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How rigid is Europe's lithosphere?

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[1] The integrated strength distribution and variations of the effective elastic plate thickness (T_e) have been estimated for the European lithosphere based on thermal and rheological data for the crust and upper mantle. The new results show a significant spatial variability demonstrating that both 'jelly sandwich' and 'crème brûlée' models might be valid depending on lithospheric physical conditions. In most of Europe crustal strength provides a relatively large contribution (∼50%) to the lithospheric strength. Western Europe appears mostly characterized by mechanically decoupled lithospheric layers, low strength and T_e < 30 km. The contribution of the mechanically strong mantle to T_e is low in most parts of western Europe. No clear relationship between T_e and thermal age is found in the continent: the values for the tectonic provinces older than 85 Ma are significantly smaller than theoretically expected for their age and crustal thickness, whereas the opposite is true for the younger provinces. **Citation:** Tesauro, M., M. K. Kaban, and S. A. P. L. Cloetingh (2009), How rigid is Europe's lithosphere?, *Geophys. Res. Lett.*, *36*, L16303, doi:10.1029/2009GL039229.

1. Introduction

[2] The strength of the Earth's lithosphere has been debated since the beginning of the last century, when the concept of a strong lithosphere overlying a viscous asthenosphere was introduced [*Barrell*, 1914]. The strength of the lithosphere and its spatial and temporal variations is important for many geodynamic applications [e.g., *Jackson*, 2002; *Burov and Watts*, 2006]. One of the important parameters directly related to the strength distribution is the effective elastic thickness of the lithosphere (T_e), which corresponds to the thickness of the equivalent elastic layer, characterized by the same flexural rigidity as the lithosphere plate. European lithosphere is characterized by large spatial strength and T_e variations, with a pronounced decrease from the Archean Craton to Phanerozoic western Europe [e.g., *Pérez-Gussinyé and Watts*, 2005]. At the same time, methods based on cross-spectral analysis of gravity and topography data [e.g., *Forsyth*, 1985; *McKenzie*, 2003] and on the analysis of the Yield Strength Envelope (YSE) [*Burov and Diament*, 1995] often provide different estimates of T_e. In this paper, we combine the recent data for the crust and upper mantle to construct a comprehensive rheological model of the lithosphere for central and western Europe. One of the principal data sources is EuCRUST-07 [*Tesauro et al.*, 2008], a new 3D crustal model, based on several hundred seismic profiles and receiver functions data. This model is used to determine crustal parameters and lithology. New information also comes from the recent tomography model [*Koulakov et al.*, 2009], which is a-priori corrected for crustal effects. These data are important for a robust determination of temperature variations within the lithosphere [*Tesauro et al.*, 2009] (Data Set S1 in the auxiliary material).[4] In this study we use these new constraints to examine quantitatively the contribution of the crustal strength to the total lithospheric strength and to calculate T_e variations from strength of different lithospheric layers. Furthermore, the new results show that some area are better described by 'jelly sandwich' and other by 'crème brûlée' models, much debated recently [*Jackson*, 2002; *Burov and Watts*, 2006].

2. Jelly Sandwich and Crème Brûlée' Rheology of Europe's Lithosphere

[3] In a previous study [*Tesauro et al.*, 2009] we have estimated the strength distribution within the lithosphere by integrating the YSE. The rheological parameters are given in Figure S1 in the auxiliary material. These results show that the East European Platform (EEP) is much stronger than the relatively weak but more heterogeneous lithosphere of western Europe. Areas of high strength are characterized by a stiff crustal rheology and average thermal regime (e.g., the Bohemian Massif), or by a thin crust and low thermal gradient (e.g., North Sea). By contrast, areas affected by Tertiary volcanism and mantle plumes, such as the European Cenozoic Rift System (ECRIS) and the Massif Central, are characterized by low strengths. In order to assess the influence of the crust on total lithospheric strength we have calculated the crustal contribution to the total strength (Figure 1). It appears that in ∼60% of the study area the crust supports >50% of the total integrated strength of the lithosphere. A minor crustal strength contribution (<20%) is found only in 7% of the area, whereas its highest contribution (>70%) is observed in areas with a large crustal thickness and medium-high thermal regime (e.g., the orogens), representing 35% of the total area. In addition, thick crust with a soft rheology (e.g., the Alps and the Apennines [*Tesauro et al.*, 2008, 2009]) may retain over 90% of the total strength. By contrast, low or moderate crustal contributions (<50%) are observed in both hot (e.g., Tyrrhenian Sea and Pannonian Basin) and cold (e.g., North Sea) regions with a thin crust. The low thermal gradient in the EEP [*Tesauro et al.*, 2009] reduces the crustal strength to 30–40%, demonstrating how the strength of the mantle lithosphere grows faster than in the crust when the lithosphere becomes cold. These results

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[4]Auxiliary material data sets are available at ftp://ftp.agu.org/apend/gl/2009GL039229. Other auxiliary material files are in the HTML.

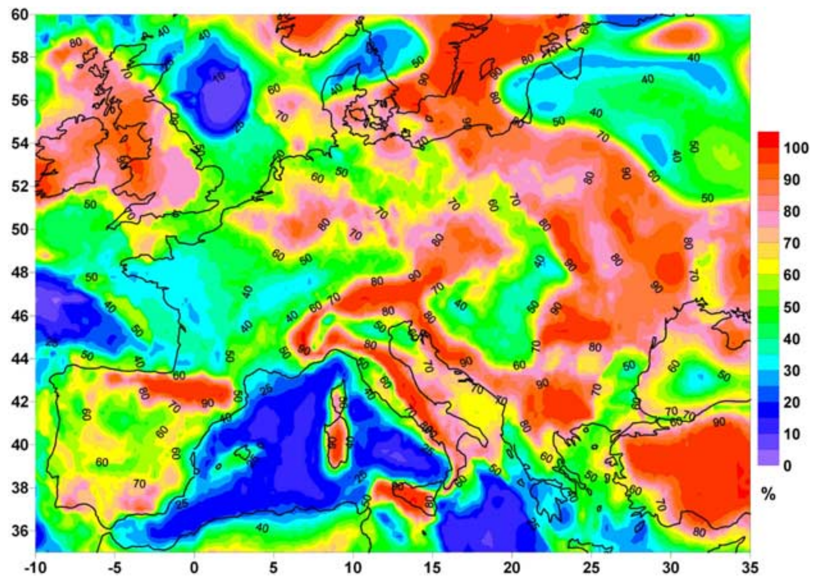

Figure 1. Percentage to total lithospheric strength due to the crust.

confirm the hypothesis that the upper mantle of thermally stabilized, old cratonic regions is considerably stronger than the strong part of its upper crust [*Moisio et al.*, 2000]. Furthermore, we demonstrate that both 'jelly sandwich' and 'crème brûlée' models [*Burov and Watts*, 2006; *Jackson*, 2002] can be valid depending on specific thermal and rheological conditions (Figure 2), as was supposed by *Afonso and Ranalli* [2004] and *Gueydan et al.* [2008].

3. Effective Elastic Thickness of the Lithosphere

[4] T_e was initially introduced in studies investigating the response of the lithosphere to surface loads by means of the cross-spectral analysis [*Banks et al.*, 1977]. Using admittance and coherence technique, *Pérez-Gussinyé and Watts* [2005] have estimated the T_e distribution in Europe. However, different methods used for T_e estimations often yield different results, presumably because they study different phenomena. For instance, T_e values obtained from foreland flexure represent the situation at the time of loading rather than current properties. By contrast, inverse (e.g., spectral) methods provide mostly information on the current T_e. In oceanic areas T_e is mainly controlled by thermal structure of the oceanic lithosphere related to its age and approximately correspond to the depth of the 450°–600°C isotherm [e.g., *Watts et al.*, 1980]. By contrast, the continental lithosphere is characterized by a more complex rheological stratification than oceanic plates, due to its thicker and more heterogeneous crust and an upper mantle modified by various tectonic processes (e.g., mantle underplating). During its long tectonic history it might also experience additional reheating, which leads to its rejuvenation, resetting its thermomechanical age (e.g., Adriatic lithosphere [*Kruse and Royden*, 1994]). As a result, T_e estimates for the continents have a wide range of values (5–110 km), typically with a bimodal distribution around two peaks at 10–30 km and 70–90 km [*Burov and Diament*, 1995]. This clustering probably reflects a prime influence of plate structure: depending on the ductile strength of the lower crust, the continental crust can be mechanically coupled or decoupled from the mantle, resulting in large differences in T_e. Crust-mantle decoupling occurs if the temperature at the Moho is higher than the temperature of creep activation [*Burov and Diament*, 1995]. Therefore, reliable predictions of the effective elastic plate thickness of the continental lithosphere require accounting for many factors describing its complex structure and history.

[5] Following *Burov and Diament* [1995], we assume that the lithosphere consists of n decoupled layers and T_e is:

$$T_e^{(n)} = \left(\sum_{i=1}^{n} \Delta h_i^3 \right)^{1/3} \tag{1}$$

where Δh_i is the effective elastic thickness of the i_{th} layer. This equation shows that T_e is less than the total thickness of the competent layers in case of decoupling.

[6] For a coupled rheology, the crust and mantle are mechanically "welded" together, and the upper limit of T_e represents simply a sum of all competent layers:

$$T_e^{(n)} = \left(\sum_{i=1}^{n} \Delta h_i \right) \tag{2}$$

The bottom of each competent layer is defined as the depth at which the yield strength is below 1–5% of the lithostatic pressure, or as the depth at which the vertical yield stress gradient is less than 10–20 MPa/km. In the latter case, the bottoms of the competent layers are associated with a specific geotherm for each lithology (e.g., ~750°C for olivine and ~350°C for quartzite). These two possible definitions of the bottom of a competent layer provide lower and upper bounds for the corresponding values of Δh_i [*Cloetingh and Burov*, 1996]. We have calculated the T_e distribution using the second definition for the mechanically strong layers, assuming that the pressure scaled minimum yield strength is 10 MPa/km. When the strength decreases

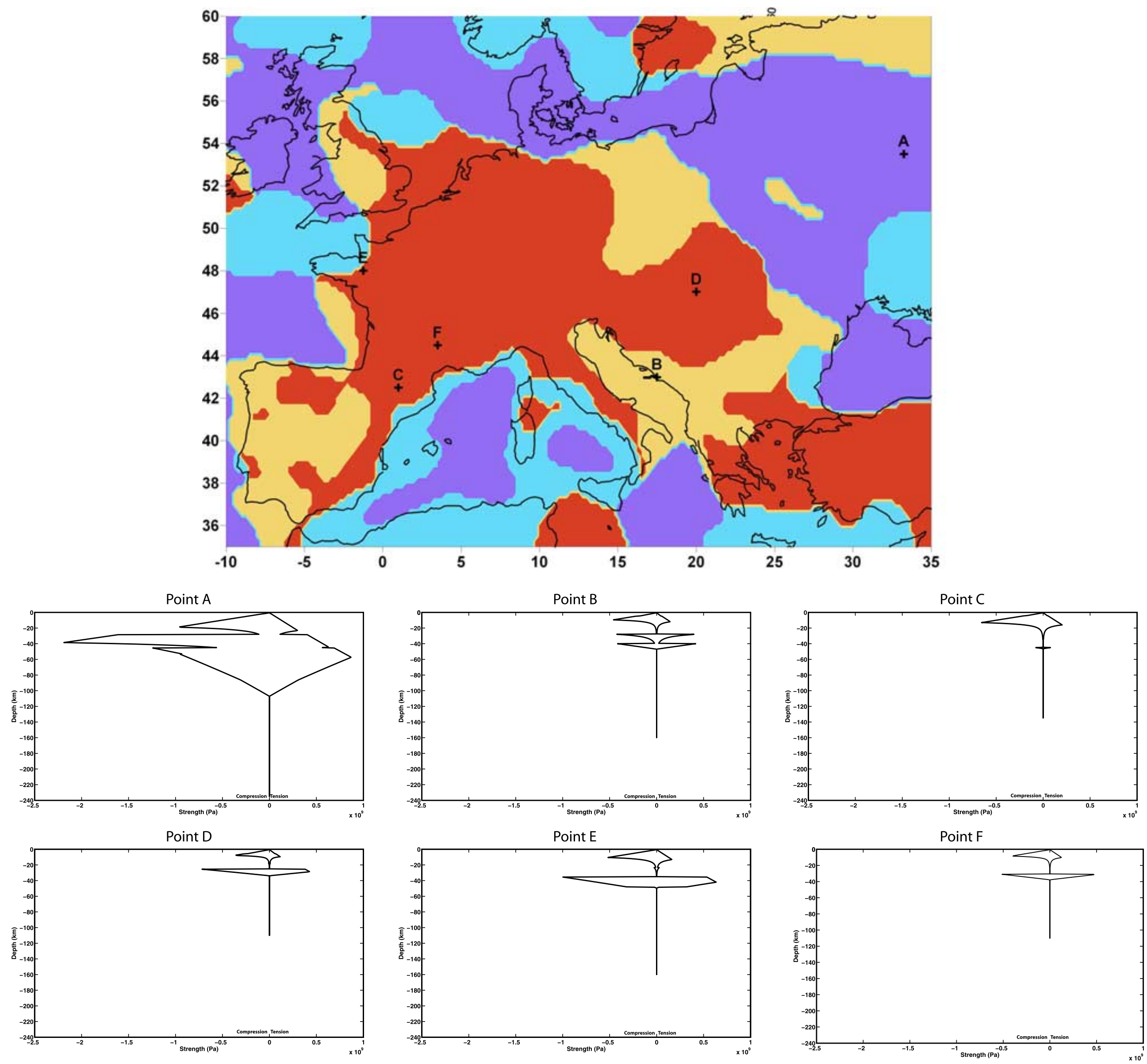

Figure 2. Rheological coupling and decoupling in Europe's lithosphere: 1, Crustal layers and mantle lithosphere are mechanically coupled; 2, Crustal layers are coupled and the mantle lithosphere is decoupled from the lower crust; 3, Crustal layers are decoupled but the lower crust and the lithospheric mantle are coupled; 4, All layers are decoupled. Capital letters show location of points for which the strength profiles are displayed. For convention values estimated under compressional and extensional conditions are assumed negative and positive, respectively. The lithosphere structure can be described by a 'jelly sandwich' model in point A, D, and E and by a 'crème brûlée' model in points B, C, and F.

below this threshold the layers are considered decoupled, whereas they are welded in the opposite case.

4. Spatial Variation in Effective Elastic Thickness

[7] The strength estimates are used as input for T_e using the approach described in the previous section. The coupling and decoupling conditions and the elastic thickness distribution are shown in Figures 2 and 3. To quantify different contributions to the total T_e value, thicknesses of each competent layer of the lithosphere corresponding to the mechanically strong upper crust (MSUC), lower crust (MSLC) and mantle (MSL) are displayed in Figures 4a–4c (Data Set S2 in the auxiliary material).

[8] A local study of T_e in Fennoscandia [*Poudjom Djomani et al.*, 1999] has demonstrated that the largest changes of T_e occur at the sutures that separate different tectonic provinces characterized by major changes in the lithospheric strength. T_e is generally consistent with other physical properties of the lithosphere: the high T_e regions correspond to areas of large thermal thickness and fast seismic velocities and vice versa. In this context, our results show a good correspondence between the distribution of T_e values and geological features, with a sharp decrease of T_e west of the Trans European Suture Zone (TESZ) (<30 km). In most of the EEP, which is characterized by high crustal and lithospheric thickness and a low thermal gradient [*Tesauro et al.*, 2008, 2009], both crust and mantle layers

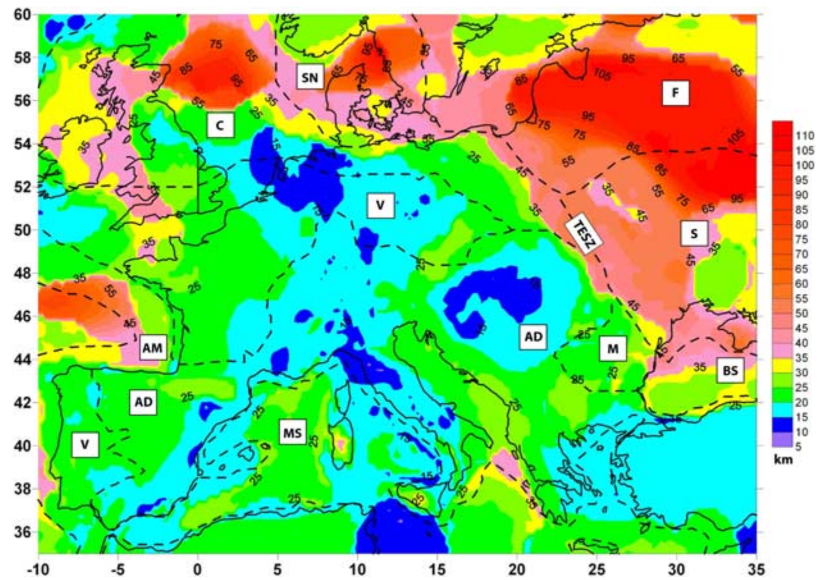

Figure 3. Effective Elastic thickness (T_e) distribution of the European lithosphere derived from integrated strength of the lithosphere (km). Abbreviations are as follows: F, Fennoscandia; S, Sarmatia, SN, SvecoNorvegian; BS, Black Sea, M, Moesian Platform; C, Caledonides; V, Variscides; AD, Alpine Domain; AM, Atlantic Margin; MS, Mediterranean Sea; TESZ, Trans European Suture Zone.

are coupled (Figure 2), as might be expected from its age (>750 Ma). In this area the largest values of T_e in Europe (up to 80–100 km) are observed (Figure 3), due to the thick MSL (>60 km) (Figure 4c). These conditions are also responsible for significant strength of the subcrustal layers. Similar values of T_e and MSL are also found in the North Sea and North German Basin, mostly due to a low thermal regime [*Tesauro et al.*, 2009]. However, it should be noticed that in these areas the tomographic model is not well resolved.

[9] In general, lateral heterogeneity of the crust has a strong effect on the coupling conditions: in most of the area characterized by a 'soft' crustal lithology ('dry quartzite' and 'wet diorite') the mantle (and often the crustal layers) are decoupled (Figure 2). The exceptions are the areas with a very thin crust, where layers of very young (<10 Ma) and hot lithosphere (like the Tyrrhenian Sea) are characterized by a T_e of about 20 km, largely due to the contribution of the MSL (15–20 km) (Figures 3 and 4c). At the same time, the mantle and often the crustal layers are decoupled in the young lithosphere of the Variscan and Alpine domains, which is characterized by average thermal conditions and mean/high crustal thickness [*Tesauro et al.*, 2008, 2009]. In these areas a strong reduction of the MSL (<10 km) is observed as a result of a decrease of the upper mantle strength (Figure 4c). MSL values are even lower (<5 km) in the areas associated with large crustal thickness and average/high thermal conditions (e.g., the orogens and the Anatolian Platform). Therefore, low values of T_e (<20 km) are found in the Massif Central, the ECRIS, the North German Plain, the Pannonian Basin and the Alps (Figure 3). In these areas, T_e mostly depends on MSUC values, which span from 15 to 25 km, while the contribution of the MSLC is negligible (mostly <10 km), Figures 4a and 4b. The

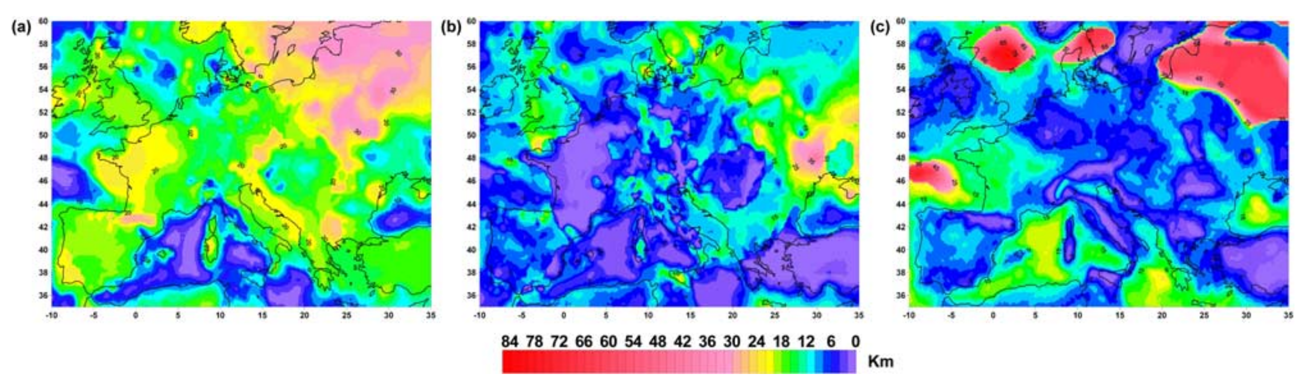

Figure 4. Thickness of the competent layers of the lithosphere (km). (a) Thickness of the mechanically strong upper crust (MSUC). (b) Thickness of the mechanically strong lower crust (MSLC). (c) Thickness of the mechanically strong upper mantle (MSL).

MSUC displays a very heterogeneous distribution, with the highest values (>20 km) concentrated in areas with large crustal thickness (e.g., the Dinarides) and low thermal regime (e.g., the Armorican Massif and the Paris Basin (Figure 4a). By contrast, values of MSLC higher than 10 km are observed only in regions characterized by a strong lower crustal rheology (Figure 4b), on account of the high thermal gradient at the Moho in most parts of Europe.

[10] We found a general consistency between our results and the previous ones [*Pérez-Gussinyé and Watts*, 2005; *Tesauro et al.*, 2007] for the first order features, such as the strong contrast between eastern and western Europe. However, in detail, pronounced differences are visible. We infer a more gradual transition from low strengths in areas such as the Apennines and the Pannonian basin, to high strength areas in the Adriatic Sea and the Bohemian Massif (20–35 km) (Figure 3). In order to facilitate a quantitative comparison between the different methods, T_e has also been estimated independently from the integrated strength as a function of age and crustal thickness ($T_{e(age/h)}$), following the approach of *Burov and Diament* [1995] (Table S1 in the auxiliary material). The results show that T_e derived from strength estimates ($T_{e(strength)}$) are generally smaller than $T_{e(age/h)}$. In the Archean provinces both parameters are similar (~70 km in Fennoscandia). The maximum difference is observed in the Sveco-Norwegian province, where $T_{e(age/h)}$ is 80 km, while $T_{e(strength)}$ is reduced to 44 km, on account of the decoupling between the crust and the mantle (Figure 2). In the Proterozoic provinces, $T_{e(age/h)}$ is remarkably larger than the values predicted by $T_{e(strength)}$ (55–60 km versus 22–35 km). However, in these areas repeated tectonic events have possibly modified the lithospheric thermal regime and thickness, also reducing strength. By contrast, tectonic provinces younger than approximately 85 Ma (the Alpine domain, the Northern Atlantic Margin and the Western Black sea) are characterized by $T_{e(strength)}$ significantly larger (20–34 km) than $T_{e(age/h)}$ (13–18 km). Therefore, apparently, the strength increased fast enough in these young provinces to enlarge T_e over the values theoretically expected.

[11] The observed differences confirm that in addition to thermal age, T_e in continental areas is also influenced by tectonic processes. Furthermore, $T_{e(age/h)}$, which is referred to the average age and crustal thickness over large areas, might not be representative due to the non-linear relationship between these parameters. One of the main uncertainties of $T_{e(strength)}$ estimates could be due to the effect of horizontal regional stresses, which may promote weakening of the lower crust with subsequent crust-mantle decoupling. This parameter might have a strong effect on T_e [*Cloetingh and Burov*, 1996]: tectonic stresses of 200–500 MPa can decrease T_e values of the mid-age lithosphere (400 Ma) by 15–20% and for lithosphere younger than 200 Ma by 30%.

5. Conclusions

[12] Based on new thermal and compositional data we have calculated the integrated strength distribution and variations of the effective elastic plate thickness (T_e) for the European lithosphere. The employment of more robust models has increased the reliability of the strength and T_e estimates. We have found a large contribution (50%) of the crustal strength to the integrated strength for the whole lithosphere for a significant part (~60%) of the study area. In particular, regions with large crustal thickness (e.g., the Anatolian Plateau) are characterized by a high proportion of crustal strength, whose contribution is much larger (>80%) than the contribution of the mantle lithosphere. Western Europe is mostly characterized by decoupled lithospheric layers, lower values of estimated integrated strength and $T_e < 30$ km. The contribution of the mechanically strong mantle lithosphere to T_e is low (<10 km) for most parts of western Europe. By contrast, the lithosphere of the EEP displays high values of T_e (80–100 km) and mechanically coupled layers. No straightforward relationship between T_e and thermal age is found in the continental part of the study area. For tectonic provinces older than 85 Ma, T_e values are significantly smaller than theoretically expected as a function of age and crustal thickness, whereas the opposite is true for younger tectonic provinces of Europe.

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