Trabajos de Geología, Universidad de Oviedo, 29 : 254-259 (2009)

Lithospheric-scale folding in Iberia from the perspective of analogue modelling

J. Fernández-Lozano[1, 2*], D. Sokoutis[1], E. Willingshofer[1], G. De Vicente[2] and S. Cloetingh[1]

[1]*Faculty of Earth and Life Sciences. Vrije Universiteit, Amsterdam, Netherlands.*

[2]*Applied Tectonophysics Group. Universidad Complutense de Madrid, Spain.*

e-mail: javier.fernandez@falw.vu.nl

Abstract: The Iberian Peninsula is characterized by the presence of regularly spaced and generally E-W to NE-SW trending mountain ranges with mainly E-W crustal-scale thrusts across the whole Peninsula. Intraplate deformation resulting from the convergence between the African and European plates during the Tertiary caused a regular distribution of the main topographic heights and is often related to lithospheric buckling. Consequently, basement structures were reactivated as fault corridors coeval with inversion of the Mesozoic rifts. For gaining insights into the effects of different crustal and mantle rheologies, on the structural and topographic expression of lithospheric buckling, the analogue modelling approach has been employed. Varying the shortening velocity and, hence, the strength of the ductile layers demonstrate that high strength of the ductile crust and upper ductile mantle leads to an increase in lithospheric fold wavelength(s). The folding is associated with the formation of narrow mountain ranges, which are represented by upper crustal pop-ups forming the main topographic reliefs. Shortening is accommodated within the viscous crust underneath the pop-ups by homogeneous thickening leading to lateral thickness variations of the ductile crust. Such thickness variations are in agreement with seismic and gravity data from the Spanish Central System and Toledo Mountains. Experiments performed under low velocities (0.5 cm h^{-1}, representing 7 mm a^{-1} in nature) show close similarities to the natural laboratory Iberia in terms of the general shape and distribution of mountain ranges and basins.

Keywords: lithospheric folding, mountain uplift, pop-up, Iberia, intraplate deformation, Alpine orogeny.

The structure of Iberia is the result of multiple deformation events since the Variscan Orogeny including Jurassic and Cretaceous rifting episodes as well as the Alpine compression. During the latter, N-S compression related to the "Pyrenean" cycle reactivated crustal to lithospheric structures inherited from previous tectonic episodes giving rise to the final distribution and configuration of mountain ranges and their related basins (Fig. 1).

This distribution and configuration of mountain ranges in Iberia has been related to lithospheric folds which are relative periodic structures that affect the continental Iberia (Cloetingh *et al.*, 2002), as well as its Atlantic margin. In this light, the first group of E-W-trending relief is constituted by the Pyrenees, The Cantabrian Mountains and the Galicia Bank. Clearly, this is not an intraplate structure but it is the beginning of the nucleation of the folding process. The Duero and Ebro basins, foreland basins of the Pyrenees and Spanish Central System (to the south) would be part of an intraplate antiform. The second set of reliefs (central) is formed by the Extremadura Spur, The Central System (Portuguese

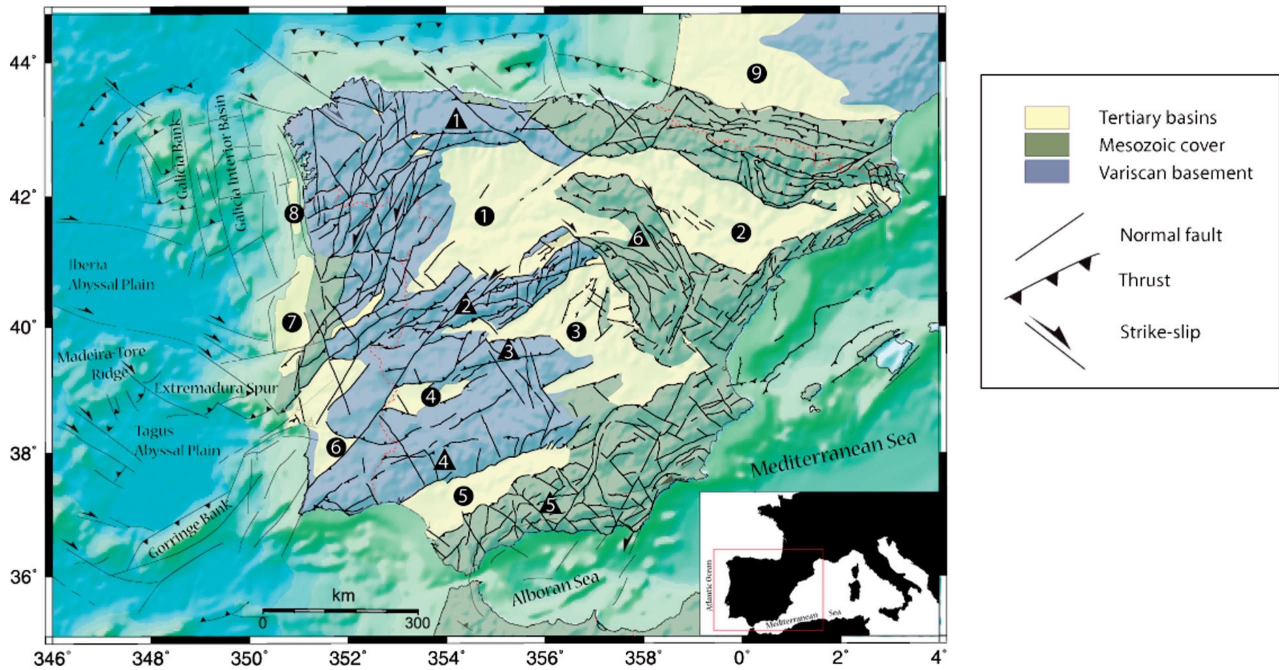

Figure 1. Simplified geologic-tectonic map of Iberia. Circles represent main basins: 1: Duero basin, 2: Ebro basin, 3: Tagus basin, 4: Badajoz basin, 5: Guadalquivir basin, 6: Lisbon basin, 7: Lusitanian basin, 8: Oporto basin, 9: Aquitania basin; triangles represent main mountain ranges: 1: Cantabrian Mountains-Pyrenees, 2: Spanish Central System, 3: Toledo Mountains, 4: Sierra Morena, 5: Betics, 6: Iberian Chain.

and Spanish) and the Iberian Chain (up to its interference with the extensional basins of the Mediterranean margin). Although, locally, the principal guidelines follow the directions of strike-slip corridors that connect different sectors of the central macrostructure, as the NW-SE-striking, right lateral faults of the Iberian Chain or the NNE-SSW-striking structures of the left lateral Vilariça fault system. Mostly, the trend of the main thrust is E-W (even in the Iberian Chain: Demanda, Montalbán, and also in the Central System: Gredos, Toledo). The Southern Border Thrust of the Spanish Central System follows a NE-SW trend, and it is explained by the constrictional strain conditions that followed lithospheric buckling (as has been established from numerical modelling). An additional and clear sign of these constrained conditions of deformation is the westward escape of the Altomira Sierra.

The thickness of the seismogenic layer (Ts) in Iberia is around 10 to 17 km. Such a thickness is less than the effective elastic thickness (Te) of 24 km, on average, obtained by finite element analyses (Martín-Velázquez, 2008). Additionally, the average heat flow in Iberia of about 60-80 mW m^{-2} (Fernández *et al.*, 1998) and the lack of seismic activity in the mantle (IGN Data Base) support the idea that the brittle deformation is confined to the upper crust whereas lower crust and upper mantle are thought to deform in a ductile manner.

Modelling set-up

Based on geophysical and seismological data sets, we adopted a 3-layer model set-up made of a brittle upper crust, a ductile lower crust and a ductile lithospheric mantle (Fig. 2).

The experiments were carried out at the Tectonic-Laboratory of the VU University of Amsterdam. Scaling of the models to the natural prototype was achieved by maintaining similarity in geometry, where 1 cm in the model corresponds to 15 km in nature, dynamics, kinematics and rheology (scaling parameters are summarised in table 1, e.g. Ramberg, 1981).

For the viscous deformation, the dynamic similitude between model and nature has been calculated using the Ramberg number (Rm, see Weijermars and Schmeling, 1986), which relates gravitational to viscous forces.

$$Rm=\rho_0 g l^2/\mu_0 V \qquad (1),$$

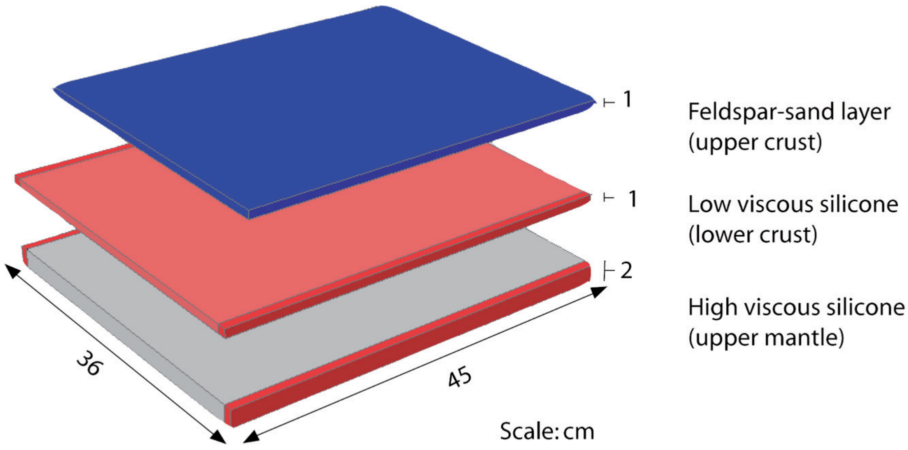

Figure 2. Model set-up. 3-layer model made of high viscous silicone representing the upper mantle, a low viscous silicone for the ductile crust and a K-feldspar sand layer representing the upper crust.

where, ρ_0 is the density, g is the gravitational force, l the thickness of the ductile layer, μ_0 the viscosity and V the velocity.

For brittle behaviour, the dynamic similitude is achieved through the relationship between gravity and frictional forces considering Smoluchowsky Number defined by Ramberg (1981).

$$Sm = \rho_0 g l / \Delta p \qquad (2),$$

where, ρ_o and l the density and thickness of the brittle layer, g the gravitational acceleration and Δp pressure difference.

The 3-layer lithospheric models consist of dry feldspar sand (upper crust), and viscous silicone mixtures (lower crust and upper mantle, see figure 2 and table 1). A weak strip of silicone was placed along the sidewalls to reduce the friction.

These layers float under isostatic equilibrium on a high density fluid resembling the asthenospheric mantle. The experiments were performed within a plexiglass tank, where a solid, vertical wall compresses the 3-layer model with constant velocity simulating unidirectional shortening. Scaled velocities are in the order of 0.5 cm h^{-1} which corresponds to 7 mm a^{-1} for 20% of shortening assumed for the whole Iberia. We test the behaviour of the model lithosphere by increasing the convergence rate (1 cm h^{-1}) for comparison of final results on deformation mechanisms and evolution (see table 1). Erosion and temperature dependent processes, like metamorphism, heating and cooling of the lithosphere as well as possible lateral strength variations are not taken into account in this study. Nevertheless, the modelling results are considered as significant since the above mentioned limitations have minor importance for the folding process.

Convergence rate: 0.5 cm/h and 1 cm/h for Iberia I and Iberia II respectively.
Length scale: 1cm $_{\text{MODEL}}$ = 15 km $_{\text{NATURE}}$
Dynamic Scaling: Ramberg Number*: $\rho g h/\eta V_{EXP} = \rho g h/\eta V_{NAT}$
Smoluchowsky Number*: $\rho_b g h_b c + \mu \rho_b g h_b$

Model Layer	Density ρ (Kg/ccc)	Coeff. of Friction μ	Viscosity η (Pa.s-1)	Power (n)
Brittle crust	1.33	0.8		
Viscous crust	1.39		4.80E+04	1.80
Viscous u.mantle	1.47		1.18E+05	1.47

*See Weijermars and Schmeling, 1986 and Sokoutis *et al.*, 2005

Table 1. Mechanical properties from analogue models.

Results

The experimental results show that the primary response to the velocity increase is that the strength of the ductile crust and upper ductile mantle increases, leading to an increase in fold wavelength(s). This increase in wavelength becomes particularly obvious

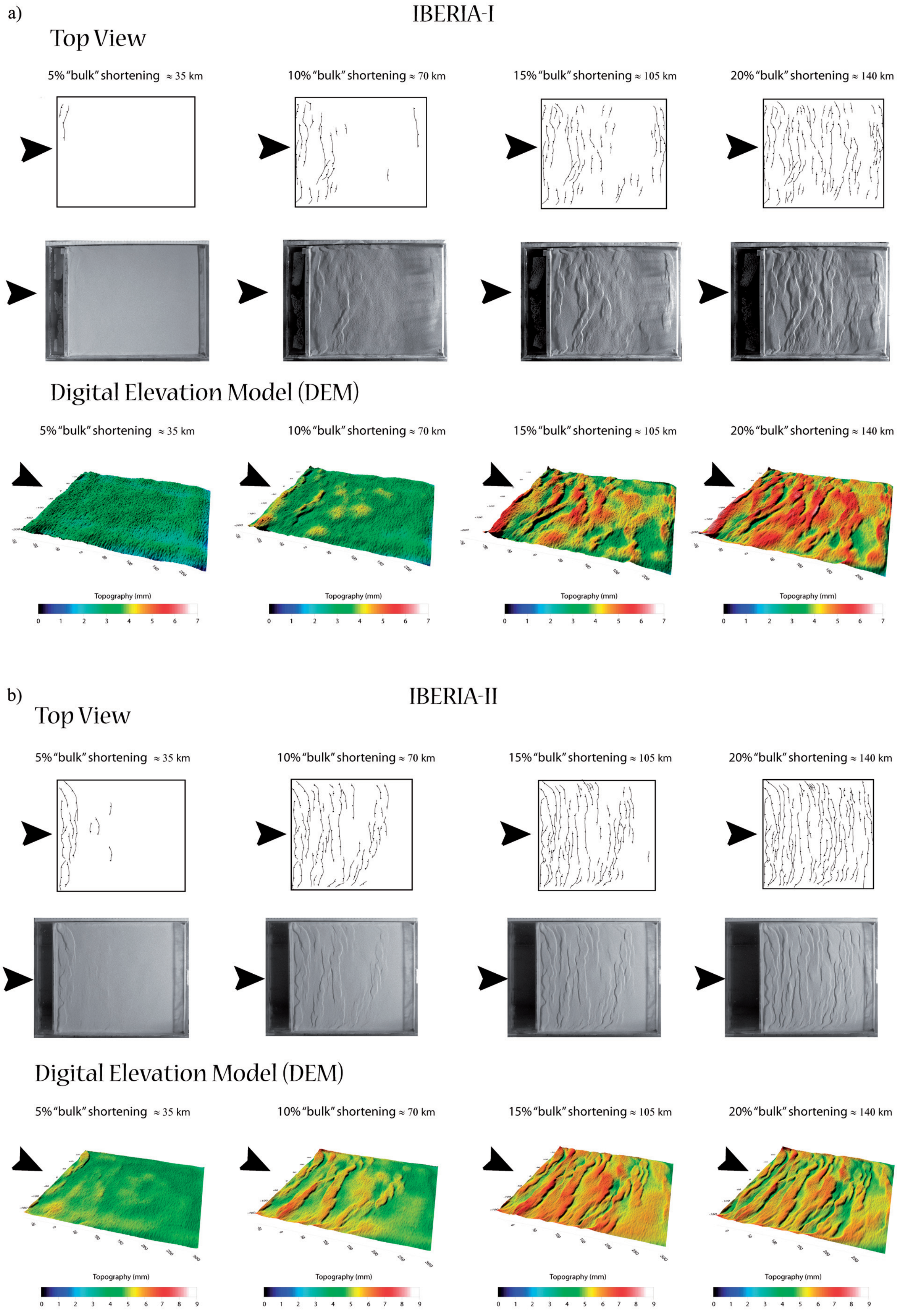

Figure 3. Top-view images and DEM for models a) IBERIA-I and b) IBERIA-II portraying the structural and topographic evolution of the experiments. Arrows indicate the direction of shortening.

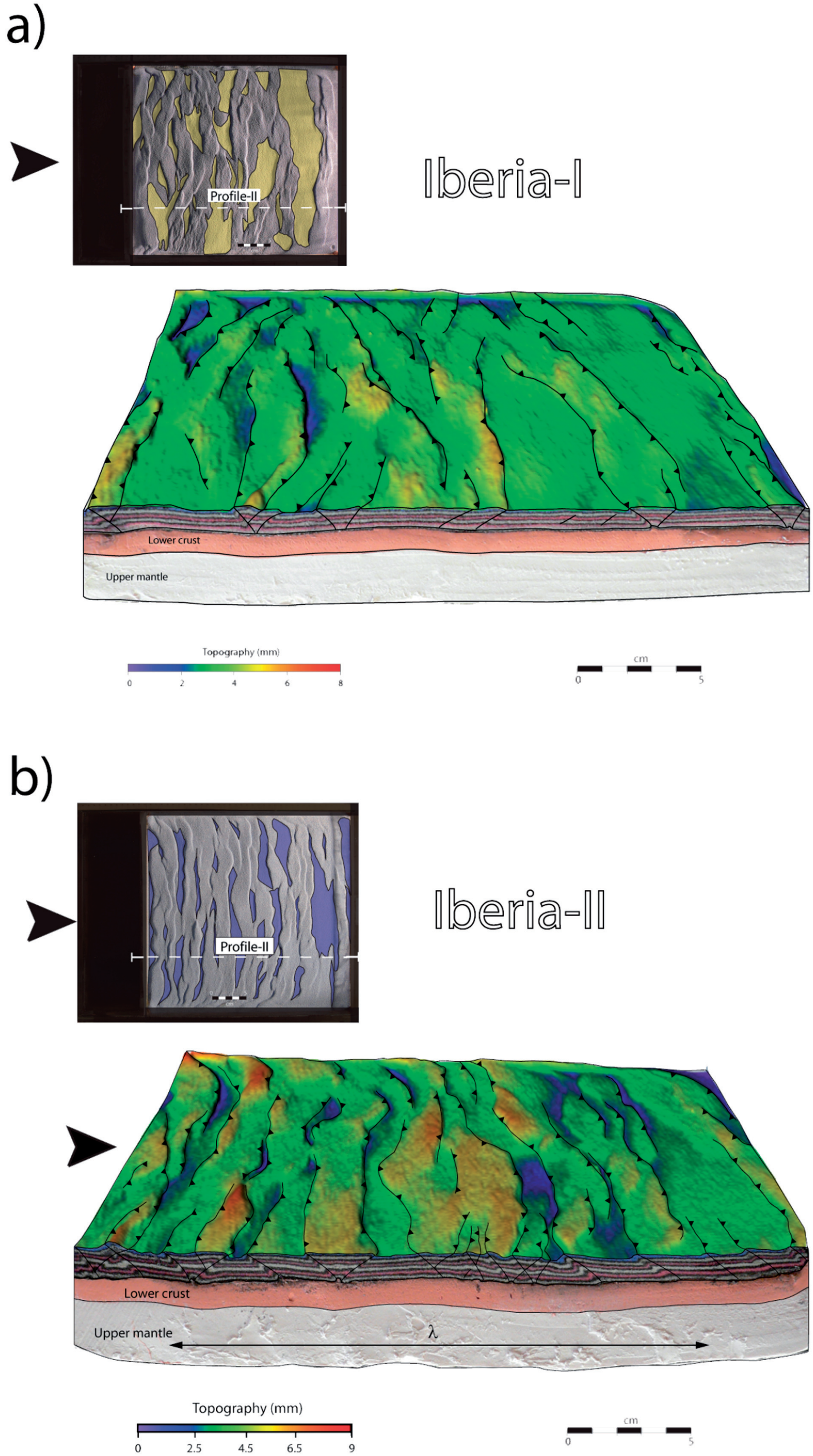

Figure 4. 3D model, (a) from Iberia-I and (b) Iberia-II. Black arrows indicate direction of compression (from left to right). Top images show the situation of cross-sections and display main basins (yellow for model Iberia-I and blue for model Iberia-II).

in the early stages of the model development as shown in the case of model Iberia II (figure 3, lower panel), where regularly spaced pop-ups portray the first order wavelength. Subsequently, these folds are modified by a second order, crustal scale wavelength deformation as characterised by closer spaced pop-ups (Fig. 3b). During the first stages of deformation, mountain ranges formed at inflexion points of the folds are represented by upper crustal pop-ups (see also Davy and Cobbold, 1991; Martinod and Davy, 1994). Thereafter, thrusting advances toward the inner part of the folds giving rise to the main topographic reliefs. Shortening is accommodated within the viscous crust by homogeneous thickening, filling the space provided by the upper crustal pop-ups (Figs. 4a and 4b). Comparison of the cross-sections (Figs. 4a and 4b) also reveals that, in the case of model Iberia II, deformation of the upper crust is more complex such that reverse faults show overprinting relations suggesting their reactivation at different stages of the model evolution.

Discussion and conclusions

The mountain relief from the Iberian Peninsula constitutes Variscan basement uplifts, folds with E-W to NE-SW trend and fault corridors with dominant strike-slip movements (Vegas, 2005).

During the last few years, different research groups tried to relate the relief of Iberia to different processes that take place at lithosphere scale. On the one hand, Fullea *et al.* (2007) propose a homogeneous thickening model based on the redistribution of mass by lower crustal flow. On the other hand, their models show "basin and range-type" structures applied exclusively to the southern part of Iberia that can also be interpreted as a short wavelength folding in that area (Fig. 4).

Long and short wavelength folding has been proposed for whole Iberia by Cloetingh *et al.* (2002) as a result of mechanical decoupling between the different layers of the lithosphere with distinctly different wavelengths for mantle and crustal folds.

The experiments show that the first response to shortening is folding what is consistent with the results of Sokoutis *et al.* (2005). The fact that there is a mechanical decoupling between the different levels of the lithosphere is enough to produce buckling. Consequently, the regularity and wavelength of the topographic uplifts are the response of the different mechanical behaviour between the different layers that comprise the model lithosphere and that of Iberia.

References

CLOETINGH, S., BUROV, E., BEEKMAN, F., ANDEWEG, B., ANDRIESSEN, P. A. M., GARCÍA-CASTELLANOS, D., DE VICENTE, G. and VEGAS, R. (2002): Lithospheric folding in Iberia. *Tectonics*, 21, 5: 1041-1067.

DAVY, P. and COBBOLD, P. R. (1991): Experiments on shortening of a 4-layer model of continental lithosphere. *Tectonophysics*, 188: 1-25.

FERNÁNDEZ, M., MARZÁN, I., CORREIA, A. and RAMALHO, E., (1998): Heat flow, heat production and lithospheric thermal regime in the Iberian Peninsula. *Tectonophysics*, 219: 29-53.

FULLEA, J., FERNÁNDEZ, M., ZEYEN, H. and VERGÉS, J. (2007): A rapid method to map the crustal and lithospheric thickness using elevation, geoid anomaly and thermal analysis. Application to the Gibraltar Arc System, Atlas Mountains and adjacent zones. *Tectonophysics*, 430: 97-117.

IGN DATA BASE: www.igme.es

MARTÍN-VELÁZQUEZ, S., DE VICENTE, G. and ELORZA, F. J. (2008): Resistencia, espesor elástico efectivo y deformación de la litosfera Ibérica (Sistema Central y cuencas del Duero y Tajo). *Geotemas*, 2008.

MARTINOD, J. and DAVY, P. (1994): Periodic instabilities during compression of the lithosphere 2. Analogue experiments. *J. Geophys. Res.*, 99: 12057-12069.

RAMBERG, H. (1981): *Gravity, deformation and the Earth´s crust in theory, experiments and geologic application* (2nd Ed.). Academic Press, London, 452 pp.

SOKOUTIS, D., BURG, J. P., BONINI, M., CORTI, G. and CLOETINGH, S. (2005): Lithospheric-scale structures from the perspective of analogue continental collision. *Tectonophysics*, 406: 1-15.

VEGAS, R. (2005): Deformación alpina de macizos antiguos. El caso del Macizo Ibérico (Hespérico). *B. Real Soc. Esp. Hist. Nat. (Secc. Geol.)*, 100, 1-4: 39-54.

WEIJERMARS, R. and SCHMELING, H. (1986): Scaling of Newtonian and non-Newtonian fluid dynamics without inertia for quantitative modelling of rock flow due to gravity (including the concept of rheological similarity). *Phys. Earth Planet. Inter.*, 43, 186: 316-330.