cm wide taper was made, representing an erosional slope into the ocean basin.

The model is shortened at constant rate while time-lapse images are recorded. Upon completion, the model is watered and frozen, thus allowing for sectioning and analysis of cross-sections.

The first series of experiments shows that simultaneous synthetic (north dipping) and antithetic (south dipping) segments of subduction, as seen along the strike of the collision front, can be produced by subtle changes of the strength/density profiles and the geometry of the plate boundaries.

For the **eastern segment** (Figure 2a), where the two “continental” plates are separated by a narrow band of “exhumed mantle” the structure is characterized by:

1) initiation and uplift of a symmetrical pop-up structure,
2) incipient collapse of the pop-up by initiation of a conjugate, extensional fault system
3) inversion and rotation of the extensional faults
4) foreland, in-sequence-propagation of a frontal trust system with the development of piggy-back foreland basins.

In contrast, the **western segment** (Figure 2c), where the southern “continental” plate is in direct contact with the northern “oceanic” plate, a series of geometries develops including south-directed and north-directed subduction and obduction in different experiments. The most important parameter in this development seems to be the geometry of the contact between the two plates so that an inclined contact is likely to support subduction, whereas a steep contact is likely to promote obduction. In real cases, this might correspond to extended and sheared margins, respectively.

For the **central segment** (Figure 2b), various types of uplifted accommodation zones were produced. The analysis of sections through the central segment indicates complex deformation centred on a head-on zone of collision.

The simplicity of the foreland basins that develop consistently on the “south” side of the model corresponds to models with a “strong” rheology described in Simpson (2010), whereas a weaker detachment zone would be expected to create a wider fold-thrust belt with a higher structural complexity. The thin, weak layer that represents mantle exhumation prior to shortening clearly has a significant impact on the structural development during the entire deformational phase, and controls the location and topographic development of the model, as also discussed by Sokoutis et al. (2005). Topographic expression of the collision zone is moderate. In light of observations made by Harry et al. (1995), this is to be expected, as the majority of deformation takes place at lower crust level or deeper. Experiments conducted by Keep (1999) showed comparable resultant geometries to the Pyrenean/Cantabrian orogeny but are designed for another collision zone.

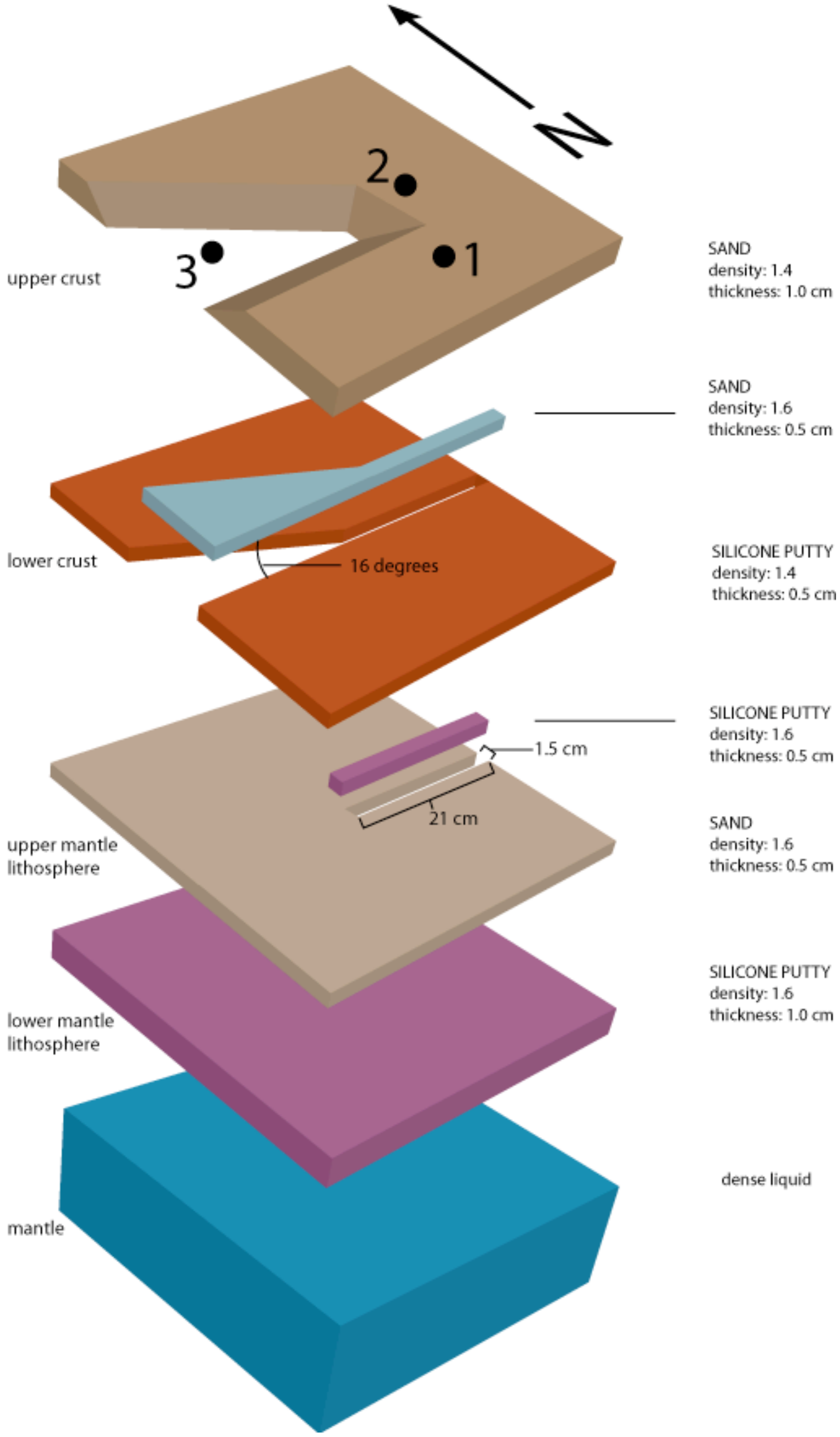

Figure 1. Model design

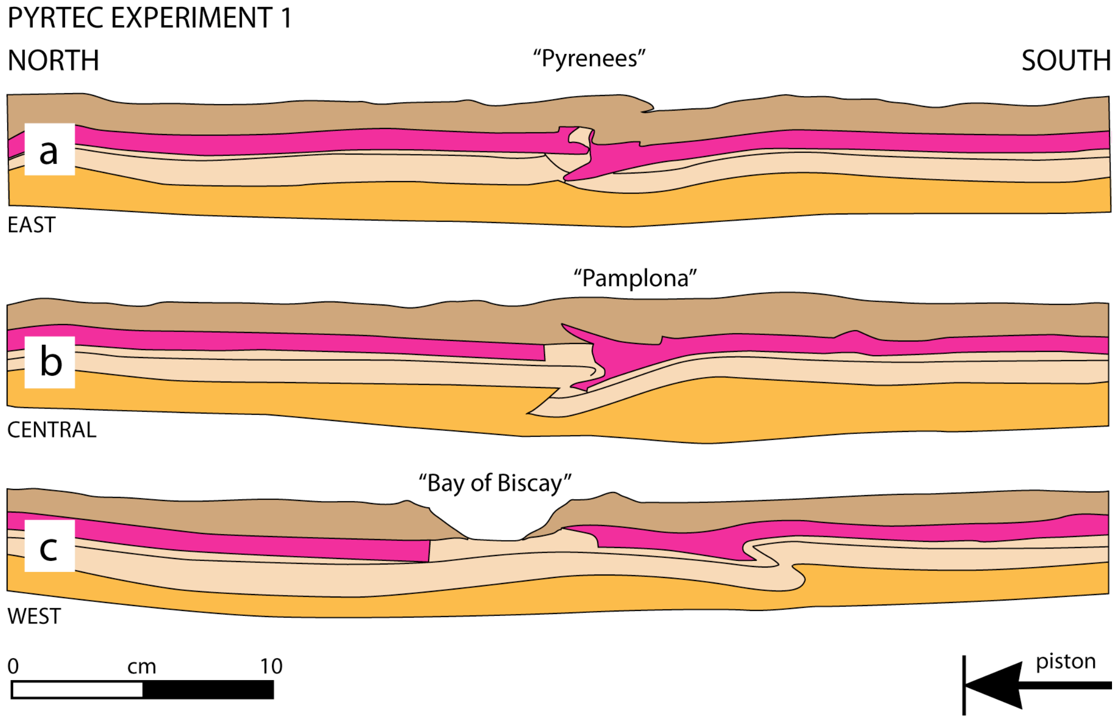

Figure 2. Results from experiment 1, with northward-directed subduction in the "eastern" segment and southward-directed subduction in the "western" segment.

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