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The Moho depth map of the European Plate

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SUMMARY

The European Plate has a 4.5 Gy long and complex tectonic history. This is reflected in the present-day large-scale crustal structures. A new digital Moho depth map is compiled from more than 250 data sets of individual seismic profiles, 3-D models obtained by body and surface waves, receiver function results and maps of seismic and/or gravity data compilations. We have compiled the first digital, high-resolution map of the Moho depth for the whole European Plate, extending from the mid-Atlantic ridge in the west to the Ural Mountains in the east, and from the Mediterranean Sea in the south to the Barents Sea and Spitsbergen in the Arctic in the north. In general, three large domains within the European Plate crust are visible. The oldest Archean and Proterozoic crust has a thickness of 40–60 km, the continental Variscan and Alpine crust has a thickness of 20–40 km, and the youngest oceanic Atlantic crust has a thickness of 10–20 km.

Key words: Crustal structure; Controlled source seismology; Body waves; Europe.

HISTORICAL BACKGROUND

In 1910, the Croatian seismologist Andrija Mohorovičić (1857–1936) published his important paper 'Potres of 8.X.1909' (Earthquake of 8 October 1909). In this paper, he studied seismograms of an earthquake in the Kupa Valley (Croatia), together with other events from this region and he discriminated two distinct pairs of compressional (*P*) and shear (*S*) waves. He writes in his paper: 'When I was sure, based on data, that two kinds of first preliminary waves exist, both kinds reaching all locations from 300 to 700 km distance, and that from the epicentre to approximately 300 km distance only the first kind arrives, whereas from 700 km distance onward only the second kind arrives, I tried to explain this until now unknown fact' (Mohorovičić 1910). In today's nomenclature, the first kind of the arrivals correspond to crystalline basement *Pg* and *Sg* phases and overcritical crustal phases P_{crustal} and S_{crustal}, while the second kind of arrivals correspond to mantle *Pn* (*Sn*) and *P* (*S*) phases. The interpretation of the two sets of arrivals led Andrija Mohorovičić to discover the existence of the velocity discontinuity in the uppermost Earth. He evaluated the depth to be at 50 km, with *P*-wave velocities 5.60 km s^{-1} above and 7.747 km s^{-1} below (respectively, 3.27 and 4.182 km s^{-1} for *S* waves). Below the boundary surface, the velocity ratio was $V_P/V_S = 1.852$, which was significantly larger than in the upper layer were it was 1.710 (Mohorovičić 1910). Studies during the next 100 yr showed that the sharp seismic discontinuity discovered by Mohorovičić was found worldwide, and that it separates crust from underlying upper mantle. It was named the Mohorovičić discontinuity or Moho in abbreviated form, or even M-discontinuity (for lazy people and people having problem with the pronunciation of this Croatian name).

The seismic discontinuity discovered by Mohorovičić is a primary definition of the boundary between crust and upper mantle, given in terms of the velocities of seismic waves. Today, the seismologically defined Earth's crust means the outer shell of our planet in which the velocity of *P* waves is smaller than about 7.6 km s^{-1}, and *S*-wave velocity is smaller than about 4.4 km s^{-1} (e.g. Meissner 1986). In general *P*-wave velocity in the lower crust is about 7 km s^{-1} and in the uppermost mantle about 8 km s^{-1}. So, the *P*-wave velocity contrast at the Moho discontinuity is quite large, being up to 1–1.5 km s^{-1}. This indicates a significant change in elastic parameters, resulting from a significant change in the rock types between crust and uppermost mantle.

Secondary definitions of the Earth's crust use other parameters, such as densities, type of rock, mineralogical and chemical compositions. In the density definition of the crust, the density value corresponding to the Moho is 3.1 g cm^{-3}. A typical density of the

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lower crust is about 3.0 g cm^{-3} and for the uppermost mantle about 3.3 g cm^{-3}. So, also in terms of density the Moho is a distinct discontinuity. The interrelation of seismic velocities and densities of rocks (Nafe & Drake, see Talwani *et al.* 1959), together with laboratory data for various rock assemblages (e.g. Birch 1960; Christensen & Mooney 1995) gives us the information for interpretation of crustal and mantle lithologies.

PREVIOUS WORK

The complicated history of the European Plate is reflected in the present day structure, particularly in the continental and regional scales of the Earth's crust. Though there are several crustal maps for Europe, we considered that in view of the quantity of high resolution data and models now available, particularly seismic models, it is an appropriate time to bring them together and produce a new integrated map of the Moho depth for the European Plate. The improvement of Moho depth map for the European Plate was an initiative of the Subcommission on Crustal and Upper Mantle Structure of the European Seismological Commission (ESC).

The only existing Moho maps covering the whole European Plate are of low resolution. The global crustal models are specified on 5°×5° (Mooney *et al.* 1998) and 2°×2° grids (Laske 2002; Meier *et al.* 2007) and are the only unified models for the whole European Plate available to date. Some models were constrained in the past, but they covered, in fact, only the continental part of Europe (e.g. Meissner *et al.* 1987; Giese & Pavlenkova 1988; Tesauro *et al.* 2008). Compilations of Moho depth are available for many regions of Europe (e.g. Radulescu 1988; Luosto 1991; Scarascia & Cassinis 1997; Chadwick & Pharaoh 1998; Jensen *et al.* 2002). They were published in last 20 yr, however, they contain the results of a number of surveys done in the 1970s and the 1980s. They do not, however, form a continuum. The integration of available models derived from recent active and passive seismic experiments should allow the construction of maps with a rather high resolution (1° or better) in many areas of Europe. From the early 1970s, many crustal models have been produced for different regions in Europe. A number of oldest surveys were also re-interpreted using modern techniques (e.g. Luosto 1986; Grad & Tripolsky 1995; Grad *et al.* 2005). Most of crustal models describe the variation of seismic parameters, velocity and layer boundary discontinuities. It is time to bring the models together and produce a new integrated crustal map of the European Plate, with the plate understood as an area extending from the mid-Atlantic ridge in the west to the Ural Mountains in the east and from the Mediterranean Sea in the south to the Barents Sea and Spitsbergen in the Arctic in the north (extended between 40°W and 70°E and 28°N and 88°N°, respectively). To compile the Moho depth map from various sources, we need to use improved structural models and to integrate the best local models available. Such a map is required for the following reasons: (1) to highlight the tectonic processes shaping surface geology; (2) to improve the accuracy of location of seismic events. A good crustal model is vital for the accurate location of seismic events (in position and depth) and therefore essential for seismic hazard studies (3) to discriminate between earthquakes and explosions at regional distances 2°–20°, this requires knowledge of how seismic waves propagate through the crust and uppermost mantle. A good model is essential to explain and predict propagation anomalies; (4) to correct for crustal effects when probing deeper into the Earth (e.g. in seismic tomography).

REVIEW OF METHODS FOR THE CRUSTAL STRUCTURE STUDIES

In terms of elastic parameters and density, the Moho is a distinct discontinuity. It can be studied relatively easily using geophysical methods—seismic waves propagated through crust and mantle with different velocities, as well as by modelling of gravity anomalies with the use of large density contrast at the Moho (Fig. 1).

Seismic methods are most effective for studing the Earth's interior, and they use different types of seismic waves—body P and S waves and surface waves. The waves have their characteristic frequencies, which result in the resolution and accuracy of obtained seismic models. Relatively long surface waves from shallow regional earthquakes (period $T = 10$–100 s) are used in the modelling of dispersion curves of phase and group velocities $V(T)$ and waveform modelling (Fig. 1a). In crustal studies using surface waves, the epicentral distance of the recordings is usually between 10° and 20°. They cover a relatively large area, but the lateral resolution is usually of the order of 50–100 km. This limits the spatial resolution for crustal velocities and Moho depth (depth accuracy of the order ±4–5km). On the other hand, surface waves are useful in studying oceanic areas, which have a rather poor coverage of seismic stations.

The best resolution for the geometry of crustal seismic boundaries and for the Moho is obtained using near-vertical reflection profiling (Fig. 1b). In this technique, the relatively short wave lengths ($T = 0.02$–0.1 s, frequency interval $f = 10$–50 Hz) permit detailed determination of the shape of the seismic boundaries, the zones of attenuation (e.g. fracture zones) and the zones of high reflectivity. The deep near-vertical reflection technique is, however, expensive. So, it is usually applied in prospecting the shallowest sedimentary cover (to a depth of a few kilometres, usually to about 4 s TWT—two-way time). The number of profiles with recording time extending to 12–20 s TWT is still limited and not nearly sufficient to constrain the Moho depth map for large areas.

Intermediate resolution can be obtained with deep seismic sounding using refracted and wide-angle reflected waves (Fig. 1d) of intermediate frequencies ($f = 5$–15 Hz and $T \approx 0.1$ s), recorded along profiles up to distances of 300–400 km from the source. Identification of the Moho is crucial in this method. Reflections from the Moho (*PmP* wave; usually the strongest observed wave), together with refractions from the uppermost mantle (*Pn* wave; recorded as first arrival in far distance from the source, some 150–300 km, with characterstic velocity about 8 kms^{-1}), unequivocally define the Moho. The method of refracted and wide-angle reflected waves gives Moho depth for long profiles with a good accuracy of the order of ±1–2 km.

In the last over dozen or so years, a considerable development in the receiver function (RF) technique has taken place. In RF the initial data are broad-band seismograms of teleseismic P waves from the earthquakes at the epicentral distance range of 30°–100°. At seismic discontinuities beneath the seismic station, a part of the P-wave energy is converted to S-wave energy (Fig. 1e). The delay time of these P-to-S converted phases (P_s) depends on the depth of the discontinuity and the S-wave velocity. The amplitudes depend on the contrast of seismic velocities at discontinuity. Different techniques of RF interpretation are applied, including 1-D inversion, forward modelling of V_S velocity, and simultaneous determination of Moho depth and Poisson's ratio in the crust. These results provide new, independent information, particularly on the distribution of S-wave velocity in the crust and Moho depth (with an accuracy of about ±3 km). In the RE technique, in a similar way to surface

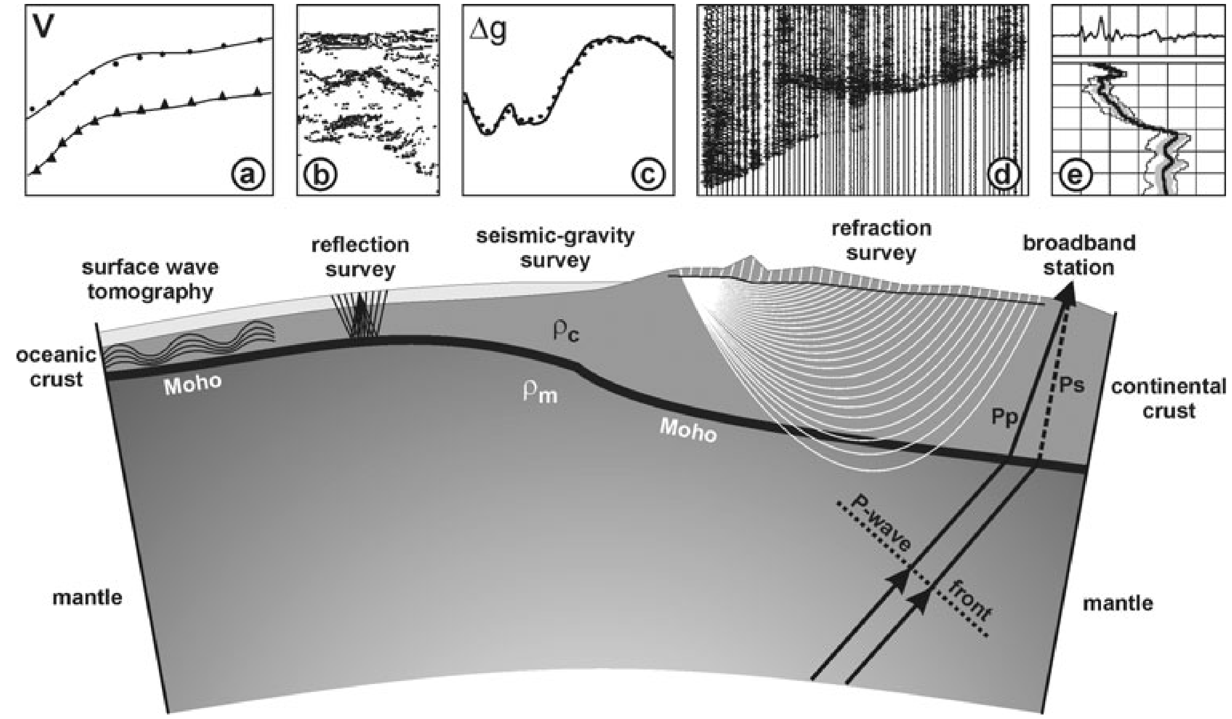

Figure 1. An illustration of the methods used to study crustal structure and a sketch of the waves penetrating into crust/mantle model: (a) dispersion curves of surface waves in surface wave tomography; (b) a seismic section in a near-vertical reflection profiling and reflected rays from the Moho; (c) a gravity model obtained using the contrast of densities of the crust (ρc) and mantle (ρm); (d) a controlled source seismic refraction profiling record section and rays of refracted waves in the crust and uppermost mantle; (e) a plot illustrating the RF technique with rays converted at the Moho—*Pp* (solid) and *Ps* (dashed)—the front of the teleseismic *P* wave is marked by dotted line.

waves investigations, capability to resolve *P*-velocity and density is very limited.

Distribution of the density in the crust can be obtained by modelling Bouguer anomalies, which reflect mostly density inhomogeneities in sediments, crystalline complex of the crust and at the Moho (Fig. 1c). Gravity modelling use seismic data: velocity distribution and geometry of seismic discontinuities result in density distribution in the crust (ρc) and mantle (ρm).

In spite of their relatively low resolution, the surface waves and RF investigations are able to resolve crustal *S*-velocity structure. Their combination with *P* velocities from refraction studies and densities from gravity modelling, gives the characteristics of the basic elastic parameters of the crust, including the geometry of discontinuities and Moho depth.

DATA TO CONSTRAIN THE NEW MOHO DEPTH MAP

We begun by collecting a database of the Moho depth values (Fig. 2 and Table 1). The oldest data come from early the 1970s and the 1980s, and most of them were compiled in regional maps that were published in the last 20 yr. A huge amount of new data were obtained in last decade, for example, in Central Europe, particularly within the refraction and wide-angle reflection projects POLONAISE'97, CELEBRATION 2000, ALP 2002 and SUDETES 2003 (Guterch *et al.* 1999, 2003). The results of different projects were evaluated, and they were given relative weighs in our compilation. The highest weigh was given to data from modern refraction and wide-angle reflection profiles with a dense system of observations and good reciprocal coverage (e.g. Guterch *et al.* 1994; EUROBRIDGE Seismic Working Group 1999; Grad *et al.* 2003, 2006; Środa *et al.* 2006; Brückl *et al.* 2007). Moho depths were directly extracted from 2-D numerical models with spacing of 5 or 10 km (depending on seismic data and model quality), and transferred to geographical coordinates: latitude φ, longitude λ, and Moho depth *h* below the sea level. Older profiles were digitized by hand from published papers (e.g. Båth 1984; Fernàndez *et al*. 2004a; Neprochnov *et al*. 2000; Lie & Andersson 1998) with spacing 10–20 km (or more for the spars recording system or low coverage of rays). Only those parts of the models that were sufficiently sampled by rays were included in the database. In case of significant disagreement of depth at crossing points of two profiles, either the results of the profile with better quality were used, or both profiles were removed from the data set.

For some areas, we used regional Moho depth maps, compiled using deep seismic data, usually both refracted and reflected. Some of them we got in digital form, for example, for Germany (Mechie 2007) and for the Barents Sea (Ritzmann *et al.* 2007). For the territory of Russia a few tens of deep seismic sounding profiles, surveyed mainly by GEON, Moscow, were compiled into Moho depth map shown in Fig. 3 (map **Ko**, for data examples see e.g. Kostyuchenko *et al.* 1998, 1999, 2004, 2006; Yegorova *et al.* 2004b). Another compilation for the same territory was done by Erinchek *et al*. 2006 (see map **Er** in Fig. 3). **Ko** and **Er** maps are rather consistent and express the deepest Moho in European Russia in a very similar way. The differences in Moho depths between the maps do not usually exceed ±3 km (**Ko**-**Er** in Fig. 3), and only in some areas does it reaches ±5 km (the Urals, the area north of Caspian Sea). Both maps show much more details in Moho topography compared with about a 30-years-old map by Giese & Pavlenkova (1988; in Fig. 3 map **GP**). Also, differences in Moho

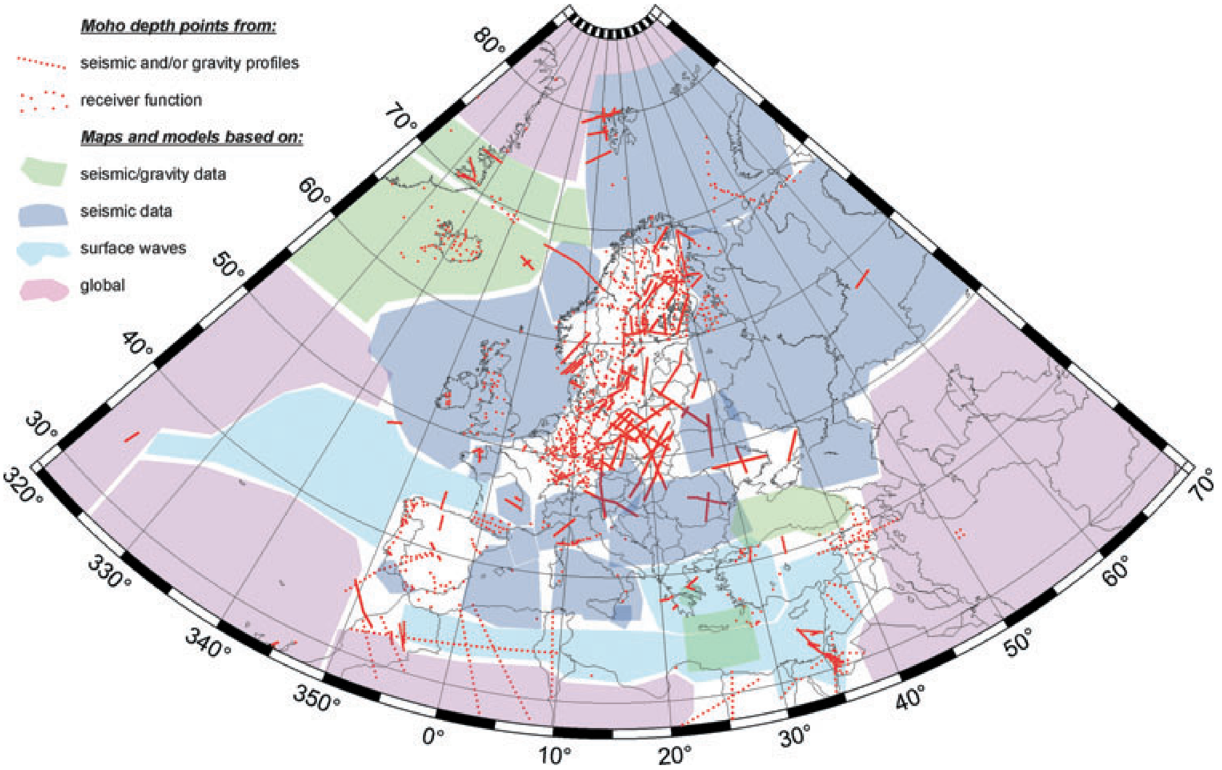

Figure 2. Spatial coverage of the data sets used in the construction of the Moho depth map for the European Plate. The database for this compilation comprises more than 250 data sets from individual seismic profiles, 3-D models obtained by body and surface waves, RF and regional maps of seismic and/or gravity data compilations. See the text for more description.

Table 1. Sources of data for Moho depth map of the European Plate.

Area	References for original seismic and/or gravity data	References for compiled data
East European platform	Aleshin *et al*. 2006; Båth 1984; Czuba *et al.* 2002; DOBREfraction'99 Working Group 2003; EUROBRIDGE Seismic Working Group 1999; EUROBRIDGE'95 Seismic Working Group 2001; FENNIA Working Group 1998; Grad & Luosto 1987, 1994; Grad & Tripolsky 1995; Grad *et al.* 1991; Komminaho & Yliniemi 1992; Kortström *et al.* 2006; Luosto 1986; Luosto *et al.* 1989, 1990, 1994; Olsson 2007; Środa & POLONAISE Working Group 1999; Thybo *et al.* 2003; Wilde-Piórko *et al*. 2002	Bogdanova *et al.* 2006; Erinchek *et al.* 2006; Korja *et al.* 2001; Korsman *et al*. 1999; Kostyuchenko *et al.* 1999, 2004, 2006; Luosto 1991; Yegorova *et al.* 2004a, 2004b
Central Europe	Bleibinhaus *et al*. 1999; Grad *et al.* 1999, 2003, 2005, 2006; Guterch & Grad 2006; Guterch *et al.* 1994, 1999; Hauser *et al.* 2001, 2007; Hrubcová *et al.* 2005; Janik *et al.* 2002, 2005; Jensen *et al.* 1999; Lie & Andersson 1998; Majdański *et al.* 2006; Malinowski *et al.* 2005; Środa *et al.* 2006; Wilde-Piórko *et al.* 2002	Grad *et al.* 2002, 2007; Guterch *et al.* 2007; Lenkey 1999; Mechie 2007; Radulescu 1988; Wéber 2002
Western Europe	Álvarez-Marrón *et al.* 1996; Banda *et al*. 1993; Bitri *et al*. 1997; Cassel *et al*. 1983; Grandjean *et al.* 2001; ILIHA DSS Group 1993; Matte & Hirn 1988; Ottemöller & Midzi 2003; Pulgar *et al.* 1996; Suriñach & Vegas 1988; Téllez & Córdoba 1998; Thybo *et al.* 2006; Zang & Langston 1995; Zeyen *et al.* 1997	Banda 1988; Kelly *et al.* 2007; Lefort & Agarwal 2000; Rijkers & Duin 1994
Mediterranean Sea and Alpine area	Behm *et al.* 2007; Ben-Avraham *et al.* 2002; Bertrand & Deschamps 2000; Brückl *et al.* 2007; Clément *et al*. 2000; Contrucci *et al.* 2005; Hirn *et al*. 1996; Karagianni *et al.* 2005; Makris *et al.* 1999, 2001; Makris & Yegorova 2006; Marone *et al.* 2003; Mele & Sandvol 2003; Netzeband *et al.* 2006; Raykova & Nikolova 2007; Serrano *et al.* 2005; Van der Meijde *et al*. 2003; Zelt *et al.* 2005; Zor *et al.* 2006	Cassinis 2006; González-Fernández *et al.* 2001; Mauffret *et al*. 1995; Nicolich *et al.* 2000; Sartori *et al*. 2004; Scarascia & Cassinis 1997
Atlantic and polar regions	Barton & White 1997; Bullock & Minshull 2005; Canales *et al*. 2000; Czuba *et al.* 1999, 2005; Du *et al*. 2002; Fernàndez *et al.* 2004a, 2004b; Grevemeyer *et al*. 1997; Ljones *et al.* 2004; Marone *et al.* 2003; Neprochnov *et al*. 2000; Ottemöller & Midzi 2003; Riedel *et al.* 2005	Foulger & Anderson 2005; Gudmundsson 2003; Leftwich *et al.* 2005; Planke *et al*. 1991; Ritzmann *et al.* 2007; Tsikalas *et al.* 2005
European Plate surroundings	Al-Damegh *et al.* 2005; Angus *et al*. 2006; Arboleya *et al.* 2004; Ayarza *et al.* 2005; Best *et al.* 1990; Dahl-Jensen *et al.* 2003; DESERT Group 2004; Doloei & Roberts 2003; Doser *et al.* 1997; El-Isa et al., 1987; Ginzburg & Ben-Avraham 1987; Ginzburg *et al*. 1981; Gürbüz & Evans 1991; Juhlin *et al.* 1996; Maillard *et al.* 2006; Makris *et al*. 1988; Mechie *et al*. 2005; Mickus & Jallouli 1999; Mohsen *et al*. 2005; Paul *et al*. 2006; Schmidt-Aursch & Jokat 2005a, 2005b; Schwartz & Wigger 1988; Snyder & Barazangi 1986; Zor *et al*. 2003	Kostyuchenko *et al.* 1998; Laske 2002; Pasyanos *et al.* 2004; Seber *et al.* 2000; Sheikh-Zade 1996; Starostenko *et al.* 2004; Ye *et al*. 1999

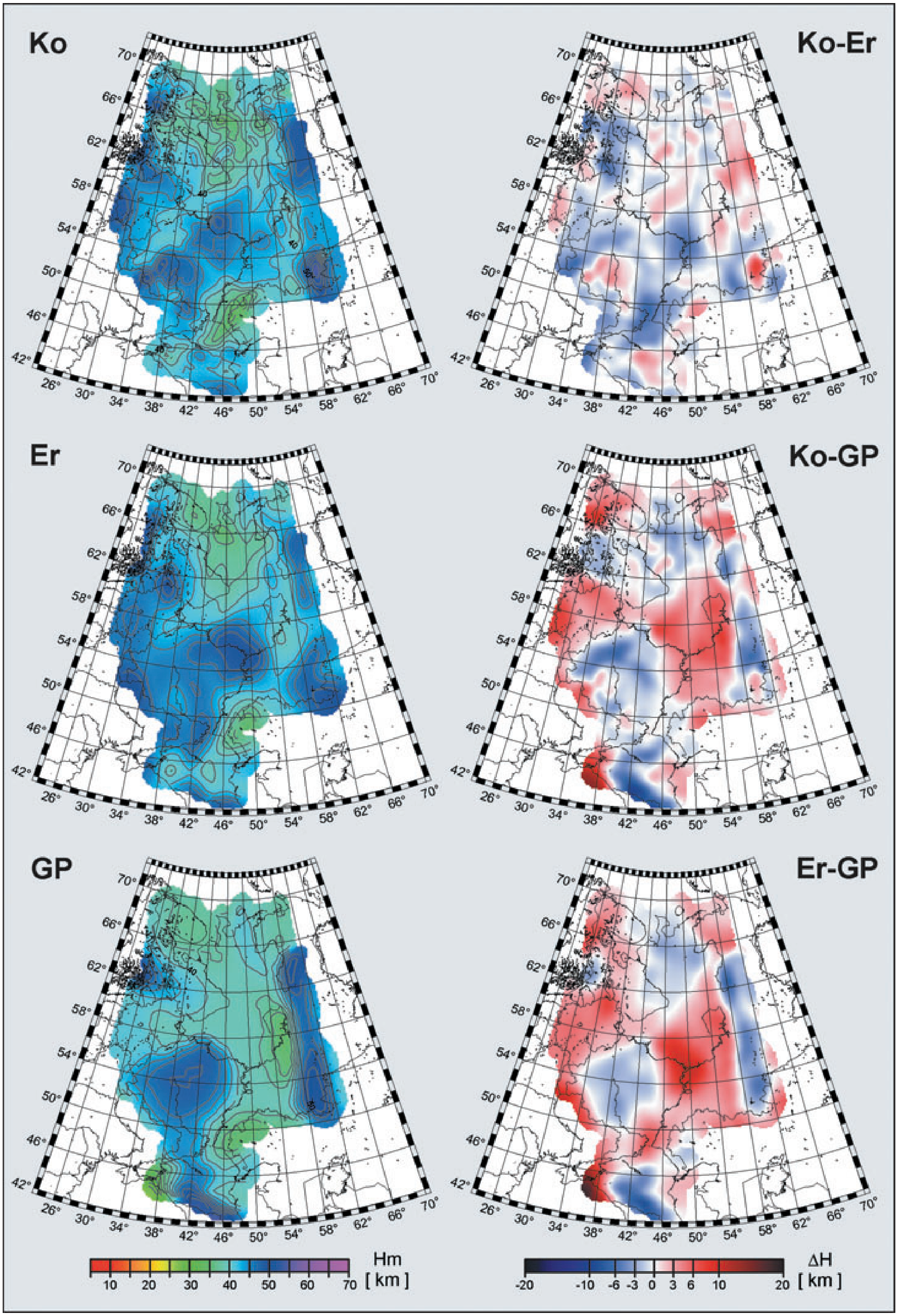

Figure 3. A comparison of the data sets from European Russia. Data of GEON Moscow were compiled into the Moho depth map **Ko** (for data examples see e.g. Kostyuchenko *et al.* 1998, 1999, 2004, 2006; Yegorova *et al.* 2004b). Map **Er**, compilation by Erinchek *et al*. (2006). Map **GP**, Moho topography by Giese & Pavlenkova (1988). The corresponding differences in the Moho depths are shown in maps **Ko**–**Er**, **Ko**–**GP** and **Er**–**GP**.

depths between map **GP** and the two new maps **Ko** and **Er** reach ±6 km, or even more (see comparison **Ko**–**GP** and **Er**–**GP** in Fig. 3). For our compilation of the European Moho we decided to use average values from the **Ko** and **Er** maps.

For the territory of British Isles and surrounding sea areas we made a similar comparison between two data sets based on seismic profiles (**KE**, Kelly *et al.* 2007; **CP**, Chadwick & Pharaoh 1998) and Moho depth determined using the RF technique (**RF**, Landes *et al.* 2006; Tomlinson *et al.* 2006). An **RF** map based on a limited number of observations gives only the generalized Moho depth of the area. All three maps and the difference between **KE** and **CP** maps are shown in Fig. 4. Maps **KE** and **CP** differ slightly, particularly in the continent-ocean transition (about 5 km in **KE**–**CP** map). Both maps have been compiled using tens of existing reflection and wide-angle/refraction seismic profiles, including the results of the large project of deep reflection profiling British Institutions Reflection Profiling Syndicate (BIRPS). However, the **KE** model was additionally verified and tuned by gravity modelling. The minimized rms misfit between observed and calculated gravity anomalies was 8.8 mGal (Kelly *et al.* 2007). We used the **KE** map in our compilation of the Moho depth map for Europe.

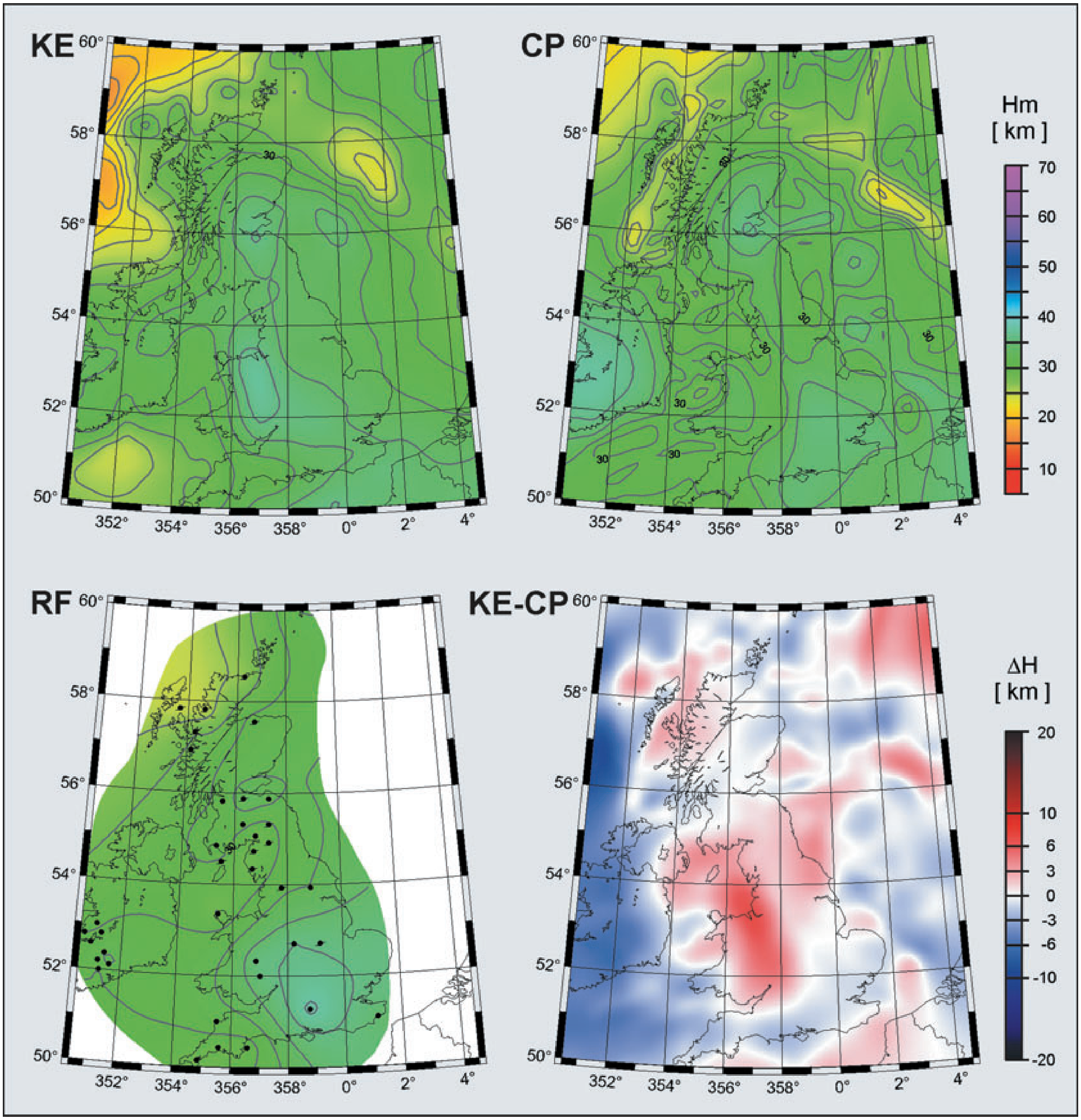

Figure 4. A comparison of the data sets from the British Isles and surounding areas. **KE**, map by Kelly *et al*. 2007; **CP**, map by Chadwick & Pharaoh 1998; **RF**, map compiled from the data published by Landes *et al*. (2006) and Tomlinson *et al*. (2006). **KE**–**CP**, differences between maps **KE** and **CP**.

We used also Moho depths in digital form from 3-D models, derived from local seismic tomography, surface waves and seismic/gravity modelling results (e.g. Środa *et al.* 2002**;** Marone *et al.* 2003; Karagianni *et al.* 2005; Schmidt-Aursch & Jokat 2005a, 2005b; Zelt *et al.* 2005; Behm *et al.* 2007; Majdański *et al.* 2007; Raykova & Nikolova 2007). In this case, maps and/or models had different grid spacings, from about 10 km ×10 km (or even smaller), to about 50 km × 50 km. The grids were resampled to a more suitable spacing according to quality of the data, resolution of the data and existence of other data for the area in question.

Another class of seismic data were RF Moho depth estimations beneath permanent or temporary seismic stations (e.g. Du *et al*. 2002; Wilde-Piórko *et al*. 2002; Angus *et al*. 2006; Olsson 2007). In addition many maps were digitized by hand (e.g. Mauffret *et al*. 1995; Starostenko *et al.* 2004; Leftwich *et al.* 2005; Tsikalas *et al.* 2005; Cassinis 2006; Makris & Yegorova 2006). Areas without regional seismic or gravity data (usually at European Plate surroundings) were filled using more general, lower-resolution global models (Laske 2002; Pasyanos *et al.* 2004).

Altogether, the Moho map database comprises more than 250 data sets from individual seismic profiles, 3-D models obtained by body and surface waves, RF, and maps of seismic and/or gravity data compilations (Fig. 2 and Table 1). All coordinate manipulation, gridding and filtration were done using The Generic Mapping Tools (GMT, Wessel & Smith 1991, 1998). The original data points were triplets: latitude φ, longitude λ and Moho depth h below the sea level. The data was transformed to the xy-coordinate system to reduce distortion caused by handling geographic data from different latitudes. Latitude and longitude values were changed to xy-coordinates using a Lambert projection in the scale 1:10000000 using origin 59.5°N, 15.0°E and standard parallels 30°N and 86°N. The Lambert projection was chosen because it produces very low distortion of an area but is still conformal. The data points were changed to a 10 km × 10 km grid, using the adjustable tension continuous-curvature surface gridding algorithm (*Smith & Wessel* 1990). Before the gridding the data were pre-processed to avoid spatial aliasing and to eliminate redundant data. This was done by transforming the original points to 10 km × 10 km block averages. The data grid was lowpass filtered using cut-off length of 100 km and passing wavelengths greater than 200 km. Finally the gridded data set was transformed from xy-coordinates back to the geographical coordinate system φ, λ, h. The final product—a Moho depth map was resampled to a 0.1° × 0.15° grid. The map to a scale of 1:40000000 is shown in Fig. 5.

In general, the Moho depth map is smooth, though we accepted small disagreements of depth at the crossing points of profiles. In some cases, disagreements result from different accuracy, different techniques used or from velocity anisotropy in the crust (e.g. Środa 2006), which can be in the order of 10 per cent. However, anisotropy was not taken into consideration in our 'isotropic' map. It should be noted, that the process of models evaluation, determination of sampling interval for models and Moho depth maps, as well as the decision to use only parts of overlapping data, sets was subjective, based first of all on the quality of original data and our own experience. Another recommendation for the quality of data and models/maps is the fact that they were published in high quality, reviewed, international journals.

Although different types of data were used, in most cases depths to the Moho were consistent. As mentioned earlier, we can expect that our map describes Moho depth with an accuracy of the order ±3–6 km. However, the uncertainties are different for different seismic techniques, even different for the same techniques in different experiments and areas. Evaluation of the Moho depth uncertainty was published only in few papers (e.g. Zeyen *et al.* 1997; Doloei & Roberts 2003; Grad *et al.* 2003; Marone *et al.* 2003; Środa *et al.* 2006; Behm *et al.* 2007; Ritzmann *et al.* 2007). We expect the lowest uncertainty of the order 5 per cent for new, modern, good quality seismic refraction profiles, available in digital form (e.g. models obtained by ray tracing modelling)—it gives about ±2 km uncertainty for 40 km thick crust. Older, reinterpreted, compiled, and/or manually digitized profiles have lower quality, with uncertainty of the order 6–8 per cent. For profiles with good-quality seismic data, but a poor coverage of shots and/or receivers, as well as for good quality RF studies the uncertainty is about 10 per cent. For manually digitized maps and results based on gravity modelling using seismic profiles uncertainty is about 15 per cent (about ±6 km for 40 km thick crust). The lowest uncertainty (about 20 per cent) was atributed to results obtained from surface waves and gravity modelling.

When available, the uncertainties were taken from the published papers. In other cases, we used values described above. For all data points used to construct the Moho depth map (for the same latitude φ and longitude λ), corresponding values of uncertainties (in km) were atributed. The map of Moho depth uncertainty (Fig. 6) was done using exactly the same projection, transformation, filtering, etc., as the Moho depth map.

The uncertainty map is shown in Fig. 6. The uncertainty ranges from 5 to 20 per cent, what gives uncertainty for the Moho depth from ±2 to ±10 km. As seen from the map we have the lowest uncertainty of the order of ±2–4 km for the continental part of Western, Central and North Europe. We have similar values for the oceanic crust; however, the Moho depth there is about 10–15 km, so, the relative uncertainty is big. The bigest uncertainty is observed for Greenland and for Europe–Africa–Arabia transition, where the resolution of the present map is the lowest.

MOHO MAP FOR THE EUROPEAN PLATE AND TECTONIC CONCLUSIONS

The new European Plate Moho depth map (Fig. 5) is a compilation of data, published before September 2007. The map has some advantages over the previous maps: (1) it contains available recent/modern results on the crustal stucture, mostly high quality seismic results; (2) the map covers the area of the whole European Plate, extending from the mid-Atlantic ridge in the west to the Ural Mountains in the east and from the Mediterranean Sea in the south to the Barents Sea and Spitsbergen in the Arctic in the north, which is much wider than areas covered by previous Moho depth maps of Europe; (3) it is consistent and (4) it is available in digital form.

The complex tectonic history of Europe reflects the breakup of a Neoproterozoic supercontinents Rodinia/Pannotia (Dalziel 1997) to form the fragment of Baltica and the subsequent growth of continental Europe, beginning with the Caledonian orogeny. Caledonian and younger Variscan orogenesis involved accretion of Laurentian and Gondwanan terranes to the rifted margin of Baltica during the Palaeozoic (Pharaoh 1999). The suite of sutures and terranes that formed, the so-called Trans-European suture zone (TESZ) adjacent to the rifted margin of Baltica, extends from the British Isles to the Black Sea region. The TESZ is far more complex than a single suture, but in a broad sense, it is the boundary between the accreted Phanerozoic terranes and Proterozoic Baltica. Understanding its structure and evolution is one of the key tectonic challenges in

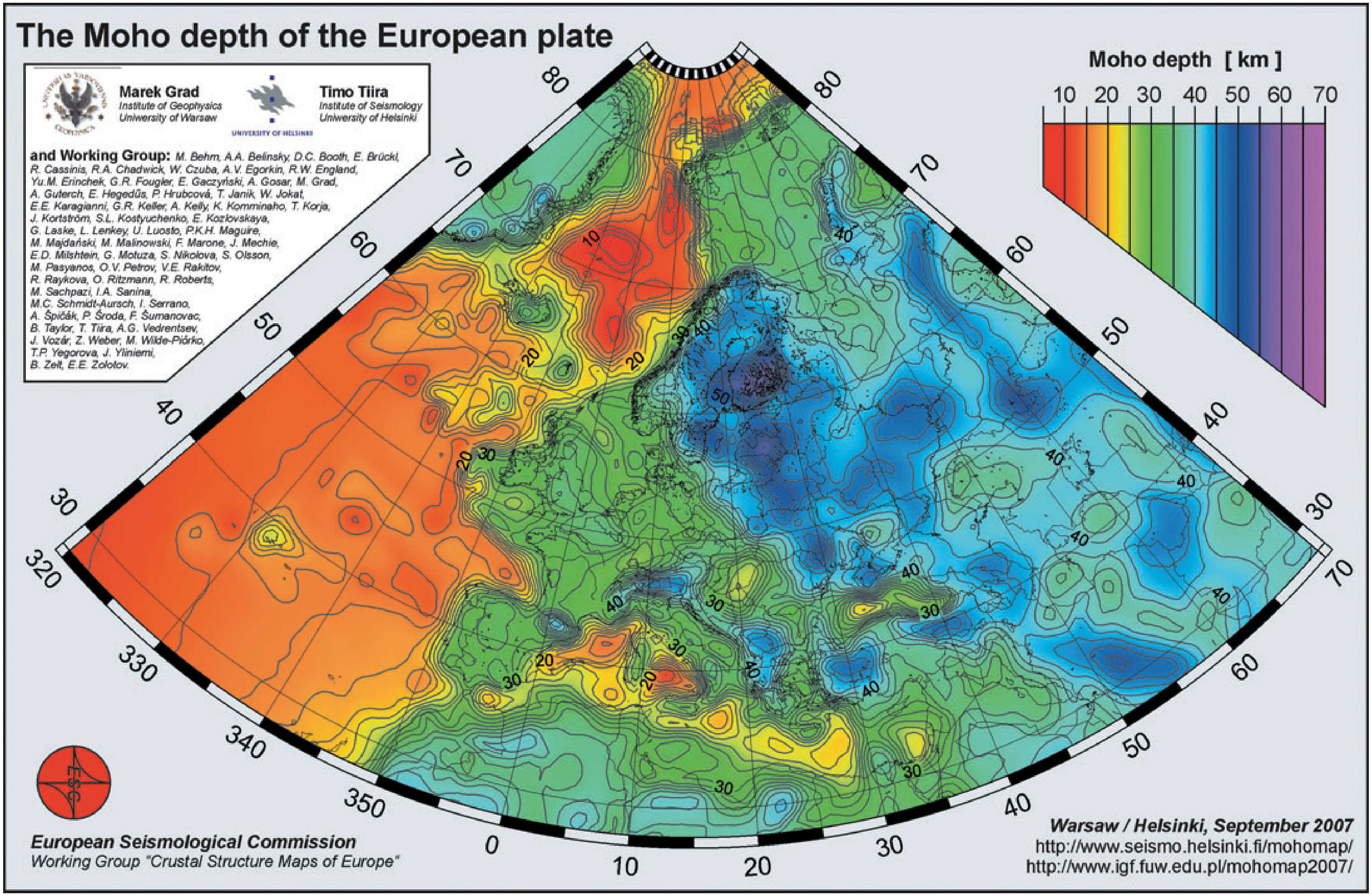

Figure 5. The Moho depth map of the European Plate. The database for this compilation comprises more than 250 data sets from individual seismic profiles, 3-D models obtained by body and surface waves, RF and maps of seismic and/or gravity data compilations (for their location see Fig. 2 and Table 1 for references). All coordinate manipulation, gridding and filtration were done using The Generic Mapping Tools (GMT) (Wessel & Smith 1991, 1998). Map in Lambert projection was resampled to 0.1° × 0.15° grid in geographical coordinate system φ, λ. Status for September 2007. See the text for more details.

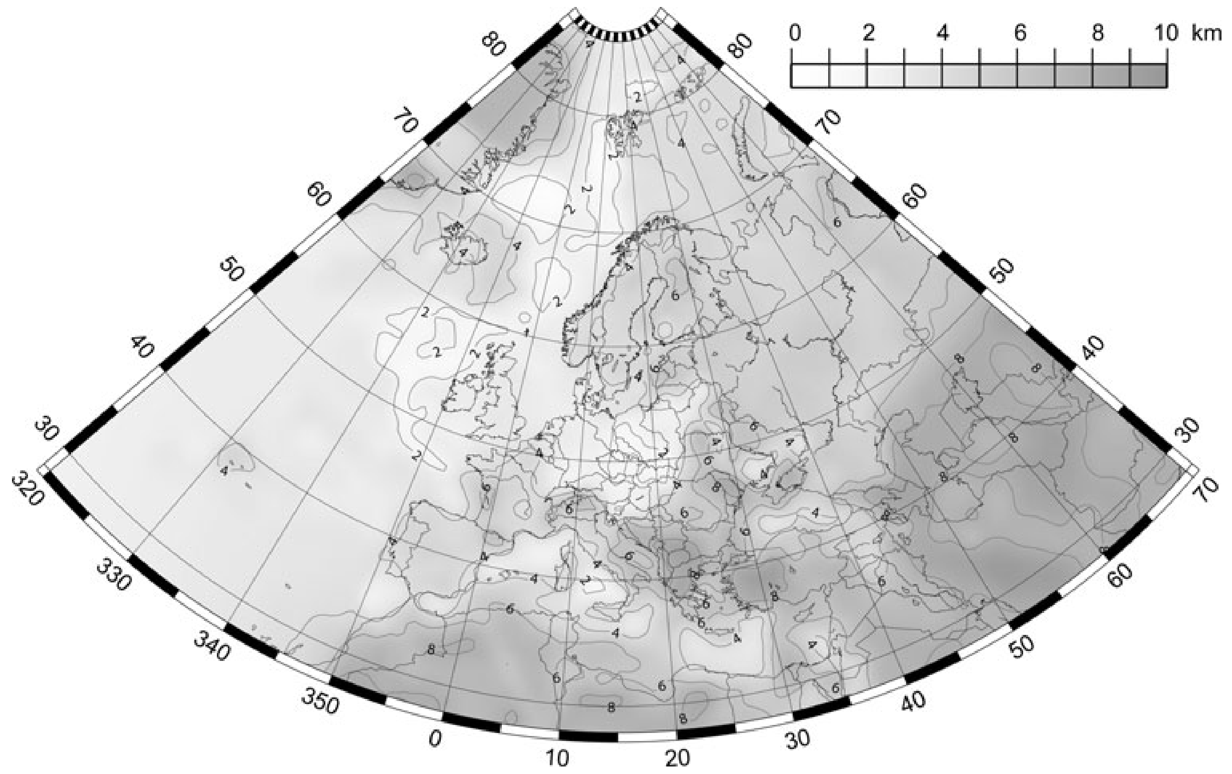

Figure 6. The map of the Moho depth uncertainty. The map was processed similarily as Moho depth map in Fig. 5.

Europe and is certainly of global importance to studies in terrane tectonics and continental evolution. The younger Alps, Carpathian Mountains arc and Pannonian backarc basin in the south form interrelated components of the Mediterranean arc–basin complex and are the result of intricate Mesozoic/Cenozoic plate interactions in the Mediterranean region as the Tethys Ocean, closed during the convergence of Europe and Afro–Arabia.

All tectonic processes and geological structures mentioned above have their images in the Moho depth map. Regional and local properties can be studied using existing models and data for relatively limited area. Here, we would like to concentrate on the continental scale of visible structures. Long wave filtration permits us to expose the main elements of the European Plate Moho on a large scale. Fig. 7 shows two maps, filtered from the original one with a characteristic length of 500 km (Fig. 7a) and 1000 km (Fig. 7b), which are devoid of the fine details of the structure. In Fig. 7(a) the thick crust of the East European platform (with the Baltic shield) is separated in the west from the Atlantic by the Caledonides. In the south, between TESZ and the Mediterranean Sea, accreted terranes form a much shallower crust (ATA, Iberia, Pannonian Basin), with the exception of the thick collisional Alpine crust. For longer characteristic length of filtration (Fig. 7b), three large domains within European Plate crust are visible. The oldest Archean and Proterozoic crust of thickness 40–60 km, continental Variscan and Alpine crust of thickness 20–40 km, and the youngest oceanic crust of Atlantic of thickness 10–20 km.

In general Moho depth map presented in this paper for the whole European Plate is consistent and smooth, although the data grid was lowpass filtered using cut-off length of 100 km and passing wavelengths greater than 200 km. The Moho map images and our current knowledge of the overall structure of the European Moho are available at webpages of the University of Helsinki and the University of Warsaw as a graphic (tiff, pdf, eps and jpg formats), as well as in data files (ASCII text and GMT format), with latitude, longitude, Moho depth and Moho depth uncertainty. We hope that new data and contributions could give an opportunity to update our map after 5–7 yr. It will be particularly useful to get new data sets from the mid-Atlantic ridge and Europe–Africa–Arabia transition, where the resolution of present map is the lowest. We also look forward to your contributions to our future map. The map can be found at: *http://www.igf.fuw.edu.pl/mohomap2007/* and *http://www.seismo.helsinki.fi/mohomap/*

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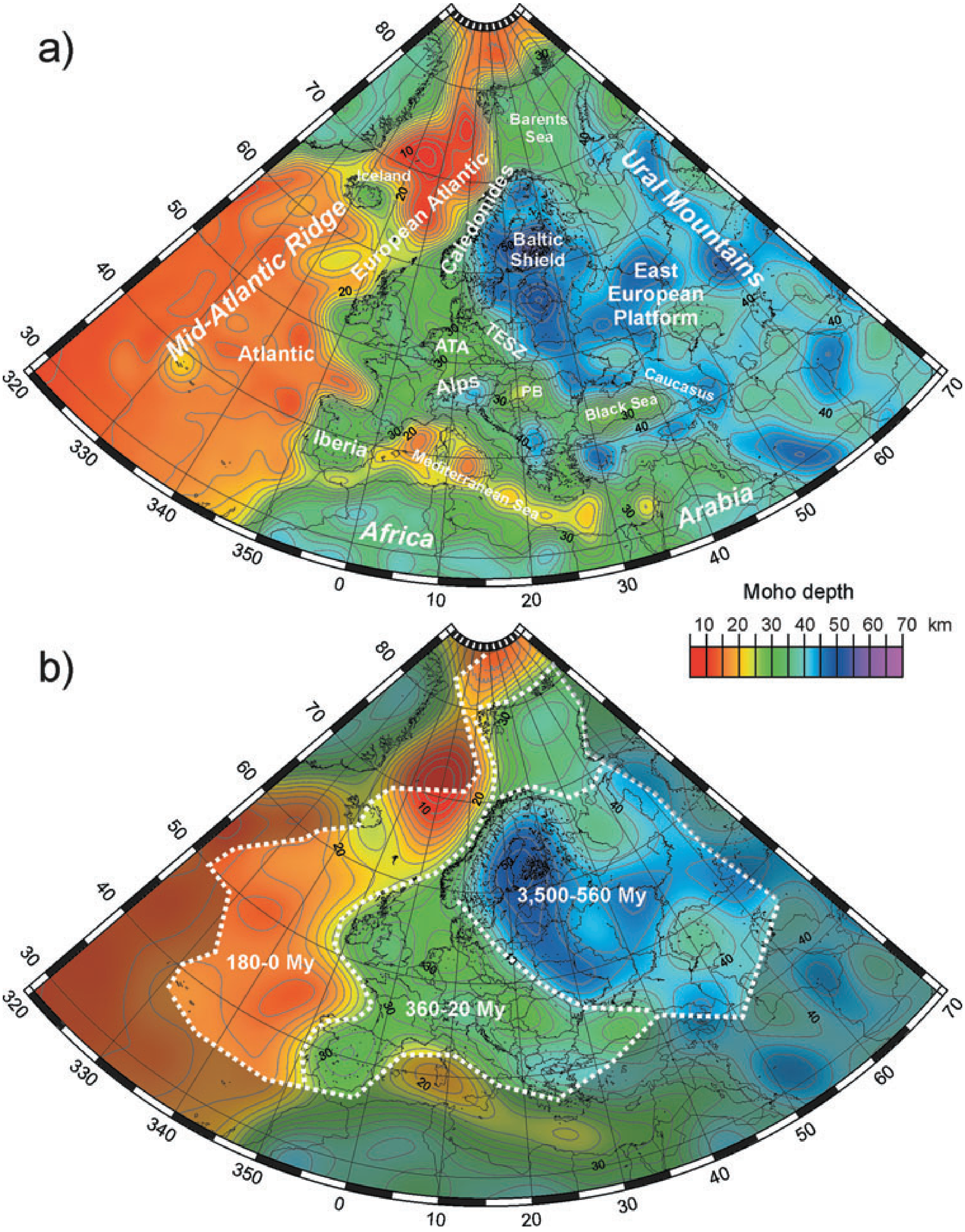

Figure 7. Filtered Moho depth maps of the European Plate: (a) A 500 km filter brings out the main terranes of the European Plate; (b) a 1000 km filter highlights the three age groups of the European crust—thin and young oceanic crust of the Atlantic Ocean, the continental crust of Variscan and Alpine Europe and thickest and oldest crust of Archean and Proterozoic Baltica.

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