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Effective elastic thicknesses of the lithosphere in the Central Iberian Peninsula from heat flow: Implications for the rheology of the continental lithospheric mantle

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Abstract

The traditional view of the rheology of the continental lithosphere, sometimes known as the "jelly sandwich model", consists of a strong upper crust, a weak lower crust, and a strong upper lithospheric mantle. Some authors argue, however, that the lithospheric mantle is weak and contributes little to the total strength and the effective elastic thickness of the lithosphere; this weakness is claimed to be due to the mantle being wet or subjected to temperatures higher than usually believed. This paper uses the relationship between rheology of the lithosphere and heat flow to calculate theoretical effective elastic thicknesses for three regions of the central Iberian Peninsula (the Duero Basin, the Spanish Central System and the Tajo Basin), taking into account the contribution of the crust and the lithospheric mantle, for dry and wet rheologies. We found that a wet peridotite rheology for the lithospheric mantle is generally consistent with independent (based on Bouguer coherence or flexural modeling) estimates of the effective elastic thickness for the study area, whereas a dry peridotite rheology cannot be reconciled with them. Moreover, the contribution of the mantle to the bending moment of the lithosphere, and therefore to both the effective elastic thickness and the total strength of the lithosphere, is important, and it may even be the dominant contribution. Therefore, the jelly sandwich model may be considered valid for the central Iberian Peninsula.

Keywords: Continental lithosphere; Effective elastic thickness; Heat flow; Iberian Peninsula; Rheology

1. Introduction

An interesting debate has developed in recent years concerning the rheology of the lithosphere of the Earth's continental areas and the strength of the crust and upper mantle. The traditional view involves a strong upper crust, a weaker lower crust, and a strong upper lithospheric mantle with a very strong upper layer. This concept was developed using laboratory experiments on rocks deformation in order to construct strength profiles for the lithosphere (e.g., Brace and Kohlstedt, 1980; Ranalli and Murphy, 1987; Ranalli, 1997; Kohlstedt et al., 1995; Burov and Diament, 1995; Cloetingh and Burov, 1996). However, this simple view is complicated somewhat by compositional, and therefore rheological, stratification of the crust (Ranalli and Murphy, 1987), although the basic points are not altered. This

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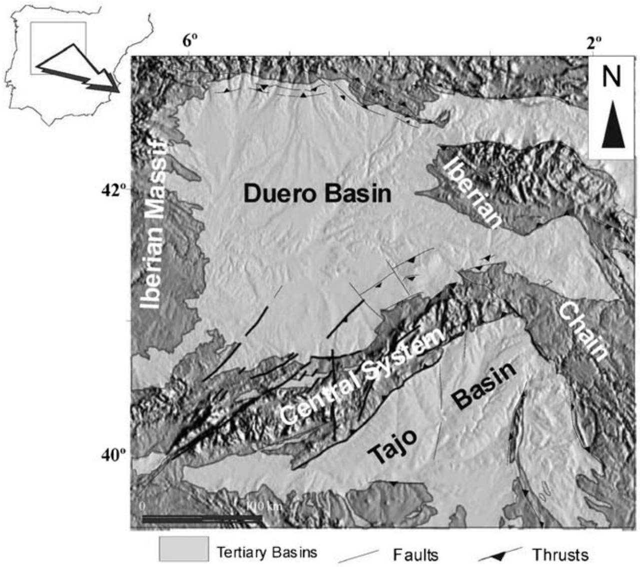

Fig. 1. Geological setting.

model is sometimes referred to as the “jelly sandwich model”, a term that has found its way into the title of several papers.

This traditional view was questioned, however, by Maggi et al. (2000) and Jackson (2002). These authors proposed that the origin of the great majority of earthquakes, if not all, in continental areas lay in the crust (with very few, if any, originating in the lithospheric mantle) and that the effective elastic thickness involved the crust only. These authors based their conclusions on (1) there is a total or near total lack of mantle earthquakes in continental areas, and (2) the effective elastic thickness of the lithosphere is generally somewhat less than the seismogenic thickness. Both observations would be indicative of a weak upper lithospheric mantle, which would make only a small contribution to the strength of the lithosphere.

In the jelly sandwich model, the mantle’s strength is largely a consequence of olivine controlling its mechanical behavior, and of assuming a dry (dehydrated) rheology for this mineral. In contrast, Maggi et al. (2000) and Jackson (2002) suggested that a wet rheology for the lithospheric mantle would be more appropriate given that metamorphic processes could provide the necessary water. Indeed, even a small amount of water would drastically reduce the strength of the rocks. In this view, the amount of water present in the minerals of the lower crust would vary from one region to another, giving rise to local differences in strength. Later, McKenzie et al. (2005) suggested an alternative explanation based on geotherms fitted to depths and temperatures obtained from garnet peridotite nodules. After these authors, this would result in increased temperatures at the Moho, thus reducing the ductile strength of the continental upper mantle. McKenzie et al. (2005) recognized, however, that the ductile strength may still be appreciable in areas with a relatively thin crust.

The above arguments were contested by Watts and Burov (2003). According to these authors, no relationship exists between the thickness of the seismogenic layer and the effective elastic thickness, and they emphasize that the latter concept refers to the total strength of the lithosphere and not necessarily to the thickness of any real layer. In turn, Afonso and Ranalli (2004) suggested that the mechanical structure of the lithosphere varies locally, depending upon the rheological stratification, the thermal regime and the thickness of the crust. For these reasons, they claim, it is inappropriate to speak of a general model for the mechanical structure of the lithosphere.

A relationship exists between the effective elastic thickness and the thermal and mechanical structure of the lithosphere (McNutt, 1984; McAdoo et al., 1985; for a review, see Watts, 2001). In research about other planetary bodies, this relationship has been used to calculate the heat flow from estimates of the effective elastic thickness of the lithosphere (e.g., Solomon and Head, 1990; Anderson and Grimm, 1998; McGovern et al., 2002; Ruiz, 2005; Ruiz et al., 2006a). The present work considers the opposite using available heat flow values to calculate theoretical effective elastic thicknesses in the central Iberian Peninsula. The study area (Fig. 1) consists of two Cenozoic sedimentary basins, the Duero and Tajo Basins, separated by the Spanish Central System, a NE-SW trending mountain chain. These structures were formed in an overall environment of plate convergence, which began in the Late Cretaceous and which is responsible for crustal reworking and the deformation in the interior of the Iberian plate (e.g., Gibbons and Moreno, 2002).

The calculations use either dry or wet rheologies for the crust and lithospheric mantle, and the results are compared with estimates of the effective elastic thickness obtained by other methods. The objective of these calculations is to obtain information about the dry or wet rheology of the lithospheric mantle in continental areas, and about the relative contribution of the mantle and crust to the total bending moment of the lithosphere, thus contributing to clarify the relative contribution of the mantle to the total strength of the lithosphere.

2. Effective elastic thickness and lithospheric strength

The effective elastic thicknesses are calculated from the surface heat flow using the methodology described by McNutt (1984), which relates the effective elastic thickness and the strength envelope of the lithosphere, as modified by Ruiz et al. (2006b), for a rheologically stratified lithosphere. This allows estimation of the total bending moment of the lithosphere from the respective contributions from the crust and mantle.

This methodology is based on the condition that the bending moment of the mechanical lithosphere must be the same as that of the equivalent elastic plate. Since the former is estimated from the strength envelope of the lithosphere, the link between the effective elastic thickness and the heat flow is due to the dependence of the ductile strength on the temperature profile.

The bending moment of the elastic plate is given by:

$$M = \frac{EKT_e^3}{12(1-\nu^2)}, \tag{1}$$

where E is the Young's modulus, K is the plate curvature, T_e is the effective elastic thickness, and ν is the Poisson's coefficient. The effective elastic thickness is not the thickness of a real layer but a measure of the total strength of the lithosphere which integrates the contributions from both the brittle and ductile layers of the lithosphere (for reviews, see Watts, 2001; Watts and Burov, 2003). In the case of mechanically decoupled crust and mantle, the total bending moment must be calculated from the respective contributions of each. Assuming equal elastic constants (and therefore equal plate curvature, according to Eq. (1)) for the crust and lithospheric mantle, the total bending moment is (McNutt et al., 1988; Burov and Diament, 1992):

$$M = \frac{EK}{12(1-\nu^2)}(T_{e(crust)}^3 + T_{e(mantle)}^3) = M_{crust} + M_{mantle}, \tag{2}$$

where $T_{e(crust)}$ and $T_{e(mantle)}$ are the effective elastic thicknesses of the crust and mantle, respectively, and M_{crust} and M_{mantle} are the crust and mantle contributions to the total bending moment. The effective elastic thickness of the lithosphere is:

$$T_e = (T_{e(crust)}^3 + T_{e(mantle)}^3)^{1/3}. \tag{3}$$

The bending moment of a mechanical lithosphere with a decoupled crust and mantle is given by the addition of the contributions of the crust and lithospheric mantle:

$$M = \int_0^{b_m} \sigma(z)(z - z_{n(crust)})\,dz + \int_{b_c}^{T_m} \sigma(z)(z - z_{n(mantle)})\,dz, \tag{4}$$

where b_m and T_m are the mechanical thickness of the crust and lithosphere, respectively, $\sigma(z)$ is the smallest value (at depth z) for the brittle strength, the ductile strength or the fiber stress, $z_{n(crust)}$ and $z_{n(mantle)}$ are the depths to the neutral stress planes in the crust and lithospheric mantle, respectively, and b_c is the total thickness of the crust. T_m is defined as the depth at which the strength becomes noticeably low, for example 10 MPa (Ranalli, 1994), and below which there are no further significant increases in strength. By analogy, b_m can be defined as the depth at which the crust strength reaches the value of 10 MPa.

Table 1
Rheological parameters (after Ranalli, 1997)

	A (MPa^{-n} s^{-1})	n	Q (kJ mol^{-1})
Dry quartzite	6.7×10^{-6}	2.4	156
Wet quartzite	3.2×10^{-4}	2.3	154
Dry peridotite	2.5×10^{4}	3.5	532
Wet peridotite	2.0×10^{3}	4.0	471

The brittle strength is calculated according to the expression:

$$\sigma_1 - \sigma_3 = \alpha\rho g(1-\lambda)z, \tag{5}$$

where α is a factor depending on the stress regime (0.75 for tension and 3 for compression, according to Ranalli and Murphy (1987), ρ is the density, g (= 9.8 ms^{-2}) is the acceleration due to the gravity, λ is the pore pressure factor, and z the depth. The ductile strength is calculated according to the equation:

$$(\sigma_1 - \sigma_3)_\mathrm{d} = \left(\frac{\dot{e}}{A}\right)^{1/n} \exp\left(\frac{Q}{nRT}\right), \tag{6}$$

where $\dot{e}$ is the strain rate, A, p, and n are laboratory-determined constants, Q is the activation energy of creep, R (= 8.3145 J mol^{-1} K^{-1}) is the gas constant, and T is the absolute temperature. The fiber stress is calculated from the expression:

$$\sigma_\mathrm{fib} = \frac{EK(z - z_\mathrm{n})}{1 - \upsilon^2}. \tag{7}$$

Finally, the condition of zero net axial force is imposed for crust and mantle,

$$\int_0^{b_\mathrm{m}} \sigma(z)\,\mathrm{d}z = \int_{b_\mathrm{c}}^{T_\mathrm{m}} \sigma(z)\,\mathrm{d}z = 0. \tag{8}$$

The brittle strength is calculated for tension, since the maximum curvature is concave downward, due to the flexural response of the lithosphere to the load of the Central System. Tension therefore develops in the upper part of the curved plate. The density of the brittle crust, adequate for rocks in the upper crust, is taken as 2700 kg m^{-3}, and the pore pressure is assumed as 0.37, which corresponds to the ratio between the hydrostatic pressure and the lithostatic pressure of the crust.

The ductile strength of the crust is calculated using the flow laws of dry or wet quartzite without taking into account a possible rheological stratification. The lower crust of the central Iberian Peninsula is of a felsic granulite nature (Villaseca et al., 1999), and bearing in mind its flow law it should not appreciably contribute to the strength of the lithosphere; it is therefore not taken into account in the present work (see Tejero and Ruiz, 2002). In fact, the felsic lower crust guarantees the mechanical decoupling between the upper crust and the lithospheric mantle. In turn, the mid crust of the area is made of intrusive felsic materials (Villaseca et al., 1999) similar to those forming the upper crust in many continental areas; its mechanical behavior is therefore likely to be similar. For the lithospheric mantle, either dry or wet peridotite rheologies (Ranalli, 1997) are used. Table 1 shows the constants for the flow laws.

For the calculation of the fiber stress, the plate curvature is taken as 5×10^{-9} m^{-1} (Gómez-Ortiz et al., 2005), a value deduced from Moho deflection in this zone (Suriñach and Vegas, 1988). Young's modulus and the Poisson ratio for the whole lithosphere were taken as 100 GPa and 0.25, respectively.

3. Temperature profiles

Temperature profiles are calculated by assuming radioactive heat sources homogeneously distributed in two layers: the upper crust enriched in heat-producing elements, and the middle and lower crust (taken joined for this calculation), which are poorer in heat sources. The temperature at depth z in each crust layer is:

$$T_\mathrm{z} = T_\mathrm{s} + \frac{F_\mathrm{s} z}{k} - \frac{Hz^2}{2k}, \tag{9}$$

Table 2
Values of the upper crust heat production rate (H_r), thickness of the upper crust (b_r), total crust thickness (b_c), and heat flow (F) used for the calculations of temperature profiles

	H_r (μW m^{-3})	b_r (km)	b_c (km)	F (mW m^{-2})
Duero Basin	2.0	14	31	59 ± 5[a]
Spanish Central System	3.3	11	34	70[b]
Tajo Basin	2.5	14	31	68 ± 5[a]

For further explanations see text.
[a] Mean value of heat flow measurements, and associated error.
[b] Heat flow derived from thermal isostasy.

where T_s and F_s are the temperature and heat flow at the layer top, k is the layer thermal conductivity, and H is the layer volumetric heat production rate. Linear thermal gradients are assumed for the lithospheric mantle (radiogenic sources are sparse in the lithospheric mantle), according to:

$$T_z = T_{bc} + \frac{F_m(z - b_c)}{k}, \tag{10}$$

where T_{bc} is the temperature at the crust base, and F_m is the mantle heat flow. These calculations assume $k = 2.5$, 2, and 3.5 W m^{-1} K^{-1} for upper crust, middle/lower crust and lithospheric mantle, respectively. The surface temperature was taken as 288 K. The mantle heat flow is obtained from the surface heat flow by subtraction of the crust component.

Table 2 shows the values used in the different areas for the thickness of the upper crust (b_r), the total crust thickness, the surface heat flow, and the volumetric heat production rate in the upper crust (H_r). The upper crust thickness and the total crust thickness in the Duero and Tajo Basins and the Central System are based on seismic data (Banda et al., 1981; Suriñach and Vegas, 1988; ILIHA DSS Group, 1993). The value for b_r was taken to be equal to the depth to the base of the upper crust, which implies including 1–2 km of sediments in the radiogenically productive layer of the basins. However, given the high heat production of these sediments (e.g., Fernández et al., 1998), this would have no important effect on the temperature profiles. The H_r value for the Duero Basin was taken from the results in Fernández et al. (1998) and Tejero and Ruiz (2002) (2.3 and 1.8 μm^{-3}, respectively) using the concept of thermal isostasy. The H_r values for the Central System and the Tajo basin are those provided by Tejero and Ruiz (2002).

The range of heat flow values used requires a more thorough explanation. The heat flow measurements in the Tajo basin (for a compilation see Fernández et al., 1998) fall within the range between 62 and 75 mW m^{-2} (except for one which is clearly higher), with a mean value of 68 ± 5 mW m^{-2} ($n = 6$); similarly, the thermal structure models for this area in Tejero and Ruiz (2002) fit the surface elevation, by mean of the thermal isostasy, a heat flow of 65 mW m^{-2} in the south of the basin and 70 mW m^{-2} in the north. The spread of heat flow values is greater in the Duero basin (see Fernández et al., 1998), and includes some values that are discordantly high. If these are eliminated, along with four very different values measured at sites close to one another (showing their unreliability) in the León province, the range falls between 52 and 67 mW m^{-2} (Fernández et al., 1998) with a mean of 59 ± 5 mW m^{-2} ($n = 6$). This agrees well with the 60 mW m^{-2} obtained by Fernández et al. (1998) and Tejero and Ruiz (2002) by fitting of surface elevation. No good measurements of heat flow are available for the Central System. Tejero and Ruiz (2002) obtained a value of 70 mW m^{-2} by fitting of surface elevation; this value is similar to the mean of 67 mW m^{-2} obtained by Fernández et al. (1998) for heat flow measurements in the alpine ranges of the Iberian Peninsula. Therefore, the heat flow ranges used in the calculations are 54–64 mW m^{-2} for the Duero basin, and 63–73 mW m^{-2} for the Tajo basin; for the Central System a nominal value, obtained from thermal isostasy by Tejero and Ruiz (2002), of 70 mW m^{-2} is used.

For the volumetric heat production rate in the mid and lower crust, a single value of 0.3 μW m^{-3} was used for the whole study area. For the local values of H_r, b_r, b_c and mean heat flow, this value allows a mantle heat flow of 27 ± 1 mW m^{-2} in the three zones analyzed. This value is similar to those reported for alpine areas (Cermak, 1989) and to those obtained by Tejero and Ruiz (2002) for the area here studied.

4. Results

Fig. 2 shows the effective elastic thickness in the Duero and Tajo basins in terms of surface heat flow (F). Table 3 shows results for the Central System for $F = 70$ mW m^{-2}. The four possible combinations of dry and wet rheologies

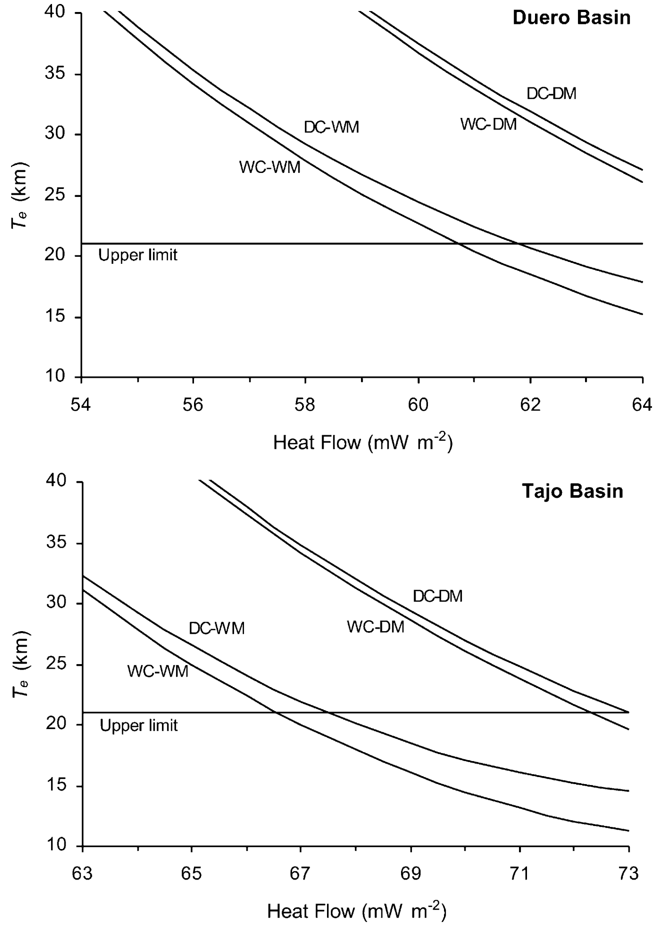

Fig. 2. Effective elastic thickness, in terms of heat flow, in the Duero and Tajo basins. DC and WC indicate dry crust and wet crust, respectively; DM and WM indicate dry mantle and wet mantle, respectively. The horizontal line shows the highest value obtained for the effective elastic thickness in the study area.

for the crust and mantle are used in the calculation. For comparison, Gómez-Ortiz et al. (2005) previously obtained an elastic thickness of 14–21 km for the central Iberian Peninsula from the coherence between topography and Bouguer anomaly; similarly, Pérez-Gussinye and Watts (2005) obtained best defined fits of 13–15 km for the Iberian peninsula from Bouguer coherence (see their Fig. 3). On the other hand, Van Wees et al. (1996) calculated an elastic thickness of 7 km for the Tajo basin using flexure modeling. Fig. 2 therefore also shows the value of 21 km as the upper limit of the effective elastic thickness for the study area.

The comparison of our results with the previously obtained values from other methods clearly favors a wet rheology for the lithospheric mantle under the central Iberian Peninsula. Indeed, in the Tajo basin a dry peridotite rheology would only be marginally possible at the upper limit of the heat flow range, and in the Duero basin it would not be possible at all; in the Central System, a dry peridotite rheology is not possible for the nominal heat flow, although this

Table 3
Results for the Spanish Central System for $F = 70\ \mathrm{mW\ m^{-2}}$

Upper mantle rheology	Upper crust rheology	T_e (km)	M_{mantle}/M_{crust}
Dry peridotite	Dry quartzite	29	5.0
Dry peridotite	Wet quartzite	28	11.8
Wet peridotite	Dry quartzite	18	0.4
Wet peridotite	Wet quartzite	15	1.0

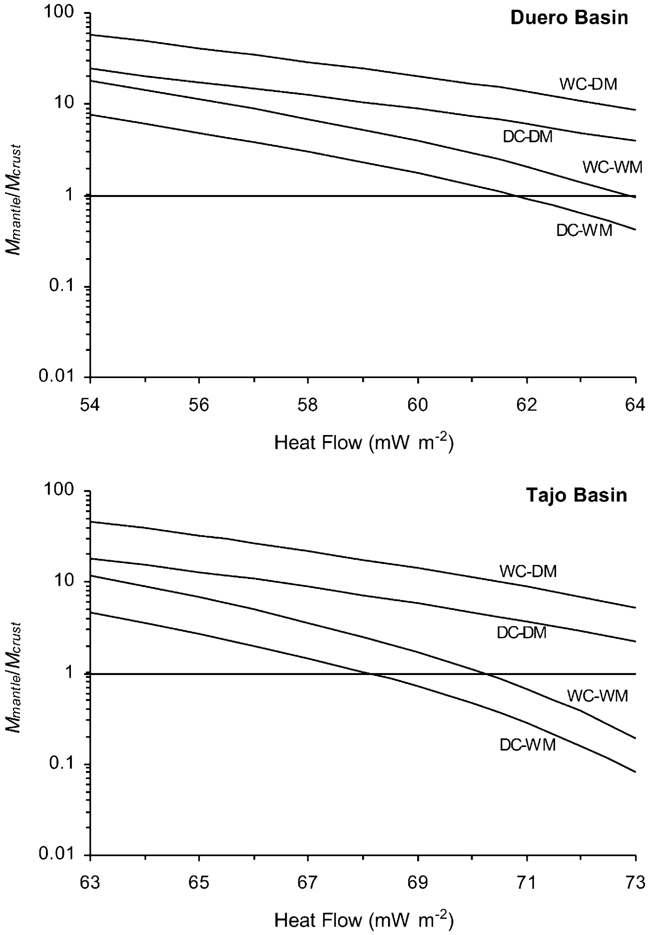

Fig. 3. Ratio $M_{\mathrm{mantle}}/M_{\mathrm{crust}}$ in terms of heat flow. DC and WC indicate dry crust and wet crust, respectively; DM and WM indicate dry mantle and wet mantle, respectively. To facilitate comparisons, the horizontal line represents $M_{\mathrm{mantle}}/M_{\mathrm{crust}} = 1$.

result is lesser robust, since this heat flow value is not derived from field measurements. In contrast, the wet peridotite rheology provides very good results for the Tajo basin and Central System, and acceptable results for the Duero basin.

Fig. 3 shows the ratio $M_{\mathrm{mantle}}/M_{\mathrm{crust}}$ for the Duero and Tajo basins in terms of heat flow, and Table 3 shows this ratio for the nominal heat flow used for the Central System. The bending moment is proportional to T_{e}^3(see Eqs. (1)–(3)), therefore this ratio provides information on the contribution of the mantle and the crust to the effective elastic thickness of the lithosphere considered as a whole. For a dry peridotite rheology $M_{\mathrm{mantle}}/M_{\mathrm{crust}} > 1$ in all the cases, which implies a dominant role for upper mantle strength. For a wet peridotite rheology the contribution of the lithospheric mantle should be significant. In this case, for the mean values of the heat flow range $M_{\mathrm{mantle}}/M_{\mathrm{crust}} > 1$ in the basins; for the Central System $M_{\mathrm{mantle}}/M_{\mathrm{crust}}$ is either ≈ 1 or < 1 depending on whether a dry or wet rheology is adopted for the crust.

Fig. 3 also shows that the relative contribution of the lithospheric crust to the bending moment of the lithosphere is drastically reduced as the heat flow increases. This is because the variation in strength as a function of the temperature is proportionally greater for peridotite (dry or wet) than for quartzite (dry or wet). In addition, the crust always has an upper brittle layer (sometimes thicker, sometimes thinner), which is not necessarily true for the mantle. Therefore, an increase in heat flow would reduce the relative contribution of the upper mantle to the total strength of the lithosphere (on some occasions to practically nil), and hence to the effective elastic thickness.

Rheologies used in this work are of a general character. Whereas we considered these rheologies adequate to represent lithosphere rocks in the Iberian Peninsula, it is worth remind that rheology of lithospheric rocks must be taken cautiously. The use of a stronger crustal rheology would increases both the effective elastic thickness and the relative contribution of the crust to the total bending moment; this, in turn, favors a weak mantle rheology to obtain consistency with the condition $T_e \leq 21$ km. The use of a weaker mantle rheology, as for example the wet Anita Bay dunite (Chopra and Paterson, 1984), somewhat reduces the mantle ductile strength, and hence both the effective elastic thickness and the M_{mantle}/M_{crust}, although insufficiently for significantly alter the main conclusion of this work.

5. Discussion and conclusions

Those authors that maintain the lithospheric mantle of continental areas to be generally weak and not to contribute greatly to the strength of the lithosphere initially argued that the presence of water reduces the viscosity of the upper mantle rocks (Maggi et al., 2000; Jackson, 2002). We have found that a wet rheology for the lithospheric mantle in the central Iberian Peninsula is consistent with independent estimates of the effective elastic thickness of the area. However, this does not imply that the upper mantle is weak or that it makes little contribution to the strength of the lithosphere. Indeed, our results indicate that for wet rheology the mantle contribution to the bending moment of the lithosphere is important (maybe dominant), and therefore to the effective elastic thickness and the total strength of the lithosphere. It is even possible that the mantle top behaves in a brittle fashion.

If the upper mantle is cold enough, the ductile strength (Eq. (6)) of the wet peridotite may surpass its brittle strength (Eq. (5)). In this case there ought to be a layer in the upper mantle that behaves in a brittle fashion. Fig. 4 shows the brittle strength for compression and tension, and the ductile strength for both dry and wet peridotite, in the mantle top. In the calculation of the brittle strengths, the mean density of the crust was taken to be 2800 kg m^{-3}. This is greater than that used to calculate the effective elastic thickness and the ratio M_{mantle}/M_{crust} since the brittle strength of the mantle top depends on the density of the entire crust, whereas, in the crust, brittle behavior would be dominant in the

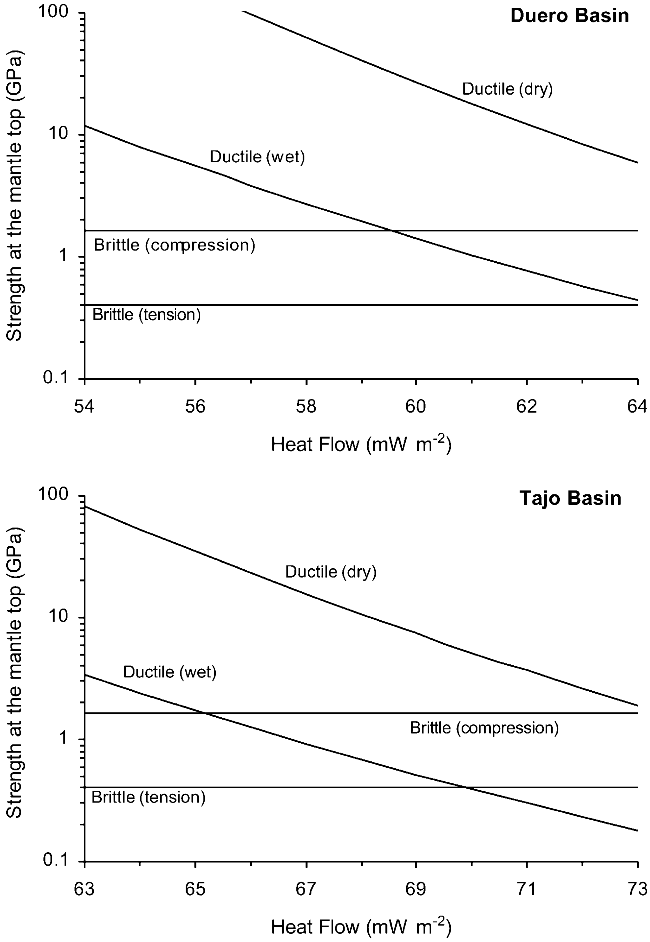

Fig. 4. Brittle strength (for compression and tension) and ductile strength (for dry and wet peridotite) at the mantle top, in terms of heat flow.

Table 4
Results for nominal models with wet peridotite rheology for the lithospheric mantle and heat flow equal to the mean heat flow in each zone

Zone and nominal heat flow (mW m^{-2})	T_e (km)	M_{mantle}/M_{crust}	Behavior at the mantle top (compression)	Behavior at the mantle top (tension)
Duero Basin (59)	25–27	2.3–5.2	Brittle	Brittle
Central System (70)	15–18	0.4–1.0	Ductile	Ductile
Tajo Basin (68)	18–20	1.0–2.5	Ductile	Brittle

upper, less dense part. Fig. 4 and Table 3 (see also Table 4) shows that for wet peridotite, either a brittle or ductile behavior could be dominant at the mantle top depending on the heat flow and stress regime. Although the dry peridotite rheology is clearly not favored by our results, this possibility was also analyzed for the sake of comparison: in this case a brittle behavior is obtained in all the cases studied.

The results here presented suggest therefore a wet rheology for the upper lithospheric mantle in the central Iberian Peninsula, and that this makes a large contribution to the strength and the effective elastic thickness of the lithosphere. (Table 4 summarizes the results obtained for wet peridotite and the mean values of the heat flows used to construct Figs. 2–4.) Consequently the strength of the mantle top in the central Iberian Peninsula would be in clear contrast with that of the lower, felsic and weak, crust: thus, the jelly sandwich model can be considered valid for this zone. These results contradict the view held by Maggi et al. (2000) and Jackson (2002), but are in agreement with that Cloetingh and Van Wees (2005), who showed that the strength of the mantle has played an important role in the deformation of the intraplate lithosphere of Europe.

As shown by Afonso and Ranalli (2004), the strength of the continental lithosphere depends on many factors. One should therefore be cautious when trying to draw any general conclusions. Factors such as crustal thickness and heat flow largely control the temperature and therefore the mechanical behavior of the lithospheric mantle. Recently, McKenzie et al. (2005) emphasized that in areas where the crust is thin, the continental uppermost mantle can be cold and strong. Our results strongly support this opinion, although they favor a wet rheology for the upper mantle. It would appear clear, therefore, that the mechanical behavior and rheological stratification of the lithosphere in continental areas are mainly a consequence of local conditions.

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