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REVIEW PAPER

How is the European Lithosphere Imaged by Magnetotellurics?

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Abstract I review recent investigations on the electrical conductivity of the lithosphere and asthenosphere in Europe. The principal method in the reviewed studies is the magnetotelluric method, but in many cases other electromagnetic methods (e.g., magnetovariational profilings and geomagnetic depth soundings) have provided additional information on subsurface conductivity or have been the primary method. The review shows that the magnetotelluric method has been used, and is being used, in all kinds of environments and for many different processes shaping the crust and lithosphere. The crust is very heterogeneous, both with respect to the scale of conductive/resistive features and interpretations: research targets vary from Archaean palaeostructures to ongoing processes. The European database of the depth to the lithosphere-asthenosphere boundary (LAB) in Europe is updated, and a new map showing lateral variations of the depth of LAB is provided. The compilation shows that (1) the Phanerozoic European lithosphere, with considerable variations (45–150 km), is much thinner than the Precambrian European lithosphere, (2) the Trans-European Suture Zone is a major electrical border in Europe separating electrically (as well as geophysically and geologically in general) two quite different settings, (3) the thinnest lithosphere is found under the extensional Pannonian Basin (45–90 km), (4) in most of the East European Craton there are no indications of a high conductivity zone in upper mantle. In many regions there is no information at all on upper mantle conductivity, which calls for pan-European projects to operate arrays of simultaneously recording instruments with long recording periods (2–8 months) and dense spatial sampling (20–50 km).

Keywords Lithosphere · Asthenosphere · Upper mantle · Electrical conductivity · Magnetotelluric · Electromagnetic · Europe

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1 Introduction

This review aims at describing how the European lithosphere is imaged by magnetotellurics, i.e., to explore spatial variations of electrical conductivity within the crust and upper mantle in Europe. Why the European lithosphere? Why magnetotellurics or deep probing electromagnetic methods? Europe provides “an outstanding field laboratory for studying lithospheric processes through time: for tracing the results of plate movements from the present back into the early Precambrian” (Gee and Stephenson 2006). The geological record of Europe extends back in time to about 3500–3700 million years ago, which record the oldest dated ages in Europe (Mutanen and Huhma 2003, for the Fennoscandian Shield and Claesson et al. 2006, for the Ukrainian Shield, respectively). The European part of the Eurasian lithospheric plate (Fig. 1) stretches from a passive continental margin in the west to the Palaeozoic Ural fold belt in the east, and from a stable Archaean cratonic core to the north in Fennoscandia to tectonically and volcanically active Mediterranean region in the south with on-going subductions and associated phenomena such as basin development, thrusting and faulting.

Electromagnetic (EM) methods are the most sensitive methods for detecting partially interconnected, volumetrically minor yet tectonically important conducting phases such as partial melt, fluids and graphite. EM methods can therefore provide models on lithospheric/upper mantle conductivity, which are complementary to other geophysical data and aid at defining constraints to other geophysical and geological models, such as seismic tomography or reflection seismic models, temperatures or fraction of melt or volatiles (Heinson 1999 for a review, and Ledo and Jones 2005 for an example on temperature determination). In the class of EM methods, the magnetotelluric method (MT), in its modern form, is the only method that can provide information on electrical properties of deep crust and upper mantle. By the modern “form” of magnetotelluric method we understand sufficiently long recordings of the time variations of the five components of the Earth’s electromagnetic field simultaneously at several sites making up a profile or an array.

In tectonically active regions, small percentages of partial melt and free saline fluids form conducting structures that are distinct for different tectonic environments (e.g., Hjelt and Korja 1993; Brown 1994). In stable regions ancient tectonic processes have often left

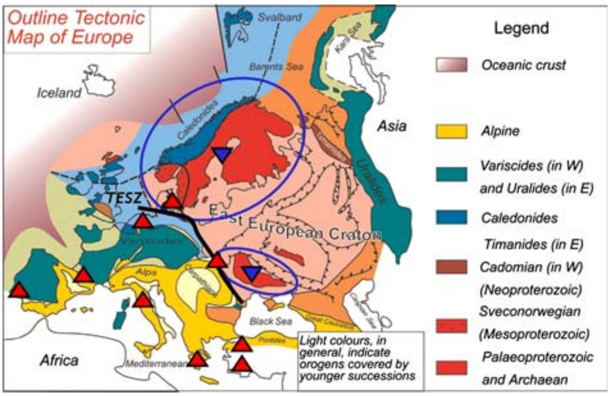

Fig. 1 Major tectono-geological units in Europe (Gee and Stephenson 2006). TESZ = TransEuropean Suture Zone. Red triangle shows the location of target region in examples on crustal and lithospheric investigations. Inverted blue triangle and an ellipsoid show the location of crustal conductance compilations. Figure by courtesy of The Geological Society of London and David Gee

electrically conducting traces of collisions of various crustal units revealing the location of palaeosuture zones or even more specific tectonic assemblages such as foredeeps (e.g., Boerner et al. 1996). Enhanced electrical conductivity is, in many cases, caused by graphite- and/or sulphide-bearing rocks of sedimentary sequences that have undergone complex deformation and underthrusting in the deep crust (e.g., Korja et al. 1996).

In the continental mantle, roughly at depths between 100 and 400 km, temperature and mineral composition control electrical conductivity, and high-pT laboratory experiments have made it possible to compile several laboratory-based conductivity-depth profiles, such as the dry adiabatic profile for olivine (Xu et al. 2000). The experimental conductivity-depth profiles serve as background models for field observations. An increased conductivity with respect to dry olivine conductivities in the upper mantle has been found in many studies and several sources to explain an enhanced conductivity have been proposed (for a review, see Heinson 1999).

Several recent reviews have described various aspects of deep probing electromagnetic methods in general, and magnetotelluric method, in particular. Jones (1998; 1999) gave a review on electromagnetic methods and their usage for upper mantle investigations and described the advantages of collocated magnetotelluric and seismic experiments for crustal and upper mantle studies. Heinson (1999) gave a review on electrical properties of the lithosphere-asthenosphere system at the global scale. Heinson's work contains a brief review of geophysical properties of both the continental and oceanic lithosphere, based mainly on seismic, geodynamic and geochemical evidence. He also reviews laboratory studies of mantle mineral conductivities. The latter aspect was recently extended by Nover (2005) with a comprehensive review on electrical properties of crustal and mantle rocks based on laboratory measurements. In addition, Heinson's review (op. cit.) gives examples of EM studies in various oceanic and continental environments (e.g., mid-ocean ridges, passive margins, continental shields, and continental extensional regions) and discusses on the implication of derived conductivity models. Finally, Wannamaker (2005) and Baba (2005) gave recent reviews on electrical anisotropy in continental and oceanic environment, respectively.

The topics described above are not covered in this review. Instead, I first select recent examples of magnetotelluric (and electromagnetic) studies that have investigated crustal/lithospheric structures and processes in Europe. I will give examples, in particular, of studies completed in active areas (Mediterranean from Iberia to Turkey, Pannonian Basin and Carpathians). From the Precambrian part of Europe I will show examples on the recent attempts to compile 3D crustal conductivity models from all existing 1D and 2D models. For the crustal part, the review does not intend to be complete because the listing of all studies carried out in Europe would make this review too long. Instead I aim to show examples from regions of new and active research (e.g., Turkey and Iberia at both ends of the Mediterranean Sea) as well as examples of new ways to use old data to, for example, compile large crustal 3D conductance models.

In the second part of this review, I concentrate on upper mantle conductivity beneath Europe. In particular, I will update the compilations of Praus et al. (1990) and Hjelt and Korja (1993) on the depth to the lithosphere-asthenosphere boundary (LAB) in Europe.

2 Crustal/lithospheric Conductivity

This chapter aims to review studies on crustal and upper mantle conductivity in Europe. The aim is not to give a comprehensive review but select a few examples to illustrate recent advances. I will, however, begin with (i) a brief description of the major tectono-geological features and evolution of the European lithosphere.

Examples of magnetotelluric (and other electromagnetic) studies will review (ii) new magnetotelluric studies and their results in the Alpine Fold Belt and the Mediterranean i.e., in tectonically active regions and (iii) studies carried in the stable East European Craton (EEC) and Trans-European Suture Zone (TESZ) using new and/or existing data. In the latter case, the emphasis is on methodological advances to improve the usage of existing data sets. The latter includes also examples on how to transform existing local conductivity models (1D, 2D, 3D) into regional 3D conductivity models. The two latter topics are important as they emphasize a need to exploit field data more efficiently; in other words, data from field campaigns usually contain much more information than that extracted in the first attempts.

2.1 Brief Outline of the European Geology

The European lithosphere is divided into two distinct parts, southwestern and northeastern, by the Trans-European Suture Zone (TESZ), the fundamental European lithosphere border extending from British Isles/North Sea to Black Sea (Fig. 1). TESZ, which was first discovered from geological and magnetic data by Teisseyre and Törnquist (Teisseyre 1903; Törnquist 1908), is a board zone of suturing and is clearly seen for example in the European magnetic anomaly map (Fig. 2; Gee and Stephenson 2006). The southwestern part of the European lithosphere is thin, warm and young, primarily Phanerozoic, whereas the northeastern Precambrian lithosphere is thicker, colder and older.

The Precambrian part of Europe consists of Fennoscandian, Sarmatian and Volgo-Uralian segments that amalgamated ca. 1880 Ma ago (Bogdanova 1993) and formed the

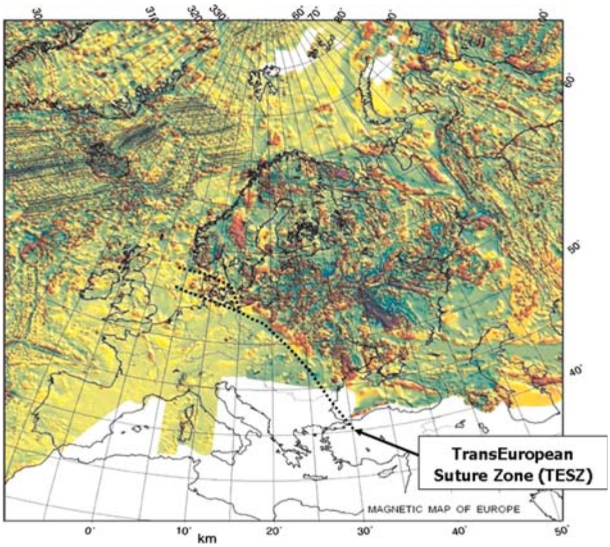

Fig. 2 Magnetic anomaly map of Europe (Gee and Stephenson 2006). Location of TransEuropean Suture Zone (TESZ) is shown by black dashed line. Figure by courtesy of The Geological Society of London, Stan Wybraniec and Hans Thybo

East European Craton (EEC). The EEC is exposed in Fennoscandia and Ukraine, but is covered elsewhere by thick Mesoproterozoic to Palaeozoic sediments, which typically have a thickness of 2–4 km but may locally reach the thickness of over 20 km. That part of the EEC which is covered by sediments is also called the East European Platform (EEP). All these three Precambrian segments have a complex structure and evolutionary history from Archaean to Meso/Neoproterozoic times. As an example, the central part of the Fennoscandian Shield, the Svecofennian orogen, evolved in five, partly overlapping orogenies in four major stages from 1.92 to 1.77 Ga: (i) accretion of several micro-continents, (ii) extension of the accreted crust, (iii) continent-continent collision, and (iv) gravitational collapse of the collided crust (Korja et al. 2006). The detailed structural and evolutionary description of the EEC and its segments is beyond the scope of this review. After cratonization, the EEC has naturally participated in younger processes or, even more, as Gee and Stephenson expressed in their introduction to Europrobe monograph (Gee and Stephenson 2006): “Two things are particularly striking: the importance of plate tectonics far back through the Proterozoic into the Archaean, and the significance of tectonic inheritance, older structures and rheologies guiding, even defining, the younger evolution”.

The EEC is surrounded by crustal segments that were accreted with the cratonic core of Europe mainly in Phanerozoic orogens. Yet to the northeast, the EEC is flanked by Neoproterozoic Timanides. Further to the east, the Palaeozoic Uralides mark the eastern border of Europe from the Arctic Ocean close to the Caspian Sea. In the north and west, the EEC is bordered by the Caledonides extending from Ireland and Scotland north-eastwards through the western part of Scandinavia to Svalbards in the Arctic Ocean. The Caledonides resulted in the Late Silurian collision of the continents Baltica and Laurentia.

The southwestern part of Europe, southeast of the TESZ, comprises a complex mosaic of crustal elements that were assembled during various Precambrian orogenic cycles followed by the Phanerozoic Caledonian, Hercynian (Variscan) and Alpine orogenies. During this long and complex crustal evolution, earlier consolidated crustal elements were repeatedly remobilized and overprinted by later events (Plant et al. 2003).

The Variscan crust is a collage of Gondwana-derived microplates (Avalonia, Armorican Terrane Assemblage; ATA), which were sequentially accreted to Baltica and eventually caught up in the collision of Gondwana and Laurussia/Avalonia). Late Devonian and Carboniferous subduction and collision created a large and heterogeneous orogen, with two zones of subduction on the northern flank and one on the southern flank of the belt (Franke 2006) (Fig. 3).

Closure of Tethyan ocean systems and collision of African and Arabian plates with Eurasia in Cretaceous and Cenozoic times resulted in the development of Alpine fold belts, such as the Betics, Pyrenees, Alps, Carpathians, Pontides and Caucasus, in southern Europe. Subduction with the development of volcanic arcs and back-arc basins, major thrusting and transcurrent and normal faulting is still on-going in Mediterranean (Fig. 4). The most characteristic features of the Mediterranean area are the arcuate orogenic belts and the opening of extensional basins within the overall compressional regime. This region is characterized by mobile subduction zones, where migration of the arcs could be up to 800 km. At the present day, active subduction occurs only beneath Calabria and the Aegean arc; in the other regions subduction has ceased and in most cases the current geodynamic setting is post-collisional. All this convergence in southern Europe was going on while in the west the North Atlantic was opening and the passive margins were developing (Harangi et al. 2006; Gee and Stephenson 2006).

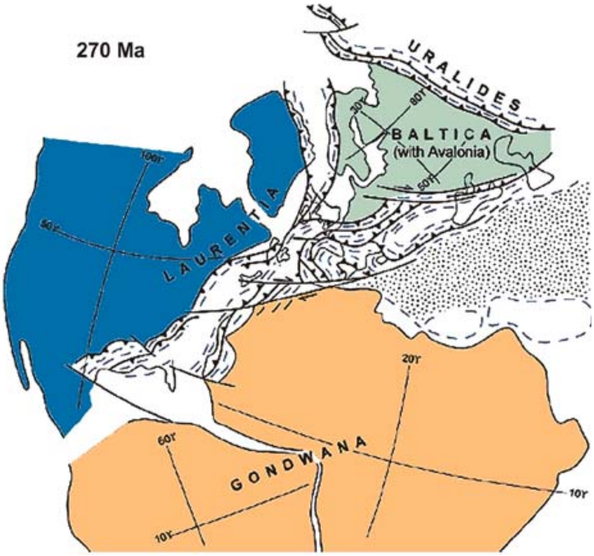

Fig. 3 Peri-Atlantic orogens ca. 270 Ma ago (Matte 1991 in Gee and Stephenson, 2006) showing the rigid continents (Fennoscandia shown with Avalonian terranes that amalgamated ca. 450 Ma ago) and intervening fold belts of Caledonides (collisions 430.420 Ma ago), Uralides (Kazakhstan and Siberian plate; 340–280 Ma) and Variscides in the formation of Pangea (rough ages from Cocks and Torsvik 2006). Figure by courtesy of The Geological Society of London and David Gee

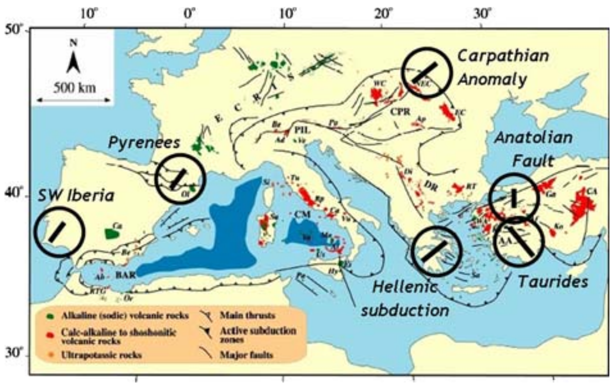

Fig. 4 Location of study areas in Southern and Central Europe discussed in this review (lines & circles; note that the lines show only the principal direction of profiles; in many cases the study includes data from 2 to 5 parallel profiles and additional perpendicular profiles). Base map is from Harangi et al. (2006) and shows the location of Tertiary to Quaternary volcanic rocks, active subduction zones and major active thrust and fault zones in Southern and Central Europe. Figure by courtesy of The Geological Society of London and Szabolcs Harangi

2.2 Magnetotelluric Studies in the Mediterranean Area

In recent years there has been a considerable increase in interest in investigating tectonically active areas in Mediterranean by magnetotellurics. Several studies have been completed in Turkey (e.g., Bayrak and Nalbant 2001; Tank et al. 2005; Caglar 2001; Gürer

1996; Gürer et al. 2004; Turkoglu et al. 2006) partly motivated by a need to know the crustal structure in one of the most rapidly deforming continental regions with among the highest seismicity rates in world (Bayrak and Nalbant 2001).

Results of a magnetotelluric study in Taurides, southwestern Turkey (Gürer et al. 2004) are shown in Fig. 5. Final model contains three sub-vertical conductors, which represent the Fethiye Burdur Fault Zone (FBFZ, an extension of the Pliny Trench in the Aegean Sea) and probably, as suggested by the authors, on-land continuation of the Starbo Trench from the Aegean Sea. The first fault zone associated with the second, SE dipping conductor marks the border between the extensional part of western Anatolia and more stable central Anatolia. Correlation of the resistivity model and seismicity shows that hypocenters are located in an area with high resistivity. Gürer et al. (2004) do not detect a conductive asthenosphere beneath their profile in SW Turkey, in contrast to NW Turkey where a shallow asthenosphere (40–60 km) was detected by Bayrak and Nalbant (2001).

Tank et al. (2005) used wide-band magnetotelluric data to investigate the fault rupture area of the 1999 Izmit earthquake in the North Anatolian Fault zone (NAFZ) in Turkey (Fig. 6). Interestingly, four MT instruments were operating at the time of the Izmit earthquake. The final models from two parallel profiles show that the hypocentres of the mainshock and afteshocks are located on the highly resistive side near the edge of a conductive zone. This follows the observations made by Gürer et al. (2004; see above) and Bayrak and Nalbant (2001).

The third example of using magnetotellurics to investigate active tectonic processes in the Mediterranean area is shown in Fig. 7. Galanopoulos et al. (2005) used data from ten

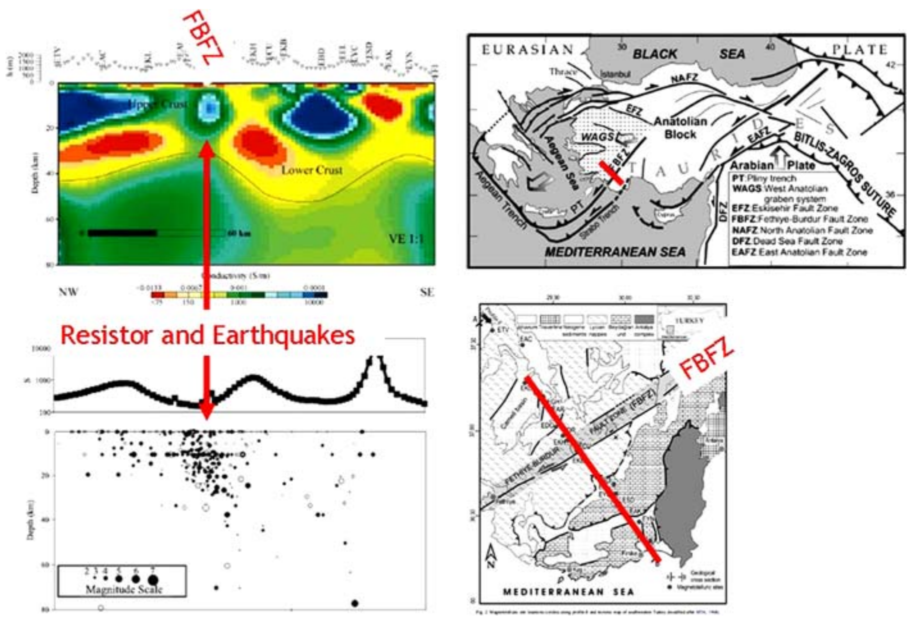

Fig. 5 Magnetotelluric study in Taurides, SW Turkey (Gürer et al. 2004). Magnetotelluric profile crosses the Fethiye Birdur Fault Zone (FBFZ) (panels in right). Final 2D model is shown top left and is compared to earthquake data (bottom left). Thick black curve below the conductivity model shows the integrated subsurface conductance to 80 km. Figure by courtesy of Elsevier

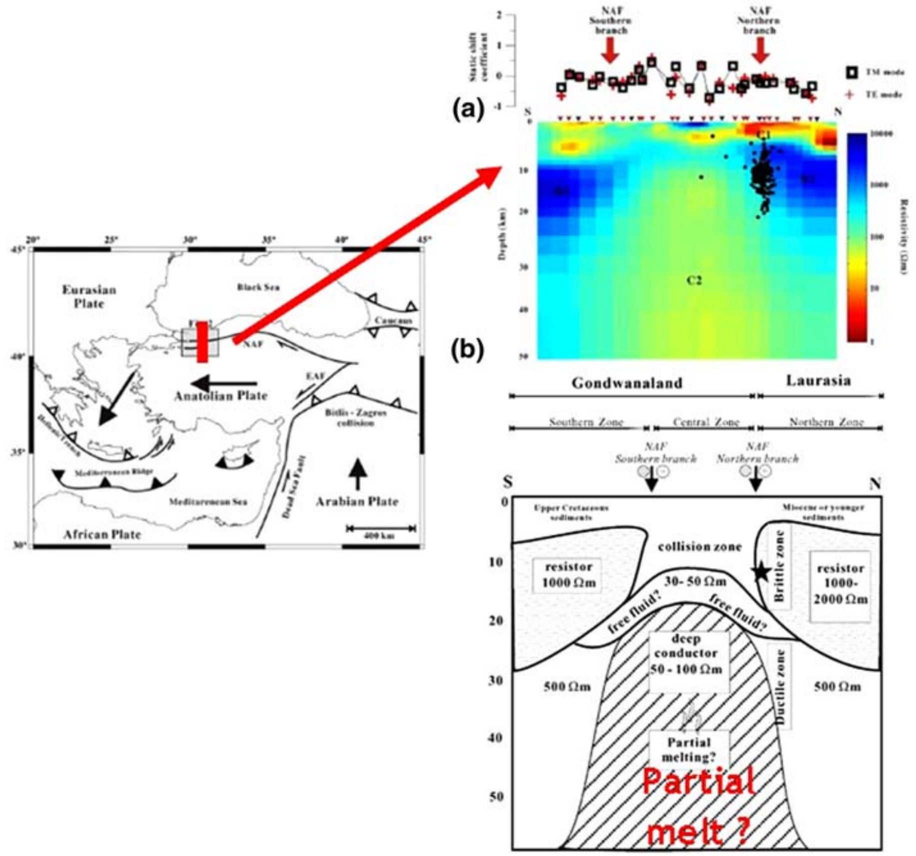

Fig. 6 Magnetotelluric study across the Anatolian fault, Turkey (Tank et al. 2005) (panel in left). Resistivity model is shown right top with the location of earthquake epicentres as black dots. Interpretation is shown in right bottom suggesting partial melt between the southern (SAF) and northern (NAF) branches of the Anatolian Fault. Figure by courtesy of Elsevier

long period (100–10000 s) sites to study Hellenic subduction zone (HSZ) beneath southern Greece. A number of magnetotelluric studies have been carried out in the region of Hellenic Volcanic Arc (HVA) (e.g., Hutton et al. 1989; Galanopoulos et al. 1991; Lagios et al. 1998) but they were primarily aimed at geothermal research and hence the profile layout have not been useful for tracing the HSZ (Galanopoulos et al. 2005). Analysis of the 2D resistivity model together with seismic (earthquake locations and the location of Wadati-Benioff zone) and heat flow data indicate that both the subducting African lithosphere and the Eurasian lithosphere are resistive, and hence the Wadati-Benioff zone, i.e., the top of the subducting slap, cannot be identified by magnetotelluric data. Yet the bottom of the subducting African lithospheric plate, i.e., the top of the asthenosphere, can be clearly identified as a conducting region deepening from ca. 170 km in SW to over 300 km in NE beneath southern Greece. The study identified also two sub-vertical zones of increased conductivity above the subducting plate. These zones coincide with HVA having a high heat flow (Fig. 7), which suggest that the conductive zones represent ascending melting part of the subducted African lithosphere.

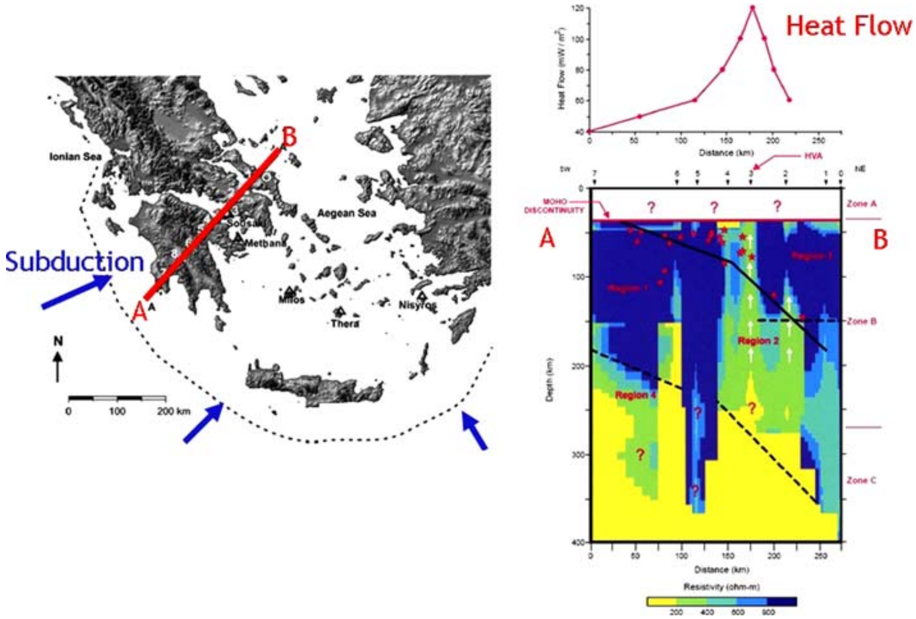

Fig. 7 Magnetotelluric study across the Hellenic Subduction Zone (HSZ) in Greece; (Galanopoulos et al. 2005). Location of the MT profile is shown in left together with the location of the Hellenic trench (dashed line), the subduction polarity (arrows) and volcanic centres (triangles). Geoelectric model together with the surface heat flow profile are shown in right. Figure by courtesy of Elsevier

Armadillo et al. (2001) studied crustal and upper mantle structure by magnetometer array across the Apennines from Adriatic Sea in the east to Northern Tyrrhenian Sea in the west (Fig. 4). Two-dimensional models of GDS data from two parallel profiles revealed a good conductor at the depth of ca. 10–20 km below the Apennine chain and volcanic arc. The enhanced conductivity is attributed to partial melt above the Apennines–Maghrebides subduction zone. The deeper conductive layer (<10 Ωm) beneath the entire model at the depth of 20–80 km (shallower in west and deeper in east) is likely representing the asthenosphere (Armadillo et al. 2001).

2.3 Magnetotelluric Studies in the Alpine Fold Belt and Variscides

Since early 1990 an extensive magnetotelluric data set has been collected in the Iberian Peninsula. Research has focused at three regions: (i) SW Iberia in Spain and Portugal, (ii) Pyrenees and Cantabrian Mountains in northern Spain and (iii) the Betics in southern Spain. The first two orogenic belts form the westernmost part of the Alpine Fold Belt (or Alpine-Himalayan fold belt) whereas southwestern (and western) Iberian Peninsula forms the Iberian Massif, which is the best exposed section of the Variscan orogen in Europe.

Research in SW Iberia (Santos et al., 1999, 2002; Almeida et al. 2001, 2005; Pous et al. 2004; Muńoz et al. 2005, 2006) has investigated electrical properties of the South Portuguese Zone, SPZ (Variscan Rhenohercynian affinity), the Ossa Morena Zone, OMZ (Saxothuringian affinity) and the Central Iberian Zone, CIZ, which form the three tectonostratigraphic terranes of southern Iberian Variscan Massif. Of particular interest have been the properties of the terrane boundaries (suture zones) and the internal structure of the Ossa Morena Zone. Extensive work in this region has provided 2D-models from four parallel profiles and one oblique profile and has made it possible to attempt 3D modelling. Two 2D models (Muńoz et al. 2005) and a 3D resistivity model (Muńoz et al. 2006) of the area are shown in Figs. 8, 9. 3D model shows the complexity of the electrical structure, which is most likely a true situation nearly everywhere: heterogeneity at deeper levels in crust is equal to the heterogeneity indicated in lithological maps.

Results from SW Iberia (op. cit) (i) show a continuity of certain structures from profile to profile and discontinuity of other features, which, in general emphasize the notation of three-dimensionality shown by the 3D model of the region, (ii) indicate that terrain boundaries (SPZ/OMZ and OMZ/CIZ) are characterized by the presence of conductors most likely caused by graphite enrichment along shear planes in the transpressive regime, (iii) reveal a presence of a range of shallow and deep seated resistors related to igneous complexes of variable age, and (iv) suggest the presence of several middle to lower crustal conductors indicating granulite facies metamorphism, which produced granulitic rocks having grain-boundary carbon.

Work in Pyrenees (Pous et al. 1995b, c; Ledo et al. 2000; Glover et al. 2000; Pous et al. 2001) and Betics (Pous et al. 1999; Marti et al. 2004aa, b) investigated orogens of the Alpine Fold Belt. In both cases magnetotelluric surveys have revealed a number of upper and middle crustal conductors, of which most can be associated with shear zones. In contrast to SW Iberia, both in the Betics and the Pyrenees, fluids are interpreted to be the principal cause to enhance conductivity in shear zones (e.g., Pous et al. 1995b; Pous et al.

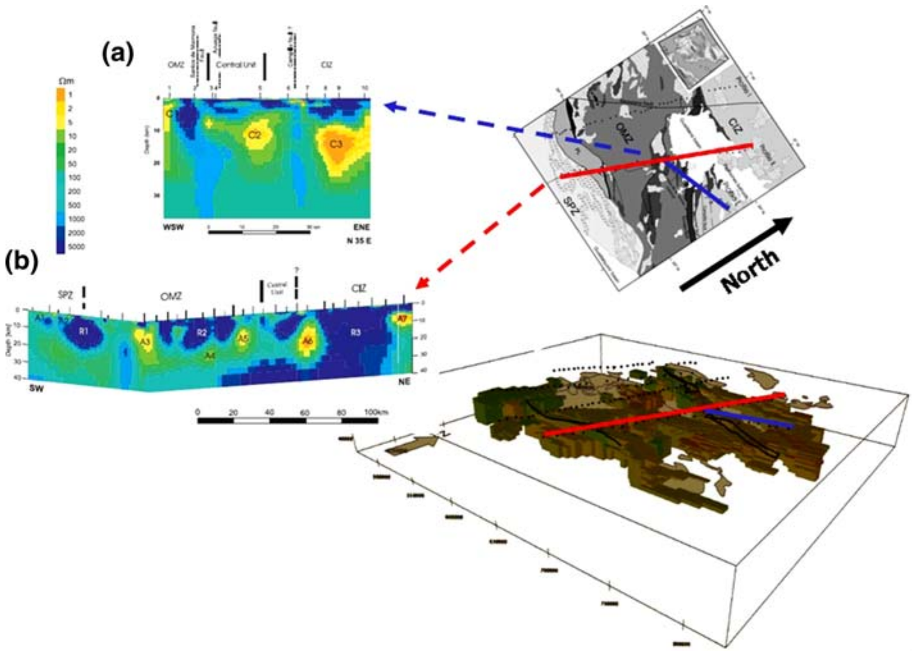

Fig. 8 Crustal resistivity in SW Iberia (Iberian Massif) across the South Portuguese, Ossa Morena and Central Iberian Zones of Variscan orogen. Site map and 2D resistivity models from Muńoz et al. 2005. 3D model is from Muńoz et al. (2006). 3D model by courtesy of Gerard Muńoz

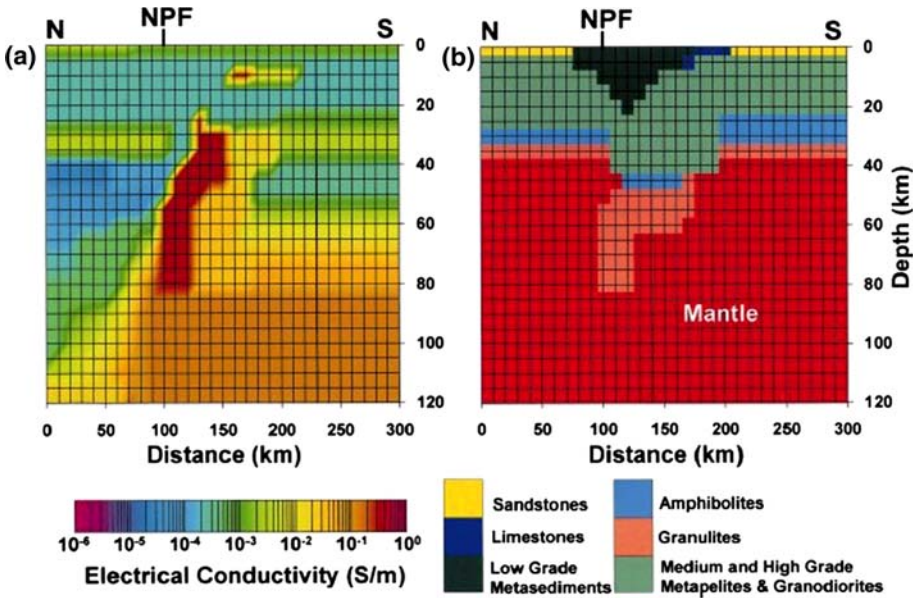

Fig. 9 Conductivity model of Pyrenees (Pous et al. 1995b, c) and an associated model on structure and lithology used to integrate magnetotelluric data (model) with laboratory data on electrical conductivity of crustal and upper mantle rocks (Glover et al. 2000). Figure by courtesy of Elsevier

1999). In both areas a major lower crustal conductor has been detected. In the Betics, a deep conductor was originally interpreted to represent melting of Iberian lower crust (Pous et al. 1999) but recent work with additional measurements (Marti et al. 2004a, b) suggests that the conductor is a 3D body, which may require re-interpretation of the conductivity mechanism.

Like in the Betics, a lower crustal conductor is identified in the Pyrenees in the contact zone between the Iberian and European plates (Pous et al. 1995b, c). Additional studies along the orogen (Ledo et al. 2000; Pous et al. 2001) shows that the deep conductor in the Axial Zone (contact zone) extends over the entire orogen. Correlation of the conductivity model with other Earth data and models (Pous et al. 1995b, c; Ledo et al. 2000) and, in particular, with the laboratory data of the electrical conductivity of appropriate crustal and upper mantle rocks (Glover et al. 2000) helped to distinguish between several alternative explanations for enhanced conductivity. The most likely explanation is partial melting during the thermal re-equilibration of the subducted Iberian lower crust (Ledo et al. 2000; Pous et al. 1995c). Finally, magnetotelluric work in the Pyrenees indicates a considerable difference in the lithospheric thickness between a thinner Iberian plate (80 km) and a thicker European plate (115 km) (Pous et al. 1995b).

Since the discovery of the Carpathian Conductivity Anomaly (CCA) (Jankowski 1967), a great number of studies have been carried out to acquire new data and to understand the nature of the conductivity anomaly (e.g., Ádám et al. 1997; Jankowski et al. 1985; Červ et al. 1997a, b, 2001, 2002; Ernst et al. 2002; Jóźwiak and Ernst 2005 ; Kováčiková et al. 2005a, b; Rokityansky and Ingerov 1999; Zhdanov et al. 1986). Jankowski et al. (2005) have recently summarized the research related to CCA and summarize well-established facts and their interpretation. For objective results they included (i) the zero line of anomaly (induction vectors rotate 180° when crossing the zero line) is well established and corresponds to the centre of a well conducting region, (ii) the line current approximation gives 30 km as the maximum depth of the anomaly, and (iii) the current concentration in the thin sheet approach suggests even shallower depths because there are no currents deeper than 20 km (Červ et al. 2002). With respect to more "hypothetic" results Jankowski et al. (2005) conclude that (i) the geometry of the cross-section of the anomaly and its lateral variations are not yet satisfactorily solved and (ii) the answer to the question on the source of the anomaly is open. Yet the comparison of resistivity models obtained from magnetotelluric data (Fig. 10a; Ernst et al. 2002) with seismic data suggests that the anomaly (conductors) is located within the sedimentary basin and favours the

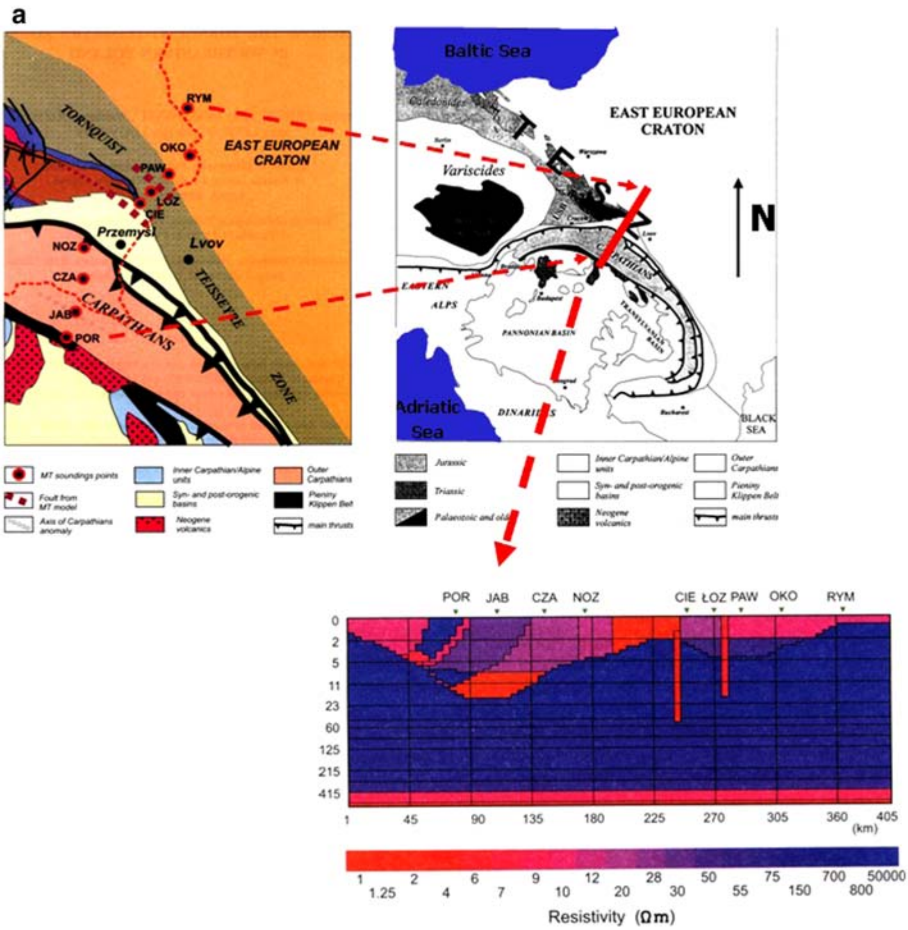

Fig. 10 (**a**) Magnetotelluric study across Carpathians. Geological map of the Carpathian Arc is shown on right top (Jóźwiak and Ernst 2005). Location of the magnetotelluric profile and the final 2D resistivity model (Ernst et al. 2002) are shown on left top and bottom. (**b**) Conductance modelling of the Northern Carpathians (Kováčiková et al. 2005b). Observed and modelled data are (induction arrows and single station vertical magnetic transfer function at $T = 32$ min) are shown bottom and top, respectively. Model responses are from the model b (minimum gradient support stabilizer applied) shown middle to the right. Other models are "maximum smoothness" and "lagged diffusivity" models (top and bottom in model panel to the right. Figure by courtesy of the Institute of Geophysics, Polish Academy of Sciences

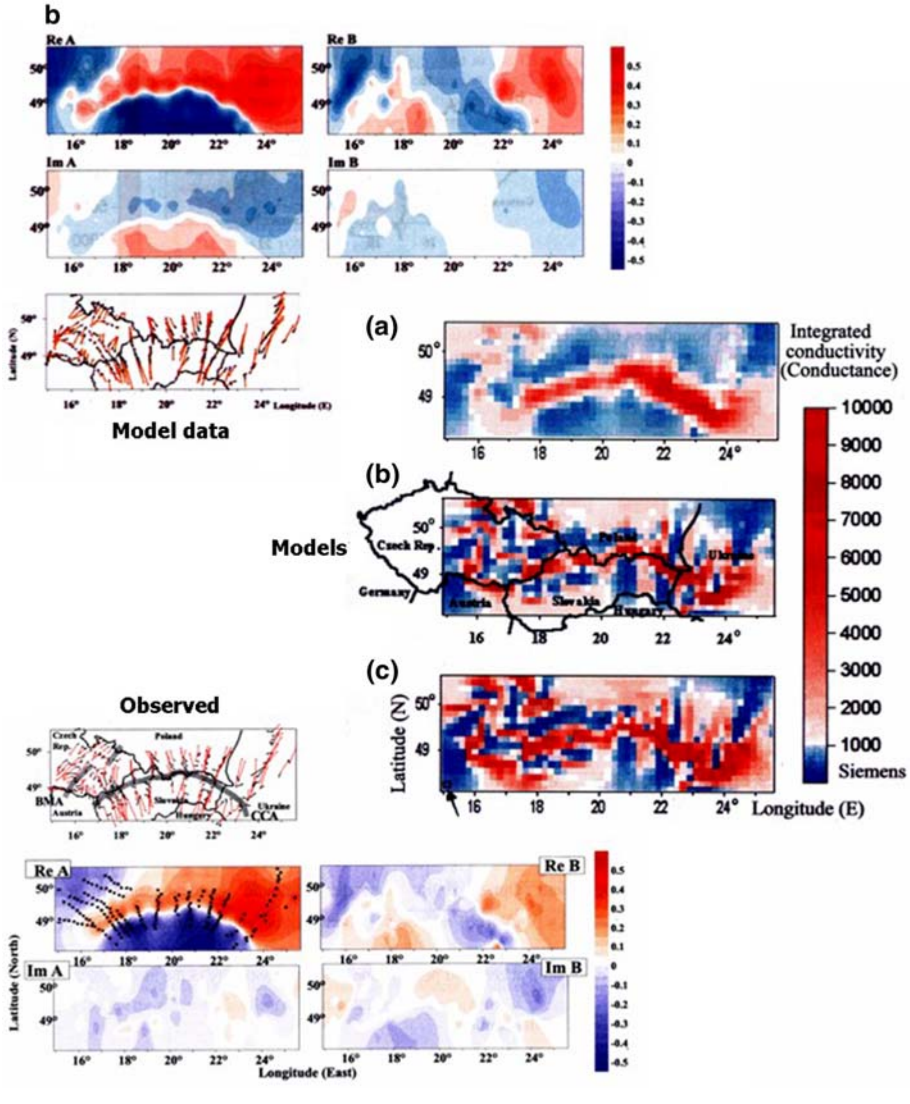

Fig. 10 continued

fluid-explanation for the cause of the anomaly (Jankowsky et al. 2005). Another example of recent modelling/inversion of the Carpathian Anomaly is from Kováčiková et al. (2005a, b). They inverted geomagnetic data (against the title of this review, non-magnetotelluric examples are also used) for conductance in a thin sheet at a specific depth (10 km in their work) in a layered medium. Observed and model responses (single station vertical magnetic transfer functions and induction arrows) and conductance model at the period of 32 min are shown in Fig. 10b. The model panel includes three models that differ by the used stabilizing functional (maximum smoothness, minimum gradient support and lagged diffusivity functional from top to bottom, respectively). The inversion models indicate clearly the presence of an anomalous belt corresponding to the Carpathian Arc

(CCA) and an additional anomaly (BMA) in the west along the eastern boundary of the Variscan (Hercynian) Bohemian Massif. Application of minimum gradient support and lagged diffusivity stabilization lead in both cases to similar models with sharp boundaries and a blocky structure especially at both ends of the CCA.

2.4 Trans-European Suture Zone and East European Craton

The Trans-European Suture Zone (TESZ), as described earlier, is a broad suture zone between the Precambrian East European Craton / East European Platform and Phanerozoic Europe in south and west (Fig. 1). In the NE, the TESZ marks the border between the German—Polish Caledonides (Avalonia) and Fennoscandian Shield (and roughly also the national border between Denmark and Germany). The North German—Polish Basin is located in Germany to the south of the TESZ, whereas in Poland these two roughly coincide. Further to the southeast, the Carpathians and TESZ again coincide in the region of SE Poland and Slovakian-Ukrainian border. From there the Carpathian Fold Belt and TESZ separates as the TESZ continues towards the Black Sea and the Carpathians turn the west to northern Romania.

Until recently, the most studied part of TESZ has been the segment in SE Poland, Ukraine, Slovakia and Hungary, because there TESZ and a well studied Carpathian Conductivity Anomaly nearly coincide spatially (see Carpathian description above). Recent huge seismic projects, such as TOR, Polonaise'97 and Celebration-2000 designed to investigate TESZ have increased a need to study also the electrical properties of the TESZ (see the map of seismic profiles and references in e.g., Gregersen et al. 2002; Jensen et al. 2002).

Smirnov and Pedersen (2006, 2007) studied lithospheric structure using long period magnetotellurics along the TOR seismic tomography array (Shomali et al. 2002, 2006). The final resistivity model from the TOR-profile is shown in Fig. 11 together with the seismic tomography model (Shomali et al. 2002). Seismic and conductivity models compare to each other well. Precambrian upper mantle in the Fennoscandian Shield is seismically fast and electrically resistive from the crust to depths of 300–350 km without any indication of a seismic or electrical asthenosphere. In the younger Phanerozoic Europe to the south (Caledonian and Variscan) the lithosphere is much thinner: seismic asthenosphere (low velocity zone; LVZ) is found at the depth of ca. 130 km and the top of the deep conductor is at much shallower depths in the southern part of the profile.

Similar results have been obtained from Pomerania, northwestern Poland, by the EM-TESZ-Pomerania project (Brasse et al. 2006; EMTESZ Working Group, 2006) from central Poland by Semenov et al. (2002) and from SE Poland by Semenov and Jóźwiak (2005). They all show that the upper mantle is devoid of conducting layers in the uppermost 300–400 km on the Precambrian craton side of the TESZ. On the contrary, on the Phanerozoic side of TESZ the major upper mantle conductor (its upper surface) is found at depths of 100–150 km. In Poland, the Precambrian basement is covered by Neoproterozoic to Phanerozoic sediments, which may prevent the detection of a "weakly developed" asthenosphere, i.e., an asthenosphere with a small content of partial melt. Yet in the Swedish part of the TOR profile, there are no sediments (except for a few tens of metres thick Quaternary overburden) to screen the detection of deep conductors, suggesting that the upper mantle has no major conductor in the EEC side of TESZ.

Thick sedimentary cover and conducting horizons within the sediments make it difficult to infer the internal structure (the structure of the sedimentary strata as well as the basement below the sediments) of the TESZ zone itself. In Poland, the North German—Polish

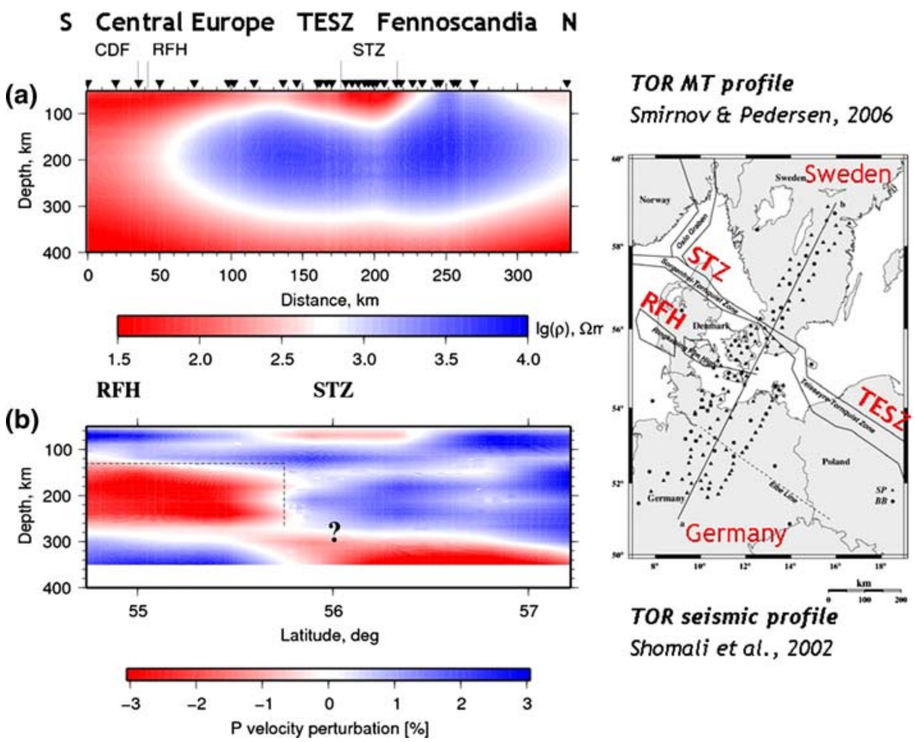

Fig. 11 TOR-models along the TOR array region from North Germany via Denmark to southern Sweden (map to the left) crossing the Trans-European Suture Zone (TESZ). 2D resistivity model at top is from Smirnov and Pedersen (2006, 2007). Seismic P-wave model at bottom is from Shomali et al. (2002). RFH = Rinköping Fyn High, STZ = Sörgenfrei-Törnquist Zone. Figure by courtesy of Blackwell Publishing Ltd. and Maxim Smirnov

basin coincides with the TESZ, therefore the knowledge of the electrical properties of the North German Basin can be extended to Poland and to TESZ research area and use to help the interpretation of the EMTESZ models. Since 1992, over 220 magnetotelluric soundings have been made in northern Germany to map the properties of the North German Basin (Hoffman et al. 2005). The site map and final resistivity model and the interpretative model are shown in Fig. 12. Results demonstrate that MT method can be used to discriminate between the highly conducting Lower Carboniferous Stillwater (black/Alum shale) facies and the less conductive Carboniferous limestone or flysch facies.

This section is completed with two examples from the East European Craton. Instead of local models, I include here examples of the shield-wide compilations of existing conductivity models.

A nearly 50-year long history of magnetotelluric work has resulted in a very extensive data set in Ukraine (Fig. 13, top). Ingerov et al. (1999) have recently compiled data from 3000 MT soundings in Ukraine, and present the results with various maps including integrated conductance of the sedimentary cover and maps of the determinant phase and apparent resistivity. They also compiled a map of the crustal conductance of the Ukrainian Shield (central part of Ukraine), which is based on 1D inversion of the MT data. This map is reproduced in Fig. 13 (bottom). The map of the conductance of the sedimentary cover

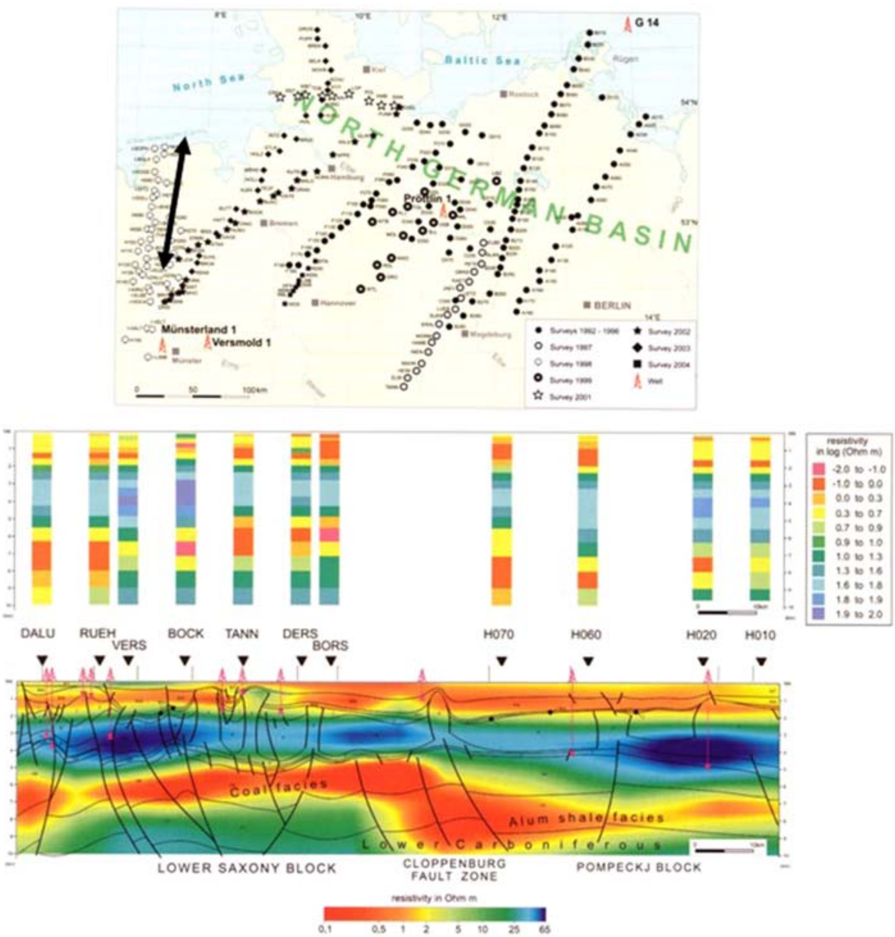

Fig. 12 Magnetotelluric sites in North German Basin (top) and an interpretation superimposed on 2D resistivity model along the profile shown by double arrow in map (roughly NS-directed westernmost profile). Figure from Hoffman et al. (2005) (by courtesy from http://www.schweizerbart.de)

shows clearly the "exposed" nature of the shield, i.e., the sedimentary conductance is only a few Siemens in contrary to 1500–2000 Siemens in the ca. 350 Ma old Pripyat-Dniepr-Donets Palaeorift in the northeastern part of Ukraine, where the thickness of the sedimentary succession may reach 20–25 km (Stephenson et al. 2006). It is interesting to note, however, that in the Donbas area (easternmost continuation of the PDD-rift), the depth of the sedimentary basis reaches 25 km but the conductance is well below 1000 S.

With respect to the crustal conductance map of the shield area (Fig. 13, bottom) the authors concluded that "we cannot show a place in the Ukraine where crustal conductor is definitely absent"; the lowest values reach a few tens of S. The map locates also two major conductors in shield, viz., the Ryasnopol (RA) and Indulo-Ingulets (II) conductors. The II conductor, which is located on the map by magnetotelluric data, is manifested by magnetovariational data as the Kirovograd anomaly. Yet, the RA conductor, whose

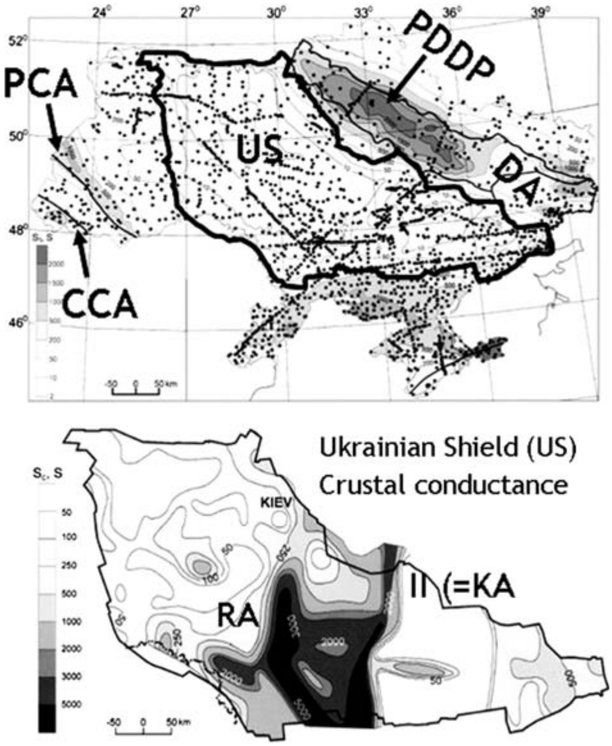

Fig. 13 Crustal conductance in Ukraine. Top: Location of magnetotelluric sites used to estimate crustal conductance (ca. 3000 sites). Base map shows the conductance of the sedimentary cover. Thick black line outlines the Ukrainian Shield (US). Bottom: Crustal conductance of the Ukrainian Shield. Figure compiled from Ingerov et al. (1999). RA = Ryasnopol, II = Indulo-Ingulets conductor, which coincide with the Kirovograd Anomaly delineated by magnetometer arrays, PDDP = Pripyat-Dniepr-Donets Palaeorift, D = Donbas, PCA = Pre-Carpathian Anomaly, CCA = Carpathian Conductivity Anomaly. Figure by courtesy of Terra Scientific Publishing Company

conductance is more than twice that of the II conductor, does not induce a pronounced MV-anomaly. Authors explain this by 3D effect, with the RA-conductor consisting of separate conductors.

As in Ukraine, also in Fennoscandia existing electrical models have been combined into a 3D model (or integrated conductance map; SMAP). In the Fennoscandian case (Korja et al. 2002) existing 1D and 2D models were combined and crust was divided into six layers, each 10 km thick. The first layer contains information on the conductance of uppermost 10 km including basement (bedrock), sediments (which in the shield area comprise of a thin Quaternary cover) and water (mainly surrounding oceans and the Baltic Sea). Figure 14 shows the map of crustal conductance for the entire "crust" (0–60 km). Note that the conductance of water areas is removed from the map. The map shows clearly the bimodal distribution of resistivities in shield areas: the shield is characterized by large highly resistive regions surrounded by narrower highly conducting zones. A detailed description of various conductors (and resistive regions) and their tectono-geological significance is given in Korja et al. (2002).

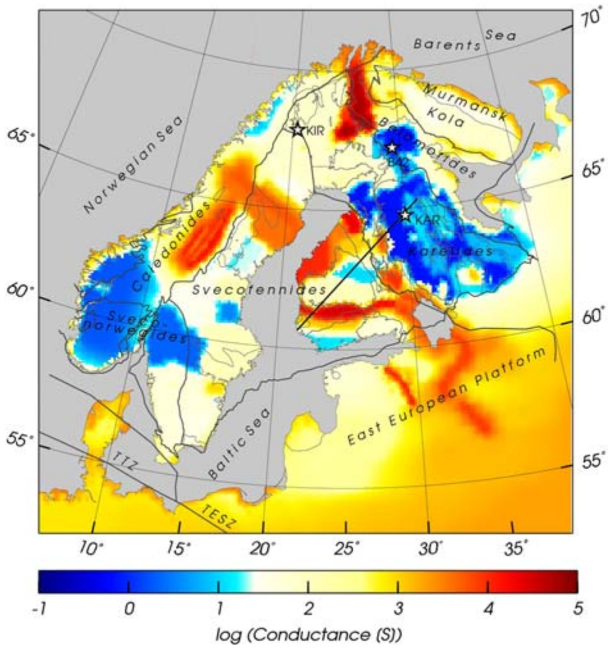

Fig. 14 Crustal conductance (Smap) of Fennoscandia at the depth interval 0–60 km. Note that conductance of water areas is removed from the map. Figure from Korja et al. (2002). Figure by courtesy of Terra Scientific Publishing Company

The most ambitious S-map compilation is probably the recently published compilation for the Russian territory (Feldman et al., 2006), which based on the analysis of over 12,000 MT soundings.

2.5 Remarks on Crustal/Lithospheric Studies

A brief survey of recent magnetotelluric and other electromagnetic studies in Europe as given above cannot naturally cover all work done. Nevertheless, it demonstrates that the magnetotelluric method can be used, and is being used, in all kind of environments and for imaging many different processes shaping the crust and lithosphere; research targets vary from Archaean palaeostructures to ongoing processes.

In Fig. 15 a map of Hilbert transformation of induction arrows over Europe at the period of T = 1,800 s is shown. It is based on data from ca. 1,800 sites (Wybraniec et al. 1999). Although there are large white areas, indicating the lack of data or the lack of the inclusion of data from areas where such would be available (e.g., Pajunpää et al. 2002 in south-central Sweden and Åland), the map clearly shows how complicated the crustal electrical structure is. However, it also helps to identify major conductors (conductivity anomalies) such as the Carpathian, North German—Polish, Kirovograd and Lake Ladoga—Bothnian Bay anomalies and others in Fennoscandia.

Results from SW Iberia (see Fig. 4 for the location) indicated that terrain boundaries are characterized by the presence of conductors most likely caused by graphite

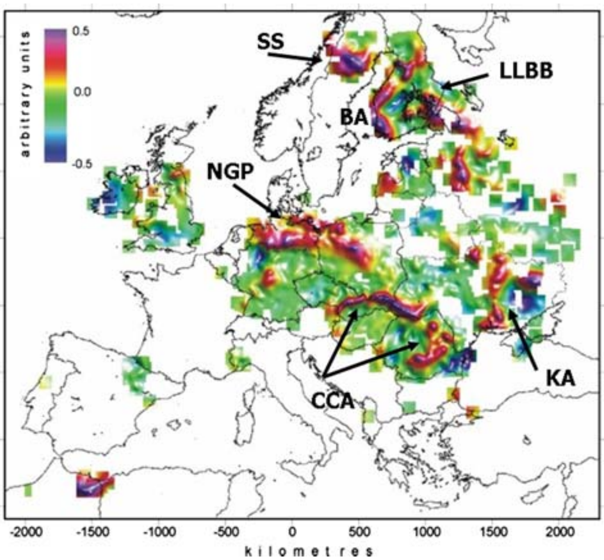

Fig. 15 Hilbert transformation of induction arrows over Europe at the period of $T = 1800$ s based on data from ca. 1800 sites (Wybraniec et al. 1999). Conductivity anomalies: SS = Storavan-Skellefteå, BS = Bothnia-Satakunta, LLBB = Lake Ladoga—Bothnian Bay, KA = Kirovograd, CCA = Carpathian Conductivity Anomaly, NGP = North German—Polish anomaly. Figure by courtesy of the Institute of Geophysics, Polish Academy of Sciences

enrichment along shear planes, reveal a presence of a range of shallow and deep seated resistors related to igneous complexes of variable age, and suggest the presence of several middle to lower crustal conductors indicating granulite facies metamorphism that produced granulitic rocks having grain-boundary carbon. These results correspond well with the results obtained, e.g., from Germany (ERCEUGT WG 1992), Fennoscandia (Korja and Hjelt 1993), Italy (Jödicke et al. 2004) and the Pannonian Basin and elsewhere as reviewed by Ádám (2005), which show that stable terrane boundaries/collisional zones/convergence zones/suture zones are in most cases characterized by enhanced conductivity caused most likely by graphite- and/or sulphide-rich rocks formed usually in shallow, restricted oceanic basins between the terranes and transported into deeper crustal levels (e.g., depths of 10–30 km) by subduction-collision related processes. However, as the brief survey for European EM studies showed, explanations for enhanced conductivity vary from graphites/sulphides/oxides to fluids, to partial melt, to elevated temperature, etc. Hence the interpretation must always be based on local geological and physical conditions.

A final note on crustal conductivity structure is from Feldman et al. (2006), who reanalysed and re-interpreted data from regional Geoelectric surveys carried out in Russia. In the abstract of their presentation in El Vendrell workshop (Feldman et al. 2006) they state, emphasizing economical aspect of the magnetotelluric work: “The resistivity of the lower part of the sedimentary layer can serve as a criterion for prediction of oil-gas-bearing areas. Virtually all oil-gas fields are situated within the areas of higher resistivity zones (>12 Ωm) and, at the same time, they are absent in areas where <10 Ωm.”

3 Lithosphere–asthenosphere Boundary

Lithosphere and asthenosphere are originally defined by rheological terms. The lithosphere is Earth's mechanically strong outer shell, which can support deviatoric stress over geologically long periods. Lithosphere is underlain by a mechanically weak asthenosphere that allows mass flow associated with isostatic adjustment (Martinec and Wolf 2005). Today, however, several types of lithosphere are defined, viz. rheological, seismic, electrical, thermal and elastic lithosphere. Seismic lithosphere is defined as the outer shell with higher seismic velocities than in the underlying upper-mantle shell (low velocity zone; LVZ), the asthenosphere whereas electrical lithosphere is defined as the resistive outer shell overlying a highly conducting shell (high conductivity zone; HCZ) in the upper mantle, also called the electrical asthenosphere (Martinec and Wolf 2005).

An explanation for the enhanced conductivity in upper mantle is needed if estimated (model) conductivities are higher than those of dry mantle minerals at relevant thermal conditions. Usually the presence of partial melt is invoked to explain increased electrical conductivity in upper mantle at depths corresponding to the depth of asthenosphere (e.g., thermally defined base of the lithosphere follows 1300°C isoline). Laboratory studies (e.g., Roberts and Tyburczy 1999), however, imply that unreasonably high amounts of partial melt (>5%) are required if the field results are explained by laboratory results (Heinson 1999). Such an amount of melt would be gravitationally unstable. An alternative explanation is given by Karato (1990): the presence of dissolved water, i.e., H+ charges, makes it possible to reduce electrical resistivity as well as to reduce seismic velocity and decrease viscosity (Karato and Jung 1998).

In Europe, Praus et al. (1990) published a map of the lithosphere-asthenosphere transition in Central Europe based on magnetotelluric and seismic data. Their compilation indicated that the top of the electrical asthenosphere (high conductivity zone; HCZ) is slightly deeper than that of seismic asthenosphere (LVZ). Following that, Hjelt and Korja (1993) extended the map including new data primarily from the East European Craton. In this chapter I update the European database of the depth to the lithosphere-asthenosphere boundary (LAB) in Europe and provide new map showing lateral variations of the depth of LAB.

It should be noted, however, that strictly speaking we are searching here for the depth to the top of the major subcrustal conductor at the depths relevant for the asthenosphere. Relevant depth range depends, of course, on local thermal and rheological environment. In other words, as we will see, the depth to the top of HCZ in the Pannonian Basin ranges from 45 to 90 km. In the Fennoscandian Shield such a layer would be partly a crustal feature since the Moho depth in Fennoscandia ranges roughly between 40 and 65 km (Korsman et al. 1999).

Since Praus et al. (1990) and Hjelt and Korja (1993) several studies on upper mantle conductivity have been completed for different parts of Europe. Some of them were already included in Heinson's review (1999). Several studies in southern Europe have provided new data on upper sub-crustal conductivity including Bayrak and Nalbant (2001) and Gürer et al. (2004) in Turkey; Galanopoulos et al. (2005) in Greece; Braitenberg et al. (1994) and Armadillo et al (2001) in Italy; Simpson (2002) and Pous et al. (1995a) in Mediterranean Islands; Pous et al. (1995b, c) and Ledo et al. (2000) in Pyrenees and Monteiro Santos et al. (20012003) on the oceanic lithosphere between Lisbon and Madeira Island.

In central Europe, research on Carpathians and surrounding regions has provided a wealth of new data. Ádám and Wesztergom (2001) compiled all existing data from 41 sites in the Pannonian Basin and investigated various ways to compensate from near-surface distortions. They provided a map on lithospheric thickness in Pannonian Basin, which shows variations from 45 to 90 km. Červ et al. (2001) and Stanica et al. (1999) provided estimates on the lithospheric thickness to the north and south of the Pannonian Basin, respectively.

In Western Europe relatively few experiments to explore upper mantle conductivity have been completed. Tezkan (1994) studied Rheingraben whereas Bahr et al. (1993) and Tarits et al. (2004) studied the roots of Alps.

In the East European Platform (=East European Craton covered by Neoproterozoic and Palaeozoic sediments), Burakhovich et al. (1996) and Logvinov (2002) have provided data from Ukraine, Fainberg et al. (1998) from Belorussia and Berdichevskii et al. (1996) from Caucasus. Further to the east in Kazakhstan, Karimov and Al'-Zhadi (2001) have compiled an extensive map on lithospheric thickness.

The Trans-European Suture Zone has been a target of intensive research during last few years. Ernst et al. (2002), Semenov et al. (2002) and Semenov and Jóźwiak (2005) and EMTESZ WG (2006) are providing data from Poland whereas Smirnov and Pedersen (2006, 2007) investigate TESZ along a profile from Denmark to Sweden.

In Fennoscandia several studies are investigating upper mantle conductivity, have Prior to the BEAR measurements, Viljakainen (1996) made four long period soundings in Central Finland. Results of BEAR, with respect to models on upper mantle conductivity have been published by Lahti et al. (2005), Hjelt et al (2006) and Korja et al. (2006a). In Jämtland, Uppsala and Oulu teams have investigated Fennoscandia's passive margin (Gharibi et al. 2000; Carlsäter 2003; Korja et al. 2006b) whereas the recent EMMA project (Korja et al. 2006c) investigates the Archaean core of the Fennoscandian Shield. Similarly recent MT-FIRE and GGT-SVEKA projects (Vaittinen et al. 2006; Lahti et al. 2007) are providing information on upper mantle in the eastern Archaean Karelian Craton.

In Appendix Table 1, references to original sources are given and data type (magnetotelluric or some other EM data) and geological environment of the sample site are described. The final data file has in its current form 471 entries of which 74 are from Praus et al. (1990). The file is a simple xyz-file. For sites where 1D-models are available, the coordinates of LAB estimate are naturally those of the MT site. In the case of 2D models, we have sampled the model (profile) and assigned for each sample site a depth value. In two cases, viz. Pannonian Basin and Kazakhstan, isoline maps of LAB variations have been re-sampled and included into our database. For the Pannonian Basin, older estimates of the depth of LAB have been replaced by the values obtained from the map of Ádám and Wesztergom (2001). In the case of Kazakhstan, new estimates have been obtained by re-sampling the map of Karimov and Al'-Zhadi (2001).

The resulting maps are shown in Figs. 16 and 17 for entire Europe and for Fennoscandia, respectively. In Fig. 18, four "lithospheric" cross-sections across European continent are displayed. The cross-sections are not from interpolated maps but depth values (see inverted triangles in cross-sections) are picked from the database using GMT-subroutines (Wessel and Smith 1998). It should also be noted that the maximum depth of 250 km in the colour scale in the European map is selected to enhance resolution in the interesting depth interval of 50–250 km. Thus the depth values of 250 km means the depth to HCZ (LAB) is 250 km or greater or that asthenosphere has not been detected. In the Fennoscandian map, a full scale from 100 km to 400 km is used.

The major features of the lithosphere–asthenosphere system/upper mantle in Europe are the following:

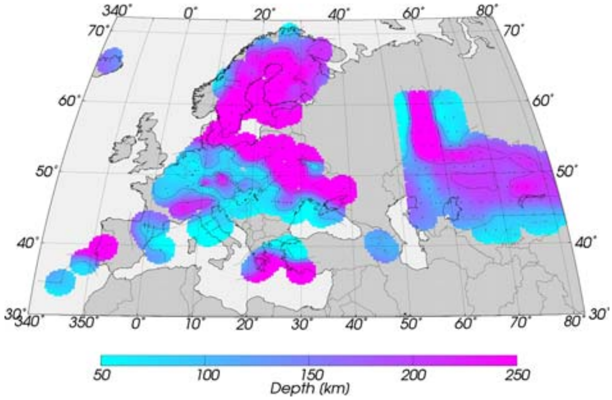

Fig. 16 Thickness of the lithosphere in Europe. Maps show the depth to the upper surface of the major high conductivity zone (HCZ) in upper mantle. Black dots denote data points. Radius of masking circle 100 km. Note that the colour scale is defined from 50 to 250 km to enhance resolution in this interval. Therefore 250 km means that (i) HCZ is at the depth of 250 km, (ii) it is deeper or (iii) it is not detected. This map should be compared with a sub-map of Fennoscandia given in Fig. 17, where colour scale from 100 to 400 km is used

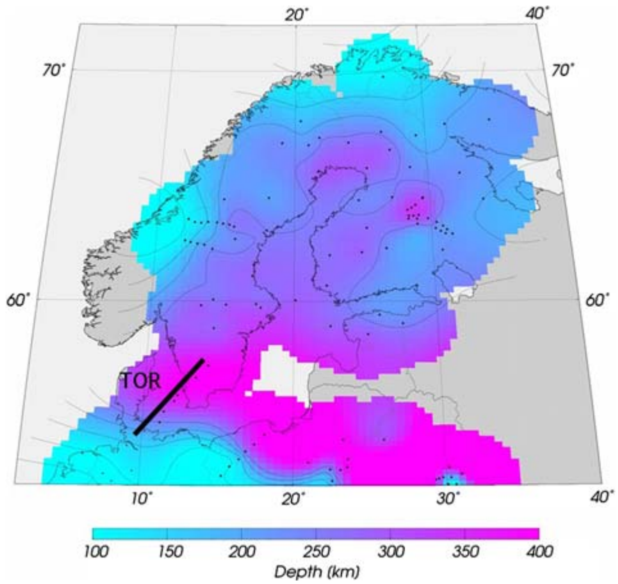

Fig. 17 Thickness of the lithosphere in Northern Europe. Details of the map as in Fig. 16, except for colour scale. Location of the TOR profile is shown. TOR-model is shown in Fig. 11

(1) variations of the lithospheric thickness are large,
(2) Phanerozoic Europe, with considerable variations (45–150 km), is much thinner than the Precambrian Europe,

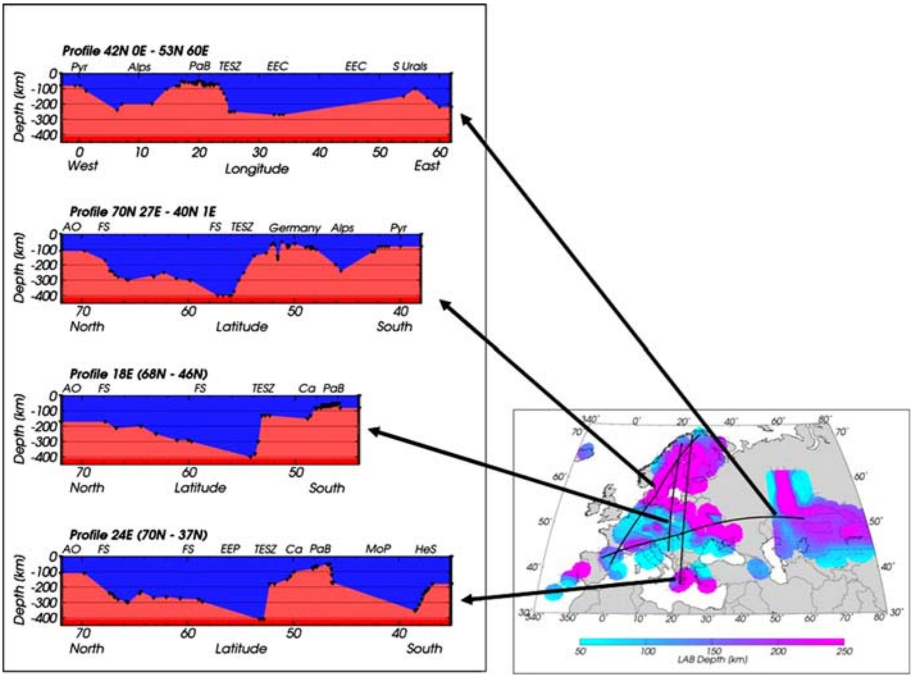

Fig. 18 Lithospheric cross-sections across the European continent. Inverted triangles denote data points, which are picked from the original database, not from the interpolated map shown in Figs. 16 and 17. Abbreviations of geological province crossed by profiles are given above the cross-sections. Alps = Alps, AO = Atlantic Ocean, Ca = Carpathians, EEC = East European Craton, FS = Fennoscandian Shield, HeS = Hellenic Subduction zone, MoP = Moesian Platform, PaB = Pannonian Basin, Pyr = Pyrenees, S Urals = Southern Urals, TESZ = Trans-European Suture Zone

(3) the thinnest lithosphere in found under the extensional Pannonian Basin (45–90 km),
(4) spatially rapid change across TESZ from thinner Phanerozoic Europe to thick EEC,
(5) in most of the EEC there are no indications of a HCZ in upper mantle; either no "electrical asthenosphere" or its dimensions (thickness and amount of conducting phase) are so small that it cannot be detected through the overlying "conductance"; yet the integrated upper mantle conductance, e.g., in southern Sweden, is very small, which should make it possible to detect an asthenospheric channel,
(6) the TESZ is a major electrical border (as in other geophysics too) in Europe separating electrically two quite different "worlds",
(7) in Fennoscandia, interestingly the "thickest" area is in the Palaeoproterzoic Svecofennian Domain not in Archaean; the lithosphere is thinning towards the Atlantic and Arctic Oceans as well as to the east (in Archaean Karelian Craton), and
(8) in many regions there is no information at all on upper mantle conductivity structure; this calls for European multinational projects such as the suggested EuroArray (Jones et al. 2006) or BEAR array (Korja et al. 2006a: arrays of simultaneously recording instruments, long recording periods (2–6 months), spatial sampling adequately dense (20–50 km)

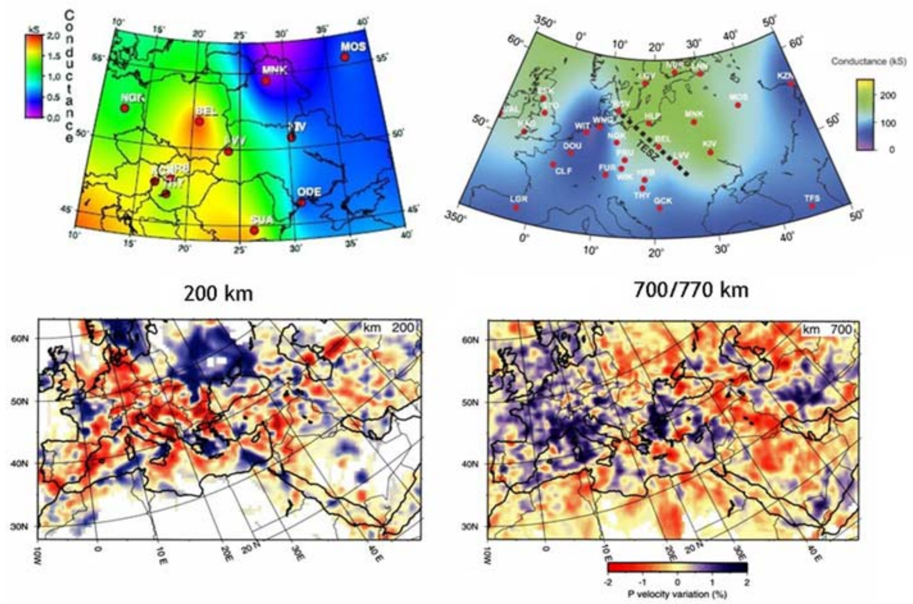

Fig. 19 Comparison of electrical conductivity and seismic P-wave velocities in southern and central Europe in upper mantle (200 km) and below transition zone (700/770 km). Seismic models are from Piromallo and Morelli (2003). The conductance model for 200 km is an integrated sub-crustal conductance from Moho to 200 km (Pushkarev et al. 2006) and the model for 770 km is a smoothed image of the integrated conductance, in kilosiemens, from the surface down to the depth of 770 km (Semenov and Jóźwiak 2006). Figure by courtesy of Elsevier, AGU, Pavel Pushkarev, and Vladimir Semenov

Finally, in Fig. 19, electrical and seismic models at depths of 200 km and 700/770 km are compared. Note that the depth of 200 km is in the lithosphere in the EEC (NE of TESZ) whereas southeast of TESZ it is below the lithosphere. The latter depth is, in both cases, in the lower mantle below the transition zone. Seismic P-wave models are from Piromallo and Morelli (2003). Conductance models are from Pushkarev et al. (2006) and Semenov and Jóźwiak (2006). The conductance model for 200 km is an integrated sub-crustal conductance from Moho to 200 km i.e., crustal conductance is excluded. The conductance model for 770 km is a smoothed image of the integrated conductance, in kilosiemens, from the surface down to the depth of 770 km.

In the upper mantle above the transition zone, the Phanerozoic Europe exhibit higher electrical conductivity and lower seismic velocity than the areas to the east of TESZ. But deeper, below the transition zone, properties are opposite, i.e., the mantle beneath the East European Craton becomes more conducting and slower compared to areas to the west of TESZ.

4 Conclusions

I have reviewed recent investigations on the electrical conductivity of the lithosphere and asthenosphere in Europe. On crustal work and structures a few examples are given.

Selected examples contain studies that have been carried out in new target areas and studied active (or semi-active) processes, such as active transform fault system, subduction zone and results of a recent continent-continent collision. Other examples show new advances in studies of major geological structures in Europe (Carpathians, TESZ, among others).

The following features are quite evident from this review:

- the magnetotelluric method can be used, and is being used, in all kind of environments and for many different processes shaping the crust and lithosphere,
- the crust is very heterogeneous both with respect to the scale of conductive/resistive features and interpretations,
  - research targets vary from Archaean palaeostructures to ongoing processes,
  - explanations for enhanced conductivity vary from graphite/sulphides/oxides to fluids, to partial melt, to elevated temperature etc.; hence the interpretation must always be based on local geological and physical conditions,
- the European database of the depth to the lithosphere–asthenosphere boundary (LAB) is updated and a new map showing lateral variations of the depth to LAB is provided
- with respect to the lithosphere:
  - Phanerozoic Europe, with considerable variations (45–150 km), is much thinner than Precambrian Europe
  - the thinnest lithosphere in found under the extensional Pannonian Basin (45–90 km),
  - spatially rapid change across TESZ from thinner Phanerozoic Europe to thick EEC,
  - the TESZ is a major electrical border (as in other geophysics too) in Europe separating electrically two quite different “worlds”,
  - in most of the EEC, no indications on a HCZ in upper mantle; either no “electrical asthenosphere” or its dimensions (thickness and amount of conducting phase) are so small that it cannot be detected through the overlying “conductance”; yet the integrated upper mantle conductance, e.g., in southern Sweden, is very small, which should make it possible to detect an asthenospheric channel if present
- in many regions no information at all is available on upper mantle conductivity structure; this calls for European multinational projects: arrays of simultaneously recording instruments with sufficiently long recording periods (2–8 months) and with an adequately dense (20–50 km) spatial sampling.

Acknowledgements I wish to express my sincere thanks to the Program Committee and LOC of the El Vendrell workshop, who offered me a chance to prepare and deliver this review. In particular, I wish to give my thanks to J. Ledo and P. Queralt. My best thanks goes also to all colleagues, who provided me material on electrical conductivity and other geophysical and geological data in Europe. Last but not least, the guest editors of the review volume, P. Queralt and J. Weaver, are thanked for their guidance and patience. Prof. Alan Jones and an anonymous referee provided many useful comments that have improved the manuscript. Finally, I would like to thank University of Oulu, the Finnish Väisälä foundation and the Academy of Finland (EMMA project) for funds to prepare the review and to attend the workshop.

Appendix

Table 1 Sources of data used to compile the database that contains depths of the electrical lithosphere-asthenosphere boundary in Europe

Region/ country	Geological/geographical/profile identity	Type of data	Reference
Atlantic Ocean	Iberia (Lisbon)	Cable/2D	Monteiro Santos et al. (2003)
	Doldrums Mid-Atlantic Ridge	OBM	Shneyer et al. (1991)
	Iceland	MT	Beblo et al. (1983)
Mediterranean	Mallorca	MT/1D	Pous et al. (1995a)
	Mallorca	MT/1D	Simpson (2002)
Turkey	Anatolia (W-Turkey)	MT/2D	Bayrak and Nalbant (2001)
	Taurides (SW-Turkey)	MT/2D	Gürer et al. (2004)
Spain	Pyrenees	MT/2D	Pous et al., (1995b, c), Ledo et al. (2000)
France	French Alps (SURF)	MT/1D	Tarits et al. (2004)
			Fournier et al., (1971) (P1990)
			Fournier (1970) (P1990)
			Reitmayr (1974) (P1990)
Belgium			Fournier (1970) (P1990)
Germany	RAB	MT/1D	ERCEUGT (1992)
	Rhine Graben (TAU, SIG)	MT/1D	Tezkan (1994)
	Black Forest (BRE)	MT/1D	Tezkan (1994)
	Schwabian Alps (HEID)	MT/1D	Simpson (2002)
	LAU, RAB, Alps	MT/1D	Bahr (1988) Bahr (1992a; b), Bahr et al. (1993)
	ATZE	MT/1D	Jödicke et al., (1983)
			Fournier (1970) (P1990)
			Scheube (1984) (P1990)
			Steveling (1984) (P1990)
			Wegenitz (1982) (P1990)
			Reytmayr (1974) (P1990)
			Richards et al. (1982) (P1990)
			Steveling (1973) (P1990)
			Blumecke (1984) (P1990)
			Buchter (1984) (P1990)
			Bejarano-Gerke and Jödicke (1983) (P1990)
			Jödicke et al. (1983) (P1990)
			Schulte (1980) (P1990)
			Junge (1984) (P1990)
			Weidelt (1970) (P1990)
			Fournier et al. (1971) (P1990)
Italy	Friuli region	MT/1D	Braitenberg and Zadro (1990)
			Braitenberg et al. (1994)

Table 1 continued

Region/ country	Geological/geographical/profile identity	Type of data	Reference
	Apennines	GDS/2D	Armadillo et al. (2001)
			Schwarz and Haak (1980) (P1990)
Greece	Hellenic Subduction	MT/2D	Galanopoulos et al. (2005)
Hungary	Pannonia	MT/1D, 2D	Ádám and Wesztergom (2001)
	Pannonia (CEL-7)	MT/2D	Ádám et al. (2005)
			Ádám (1976) (P1990)
			Ádám (1976) (P1990)
			Fournier et al. (1971) (P1990)
Austria			Ádám et al. (1986a, b) (P1990)
Czech and Slovakia	Carpathians, Bohemian (Geotraverse VI)	MT/2D	Červ et al. (2001)
Romania	C-profile	MT/2D	Stanica et al. (1999)
Poland	EEC, TESZ	MT/1D, 2D	Ernst et al. (2002), Semenov et al. (2002)
		MT, GDS/1D	Semenov and Jóźwiak (2005)
	TESZ (P-line)	MT/2D	EMTESZ WG (2006)
Ukraine	Carpathian (KAPG profile)	MT/2D	Zhdanov et al. (1986)
	Entire Ukraine	MT/1D, 2D	Burakhovich et al. (1996)
		HSG/1D	Logvinov (2002)
Belorussia	EEC (B2)	MT, GDS/1D	Fainberg et al. (1998)
Armenia	Caucasus	MT	Berdichevskii et al. (1996)
Russia	Urals	MT	Dyakonova et al. (1990)
			Antoneyev et al. (1992)
Kazakhstan		MT	Karimov and Al'-Zhadi (2001)
Fennoscandia	BEAR array	MT/1D	Hjelt et al. (2006), Korja et al. (2006a)
	B42	MT/1D	Lahti et al. (2005)
	Jamtland	MT/2D	Korja et al. (2006b), Carlsäter (2003)
	EMMA	MT/1D	Korja et al. (2006c)
	MT-FIRE	MT/2D	Vaittinen et al. (2006)
	TOR	MT/2D	Smirnov and Pedersen (2006, 2007)
	Kuhmo region	MT/1D	Kaikkonen et al. (1983)
	LMT-1994 (LOT, VII, PYL, VIR)	MT/1D	Viljakainen (1996)
	KIR, KEV, NAT	MT/1D, HSG	Jones (1980; 1982a, b; 1984), Jones et al. (1983)
	Värmland	MT/2D	Rasmussen (1988)

Notes: Column 2: Abbreviations for various regions, profiles etc. are not explained here but they can be found from original references. Column 3: 1D or 2D indicates that depths are from the results of 1D or 2D inversions, 1D/2D indicates that the data from corresponding source (sources) contain both 1D and 2D model data. MT = magnetotelluric method, GDS = geomagnetic depth sounding method, HSG = horizontal spatial gradient method, OBM = ocean bottom magnetometer data, cable = submarine cable data. Column 4: (P1990) indicates that the reference and associated depth values are taken from the compilation of Praus et al. (1990)

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