THE SCHIZOSPHERE-PLASTOSPHERE BOUNDARY THROUGH RHEOLOGICAL MODELLING ACROSS AND ALONG A FOLD-AND-THRUST BELT: CASE STUDIES FROM THE HELLENIDES, GREECE, AND SEISMOTECTONIC APPLICATIONS

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Introduction. In this work we used rheological modelling, by means of strength profiles calibration and realization, to determine the depth of the brittle-ductile transition in the Aegean Region, more specifically in relationship with the Hellenides fold and thrust belt. The final aim is to compare the rheological results with the corresponding seismicity and apply the results

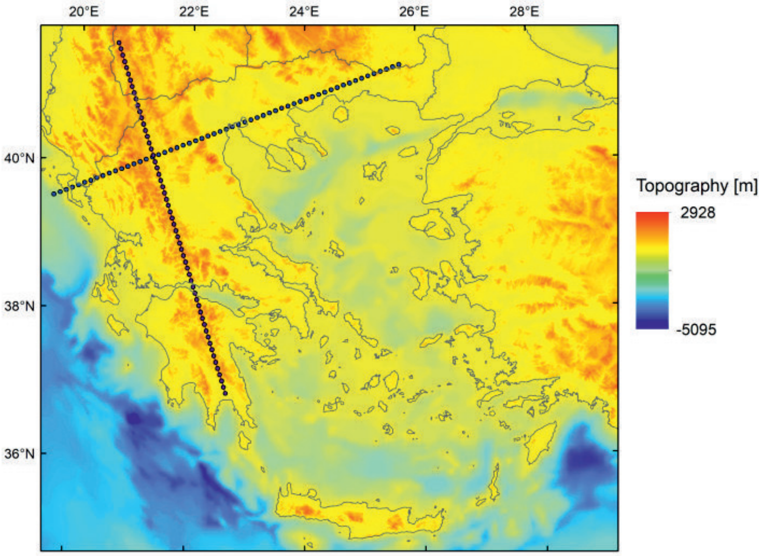

Fig. 1 - Topographic and bathymetric map of the Aegean Region. The blue dots indicate the position of the 1D strength profiles along the WSW-ENE trending transect, purple ones are for the NNW-SSE trending transect.

to seismotectonic issues. Indeed the brittle-ductile transition, though not exactly coinciding with, represents a fair approximation to the seismic-aseismic boundary, which is more precisely related to the velocity weakening-velocity strengthening transition (Tse and Rice 1986; Scholz 1988). During the interseismic period we can, in any case, consider the depth of the brittle-ductile transition (hereinafter BDT) as a reasonable indicator for the maximum depth extent of (seismogenic) faulting. Accordingly, a precise rheological modelling can help distinguishing the brittle, potentially seismogenic layer, also termed *schizosphere* (after Scholz 1988), from the undelying, ductilely deforming *plastosphere*. We then decided to apply the rheological modelling to the Aegean Region for a twofold reason: firstly, it represents one of the most seismically active area all over the world, and therefore it allows to compare and validate the rheological results with a totally independent data source, namely well-located seismicity. Secondly, the Aegean Region is characterized by a dense pattern of seismogenic faults, whose terminations at depths are not always well defined and therefore represent ideal candidates for applying the rheological modelling results, in order to help constraining the geometry and the seismogenic potential of such faults, with the final aim of improving their relative seismotectonic characterization.

Data and Methods. We realized two rheological transects (*ca*. 550 km long each) crosscutting each other, one being parallel to the Hellenides belt axis and the other orthogonal to it (Fig. 1). The latter is therefore WSW-ENE oriented, originates in Corfù (WSW) and terminates in Thrace (ENE), thus encompassing all the structural domains and tectonic nappes which constitute the Hellenic orogen. The former is, on the contrary, parallel to the main structures of the Hellenides belt and lies just to the east of the topographic watershed of the mountain chain, running from Albania/FYROM border to southern Peloponnesus. The rheological modelling has been carried out by realizing closely spaced (mean inter-distance around 10 km) 1D strength profiles and subsequently interpolating them. Yield strength profiles, which display the value of the maximum shear strength (expressed in terms of differential stress) of the rocks as a function of depth, have been produced following a simplified approach, which only takes into account two main rheological behaviours, namely the (brittle) frictional sliding and the (ductile) power-law creep. We decided to discard the semi-brittle rheological behaviours representative of the so called "brittle fracture" (Zang *et al*., 2007) or "frictional-viscous" (Bos and Spiers, 2002) rheologies, because of the following reasons. First, since we are mainly interested in the BDT depth and only secondarily in the values of the associated strength and taking into account that semi-brittle behaviours primarily modify the maximum shear strength (usually decreasing it) rather than the BDT vertical position, we considered the two rheological behaviours simplified approach, though somehow approximated, to be accurate enough for and, at the same time, more functional to our purposes. Secondly, the constitutive equations of the semi-brittle rheologies are primarily empirical and their range of applicability is seriously limited by their relative experimental characteristics, such as the (small) sample of tested lithologies and ambient conditions.

Given the exponential dependence of the power-law creep equation on the temperature at depth, we firstly focused on properly calculating the geothermal gradients for the two transects. To do so we used the temperature depth distribution equation by Cermak (1982) which takes into account the variable radiogenic heat production rate and the thermal conductivity of the different layers that make up the considered lithospheric column. Both the geothermal and the rheological constitutive equations imply the use of several input parameters (surface heat flow, thermal conductivity, strain rate, activation energy, friction coefficient, pore fluid pressure etc.) whose values should be carefully selected in order to obtain a reliable strength profile. Accordingly, we collected as many quality literature data as possible in order to define the range of the most likely values for each input parameter, always trying, when possible, to consider literature data based on different methods of measurements, observations and surveys and constraining the values with geological, tectonic and geodynamic considerations. Following this approach, as regards the depth of the Moho, we averaged between results from receiver functions studies (Sodoudi *et al.*, 2006) and gravimetric inversions constrained by seismic profiles (Makris *et al.*, 2013); in a similar manner, we used data from local and regional-scale maps (Fytikas and Kolios, 1979) as well as from continental-scale ones (Hurter and Haenel, 2002; Cloetingh *et al.*, 2010) to obtain a coherent map for the value of the surface heat flow for the whole Aegean Region. As concerns the lithotypes of the sedimentary cover and the upper crust layers, which play a crucial role in determining the resulting rheological properties, we mainly based our choices upon surface geology observations (especially for the sedimentary layer) together with geodynamic evolution and paleogeographic reconstructions (Doutsos *et al.*, 2006; Mountrakis, 2006; Papanikolaou, 2013 among others) of the Aegean Region, in order to select the upper crust most likely composition. Accordingly, the western segment of the WSW-ENE trending transect, mainly belonging to the Ionian domain, is characterized by a mostly carbonate sedimentary cover and a quartzitic basement, while the central-eastern segment around Thessaloniki has been associated with metasediments in the sedimentary layer and granitic-granodioritic intrusions for the upper crust.

The NNW-SSE trending transect lies instead between the Pindos and the Pelagonian isopic zones and it is therefore characterized by a metasedimentary cover and a quartzitic upper crust. Once defined the values for all the input parameters, as described above, we realized the two transects, consisting of 57 1D strength profiles each. We interpolated the 1D profiles applying a local polynomial algorithm for the maximum shear strength depth distribution and a kriging technique for the temperature one, while the BDT depth trends along the transects have been traced following and connecting the BDTs from the densely spaced 1D profiles.

Results and seismotectonic applications. The WSW-ENE trending transect is characterized by a decreasing shear strength and a shallowing BDT depth towards the northeast Fig. 2). More precisely, the strength values are comprised between 550 MPa in the region around Corfu and the western Ionian coast and 90 MPa in southern Thrace, while the BDT depth reaches a maximum depth of 20-22 km in the axial sector of the Hellenides and a minimum of *ca.* 10 km towards the northeastern end of the transect. Such variations are accompanied and most likely caused by a progressive increase of the geothermal gradient from the WSW to the ENE, which is thought to be related to the greater amount of extension occurred in the (backarc) northeastern Aegean Region and the consequent crustal thinning, rising of the isotherms and overall rheological weakening.

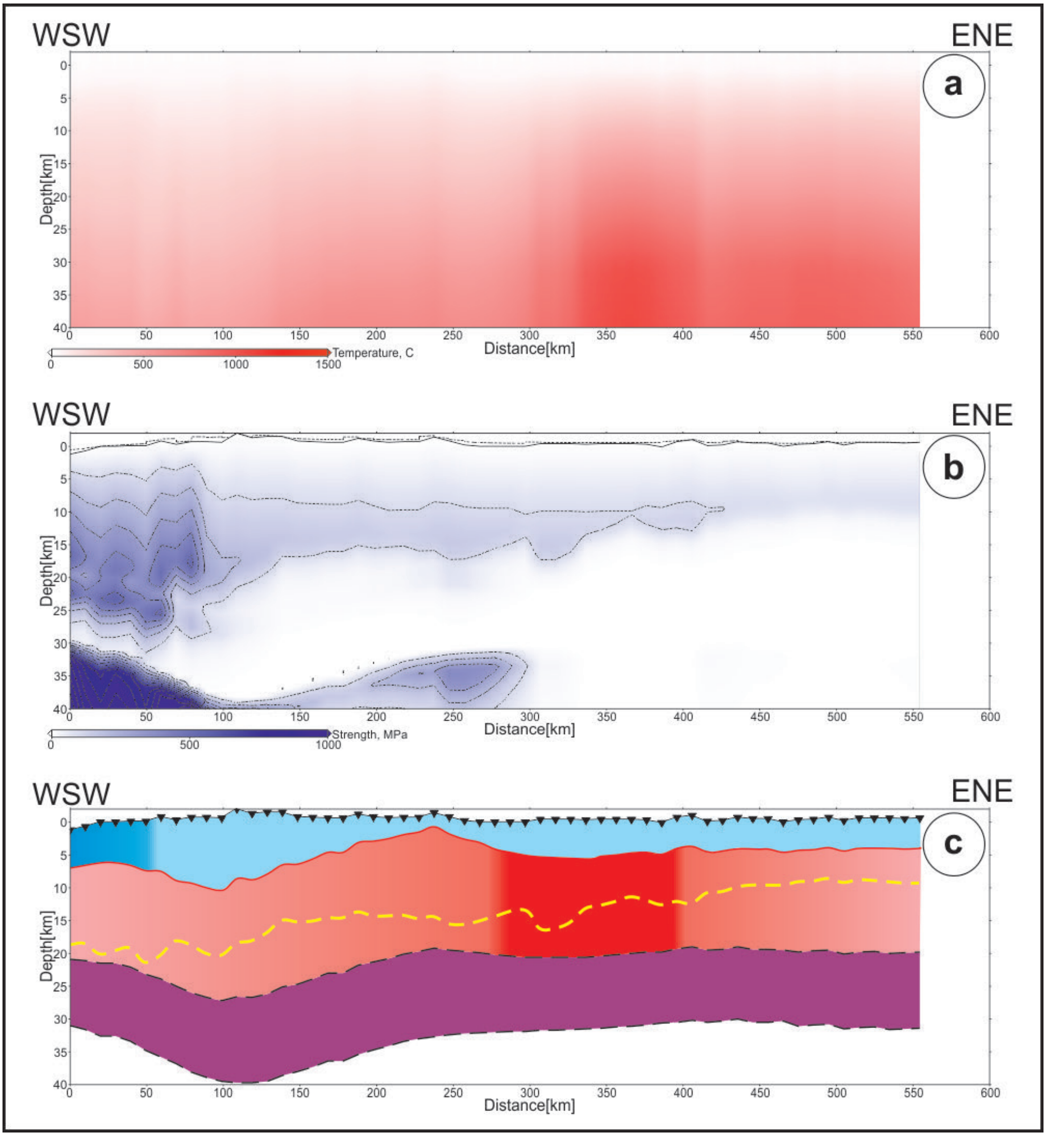

Fig. 2 - Thermo-rheological properties of the WSW-ENE trending transect: a) temperature depth distribution; b) maximum shear strength depth distribution; c) BDT depth variation along strike (yellow dashed line). The small triangles indicate the position of the 1D profiles, while the solid thin red line represents the sediments-upper crust boundary. The two dashed black lines indicate, respectively, the Conrad and the Moho depth. Dark blue corresponds to limestone, pale blue to metasediments; pink to quartzite and red to granodiorite.

The NNW-SSE trending transect also shows similar trends for the strength (maximum value, around Dibra, 315 MPa; minimum 110 MPa, towards the southern Peloponnesus), the BDT depth (going from around 25 km in the north to 10 km in the south) and the geothermal gradient along the *ca*. north-south direction (Fig. 3). In this case, the increase of the temperatures at depth and the related rheological weakening towards the southern sector of the transect may be tentatively linked to the close presence of the Hellenic volcanic arc in the southern Aegean. From a seismogenic point of view we therefore identified a thinning *schizosphere* from west to east in the Northern Aegean Region, as well as a decreasing thickness of the seismogenic layer from north to south along the transect parallel to the Hellenides belt.

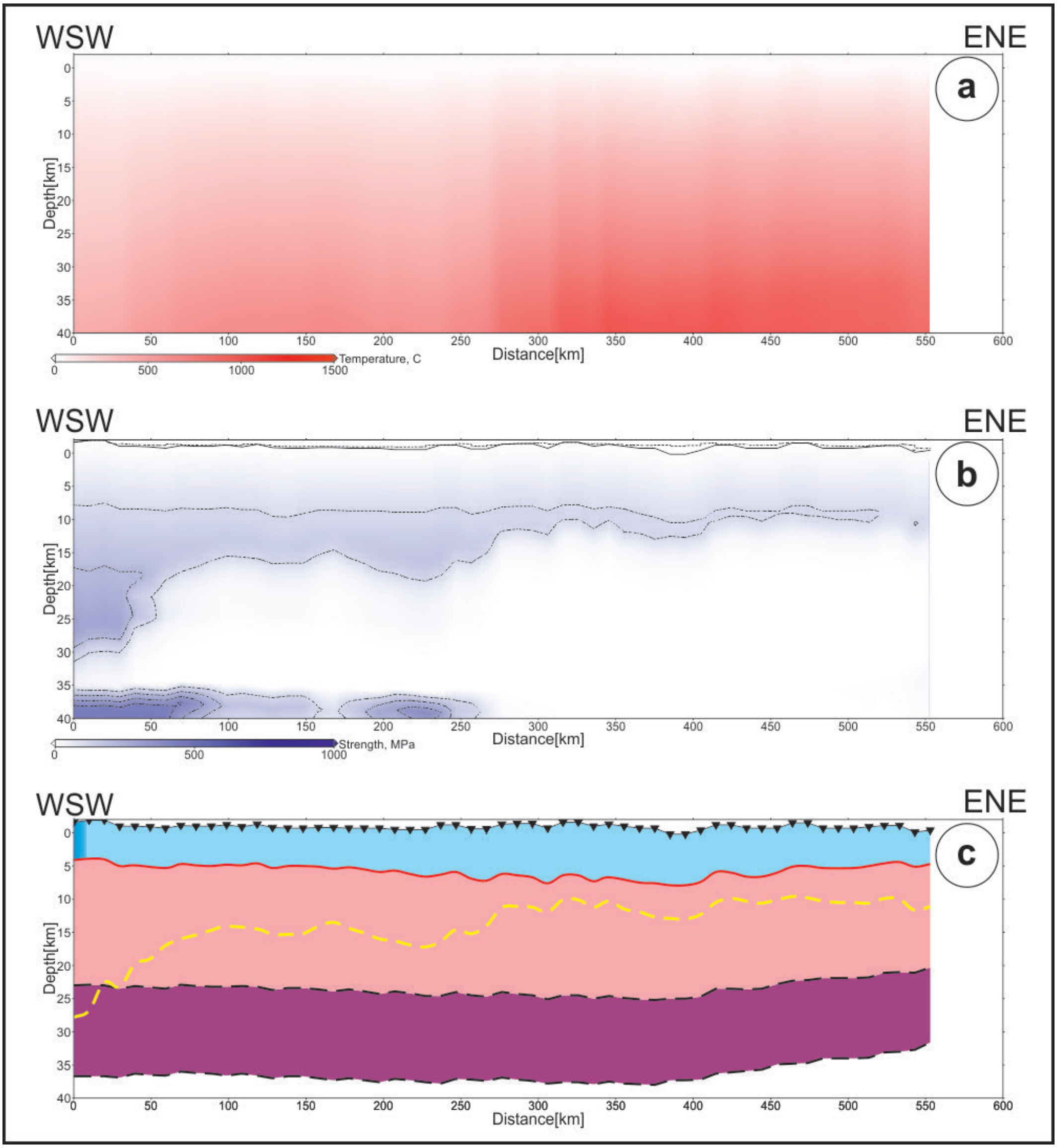

Fig. 3 - Thermo-rheological properties of the NNW-SSE trending transect: a) temperature depth distribution; b) maximum shear strength depth distribution; c) BDT depth variation along strike (yellow dashed line). Legend colors and symbols as in fig. 2.

On the basis of the corresponding seismogenic thickness we estimated the maximum width of possible master faults for some selected sectors along the two transects, taking into account also the prevailing tectonic regime and therefore selecting a dip angle consistent with the expected geometry of the structures (*i.e.* ~30° for thrust faulting and ~50°-60° for extensional settings). We then calculated the maximum expected magnitudes M_w for such structures, by applying the Wells and Coppersmith (1994) empirical relationships, considering both the regressions between fault width and M_w, length (with a length/width ratio equal to 2) and M_w and the rupture area-M_w relationship. For the WSW-ENE transect we obtained maximum expected M_w in the range 7.1-7.3 for the western sector (coastal area near Corfù), M_w 6.6-6.8 for the central one (Kozani region), decreasing to values around 6.5-6.6 for the eastern portion in the Mygdonian basin. Along the NNW-SSE transect M_W ranges from 7.1-7.2 in the northern sector around Dibra (Albania/FYROM border) to 6.5-6.6. in the western Corinth Gulf region and finally reaching minimum values in the southern Peloponnesus, being equal to 6.4-6.5. Such estimates, as well as the thickness of the seismogenic layer, are fairly consistent with, respectively, the magnitudes of the recent and historical seismicity in the Aegean Region, and its depth distribution, especially when compared with relocated sequences.

Concluding remarks. We realized densely spaced 1D strength profiles in order to interpolate them and obtain 2D pseudo-sections representative of the main thermo-rheological properties of the crust (*i.e.* maximum shear strength, BDT depth, temperature depth distribution) in the Aegean Region, with special focus on the Hellenides fold-and-thrust belt. We showed that a proper rheological modelling allows to distinguish with sufficient lateral resolution the thickness variations of the brittle, potentially seismogenic layer along 2D transects and that such information can represent an additional and independent (with respect to seismicity data) tool for the improvement of the seismotectonic characterization of the crust, especially as concerns the termination at depth of major structures, whose deep geometries are often uncertain. We also found out that the thickness of the *schizosphere* varies both across and along the Hellenides belt, thus indicating that rheological variations may occur due to several different factors, such as geothermal gradient, upper crust lithologies, geologic evolution and crustal thicknesses, and all of them must be properly taken into account. Finally, we used the results of the rheological modelling to estimate the maximum expected magnitudes along the two transects and showed that $M_{W\,max}$ tends to decrease both in a WSW-ENE (from 7.1-7.3 to 6.5-6.6) direction and in the NNW-SSE one (going from 7.1-7.2 to 6.4-6.5); such results are in good agreement with independent data represented by historical seismicity magnitudes and depth distribution, thus confirming the validity of rheological modelling in seismotectonic investigations.

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