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Recovering Moho constituents from satellite altimetry and gravimetric data for Europe and surroundings

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Abstract: In this research, we present a local Moho model, named MOHV19, including Moho depth and Moho density contrast (or shortly Moho constituents) with corresponding uncertainties, which are mapped from altimetric and gravimetric data (DSNSC08) in addition to seismic tomographic (CRUST1.0) and Earth topographic data (Earth2014) to a resolution of $1^\circ \times 1^\circ$ based on a solution of Vening Meinesz-Moritz' theory of isostasy. The MOHV19 model covers the area of entire European plate along with the surrounding oceans, bounded by latitudes (30°N – 82°N) and longitudes (40°W – 70°E). The article aims to interpret the Moho model resulted via altimetric and gravimetric information from the geological and geophysical perspectives along with investigating the relation between the Moho depth and Moho density contrast. Our numerical results show that estimated Moho depths range from 7.5 to 57.9 km with continental and oceanic averages of 41.3 ± 4.9 km and 21.6 ± 9.2 km, respectively, and an overall average of 30.9 ± 12.3 km. The estimated Moho density contrast ranges from 60.2 to 565.8 kg/m^3 , with averages of 421.8 ± 57.9 and 284.4 ± 62.9 kg/m^3 for continental and oceanic regions, respectively, with a total average of 350.3 ± 91.5 kg/m^3 . In most areas, estimated uncertainties in the Moho constituents are less than 3 km and 40 kg/m^3 , respectively, but they reach to much more significant values under Iceland, parts of Gulf of Bothnia and along the Kvitoya Island. Comparing the Moho depths estimated by MOHV19 and those derived by CRUST1.0, MDN07, GRAD09 and MD19 models shows that MOHV19 agree fairly well with CRUST1.0 but rather poor with other models. The RMS difference between the Moho density contrasts estimated by MOHV19 and CRUST1.0 models is 49.45 kg/m^3 .

Keywords: Altimetry, Europe, Gravimetry, Isostasy, Vening Meinesz-Moritz, MOHV19, Moho depth, Moho density contrast

1 Introduction

The Moho discontinuity (or Moho) is an interface, which marks the boundary between the Earth's crust and mantle. It is indeed one of the most distinct manifestations of a differentiated Earth, as major changes in petrology, mineralogy, chemistry, seismic wave velocity, density, and rheology occur across it [21]. The Moho structure is a vital parameter for many applications, such as upper-mantle tomographic studies, gravity modelling, forward seismic wave propagation, dynamic topography studies and location of seismic events. The Moho is typically estimated using either seismic or gravimetric approaches, which do not release the same result due to their different geological and geophysical hypotheses in addition to different qualities and spatial distributions of available data [36].

During the last decades, the results of seismic surveys have been primarily used in mapping the Moho depth (MD) in many regions of Europe, and the variations in the Moho Density Contrast (MDC) has been given less consideration. MD models obtained from seismic surveys for Europe, such as those in Meissner et al. [26], Giese and Pavlenkova [16], and Tesauero et al. [42] usually cover only the continental part of Europe. Although, compilations of MD models are available for many regions of Europe, e. g. Radulescu [32], Luosto [25], Scarascia and Cassinis [38], Chadwick and Pharaoh [13], and Jensen et al. [22], they only comprise the results of a number of surveys performed in the 1970s and the 1980s. Furthermore, one can find some MD models derived from some active and passive seismic experiments with somewhat better resolution in many areas of Europe, for instance, Luosto [24], Grad and Tripolsky [17], Grad et al. [18], Grad et al. [19] and Molinari and Morelli [28], which are also re-interpreted from the early seismic surveys. For global studies CRUST2.0 [12] is the most frequently used global crustal model and it contains information on the crustal density structure including the upper mantle, and it was compiled based on

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seismic data published until 1995 with a detailed compilation of ice sheet and sediment thicknesses. The MDN07 model [27] is based on azimuthally averaged global phase and group velocity maps, from which dispersion curves were constructed on a $2^\circ \times 2^\circ$ grid. CRUST1.0 is the latest version, compiled with a 1×1 arc-deg spatial resolution [23]. The qualities of the CRUST1.0 and CRUST2.0 models are not specified, but they vary from place to place with low qualities where there are few or lacking seismic data. The MDN07 model, derived by inversion of surface wave data, has a simpler parametrization, providing thickness and average S-velocity at the same resolution of $2^\circ \times 2^\circ$.

Despite the fact that the Moho interface can be studied with profitable results through seismic waves, such data are not able to discriminate uniquely between the structure of the crust and that of the mantle below. Moreover, due to the limited coverage of seismic profiles, related with economic considerations, recovering Moho by seismic data is not merely offered, highlighting the need for using gravimetric data, jointly with other geophysical data.

It is the main purpose of this article to investigate an isostatic model based on Vening Meinesz-Moritz (VMM) hypothesis (see next section) with respect to its feasibility to use in recovering the MD and MDC, for Europe and surroundings. The paper presents a new Moho model, called MOHV19, based on free-air gravity disturbances from the DSN808 model including both the altimetric and gravimetric data [7], which are corrected for the gravitational contributions of mass density variation between different layers of the Earth's crust (i. e. stripping gravity corrections) and for the gravity contributions for so-called non-isostatic effects (NIEs; see sect. 3.3) in addition to some prior seismic information.

2 Vening Meinesz-Moritz (VMM) method

The VMM inverse problem in isostasy deals with solving for the MD from known Bouguer gravity disturbances/anomalies and a mean MD. The principle of solving the VMM problem is based on generating the isostatic gravity disturbances/anomalies, such that these are equal to zero. The problem is formulated under the assumption of varying MDs, and adopting a constant value of the MDC. The isostatic gravity disturbances are taken as the sum of crust stripped gravity disturbances and the gravitational attraction of isostatic compensation masses. The crust stripped gravity disturbances are computed by applying the topography, bathymetry, ice and sediments cor-

rections to the observed gravity disturbances. In the following, the VMM problem is altered by assuming that the MD is known and the MDC is the sought constituent (see Sjöberg [36, 37]).

2.1 Solving VMM inverse problem in isostasy

The isostatic-equilibrium equation in terms of the gravity disturbance reads (cf. Sjöberg [36]):

$$\delta g_I(P) = \delta g_{DSN808}^{R(TBISN)}(P) + A_C(P) = 0, \quad (1)$$

where δg_I denotes the isostatic gravity disturbance at observation point P , located on the mean Earth sphere (approximating sea level), $\delta g_{DSN808}^{R(TBISN)}$ is the refined Bouguer gravity disturbance corrected for the gravitational contributions of topography and density variations of the oceans, ice, sediments and NIEs, and A_C is the compensation attraction at the same point P .

The VMM problem of isostasy can be formulated in the following form:

$$b(P) = R \iint_{\sigma} \Delta \rho K(\psi, s) d\sigma = -[\delta g_{DSN808}^{R(TBISN)}(P) + A_{C0}(P)]/G, \quad (2)$$

where $G = 6.674 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$ is the Newton's gravitational constant, $R = 6371 \times 10^3 \text{ m}$ is the Earth's mean radius, $\Delta \rho$ is the MDC (in kg/m^3), $d\sigma$ is the infinitesimal surface element on the unit sphere, and σ is the full spatial angle. The kernel $K(\psi, s)$ in Eq. (2) is a function of the spherical distance ψ and the MD parameter $s = 1 - D/R$, where D is the unknown MD. The spectral representation of K is given by:

$$K(\psi, s) = \sum_{n=0}^{\infty} \frac{n+1}{n+3} (1 - s^{n+3}) P_n(t), \quad (3)$$

where P_n is the Legendre polynomial of degree n for the argument $t = \cos \psi$.

The nominal compensation attraction $A_{C0}(P)$ in Eq. (2) is approximately given by:

$$A_{C0}(P) \approx -4\pi G \Delta \rho D_0. \quad (4)$$

where D_0 is the normal (or mean) MD.

2.1.1 Estimating a variable MD (D)

A direct solution to estimate the MD by Eq. (1), approximate to second-order, was derived by [36]:

$$D(P) = D_1(P) + \frac{D_1^2(P)}{R} - \frac{1}{32\pi R} \iint_{\sigma} \frac{D_1^2(Q) - D_1^2(P)}{\sin^3(\psi/2)} d\sigma_Q \quad (5)$$

where D_1 is the first-order approximation, defined by the spectral form:

$$D_1(P) = \sum_{n=0}^{\infty} \left(2 - \frac{1}{n+1}\right) \sum_{m=-n}^n b_{nm} Y_{nm}(P), \quad (6)$$

where b_{nm} is the spherical harmonic coefficient of the isostatic gravity disturbance $b(P)$, and Y_{nm} is the fully-normalized spherical harmonic of degree n and order m .

2.1.2 Estimating a variable MDC ($\Delta\rho$)

Based on the VMM problem, the MDC can be estimated under assumption that the MDC of Eq. (2) varies over the Moho boundary. The problem is generalized to that of solving this equation by a spherical harmonic series as follows:

In order to formulate the linearized observation equations for the product between the MD and MDC ($D\Delta\rho$), the integral term on the left-hand side of Eq. (2) can be expanded into a Taylor series to second order. By substituting the first two terms of the binomial series for s^{n+3} from Eq. (3) into Eq. (2) and considering that:

$$P_n(\cos \psi) = \sum_{m=-n}^n Y_{nm}(Q) Y_{nm}(P), \quad (7)$$

where Y_{nm} are fully normalized spherical harmonics with arguments Q and P being the locations of the end points of the geocentric angle ψ , one achieves:

$$\begin{aligned} R \iint_{\sigma} \Delta\rho K(\psi, s) d\sigma \\ = 4\pi \sum_{n=0}^{\infty} \sum_{m=-n}^n \frac{n+1}{2n+1} \left[(\Delta\rho D)_{nm} - \frac{n+2}{2R} (\Delta\rho D^2)_{nm} \right] Y_{nm}(P), \end{aligned} \quad (8)$$

In view of Eq. (2) and assuming that:

$$b(P) = \sum_{n=0}^{\infty} \sum_{m=-n}^n b_{nm} Y_{nm}(P), \quad (9)$$

we thus obtain the spectral equation:

$$\frac{4\pi(n+1)}{2n+1} [] = b_{nm} \quad \text{or} \quad [] = \frac{2n+1}{4\pi(n+1)} b_{nm}, \quad (10)$$

where the bracket is the same as in Eq. (8). By summing up the spectral solutions we thus arrive at the following solution for the product $D\Delta\rho$:

$$(D\Delta\rho)_P = \sum_{n=0}^{\infty} \sum_{m=-n}^n \left[\frac{2n+1}{4\pi(n+1)} b_{nm} + \frac{n+2}{2} \frac{(\Delta\rho D^2)_{nm}}{R} \right] Y_{nm}(P), \quad (11)$$

If the left-hand side of Eq. (11) is also expanded as a series in spherical harmonics, we arrive at the spectral equation:

$$(D\Delta\rho)_{nm} = \frac{2n+1}{4\pi(n+1)} b_{nm} + \frac{n+2}{2R} (\Delta\rho D^2)_{nm}. \quad (12)$$

As the last term of this equation is much smaller than the remaining terms, we may approximate $(\Delta\rho D^2)_{nm}/R$ by $(\Delta\rho D)_{nm} D_0/R$, the solution for $\Delta\rho$ becomes:

$$\begin{aligned} \Delta\rho(P) &\approx \frac{b(P)}{2\pi D(P)} - \frac{1}{4\pi D(P)} \\ &\times \sum_{n=0}^{\infty} \sum_{m=-n}^n \left[\frac{1}{n+1} - \frac{D_0/R}{2/(n+2) - D_0/R} \right] b_{nm} Y_{nm}(P). \end{aligned} \quad (13)$$

Equation (13) states that if the MD (D) is known, which can be typically obtained from a seismic or a gravimetric Moho model, the variable MDC can be estimated from the spectrum of $b(P)$.

2.2 Uncertainties in the MOHV19 model

The main objective of this section is to estimate the MOHV19 (i. e. MD and MDC) uncertainties due to errors of the VMM model and input data set used, and a proper understanding of these errors is necessary to secure the quality of the Moho model results.

The accuracy of the MOHV19 model can be evaluated as the sum of different effects. In details the considered error sources are:

1. Stochastic errors in the gravity, topographic models, ice and sediment datasets (σ_D)
2. Systematic biases due to un-modelled mantle including core-mantle boundary and other geophysical processes (i. e. NIEs)

The sum of the (stochastic) variances and bias squared, named the mean square error, is the mathematical expectation of the difference between the estimate and its true value squared.

The estimations of the mean square errors of the MOHV19 model parameters are not simple, but they could thus be obtained by summing up the two different effects as (cf.; Bagherbandi et al. [9], Abrehdary et al. [3]):

$$\sigma_{D_{\text{MOHV19}}}^2 = \text{MSE}(D) = \sigma_D^2(P) + \text{bias}^2(D), \quad (14)$$

The error variance σ_D^2 of the VMM MD can be derived using the error propagation law of Eqs. (5) and (6). Disregarding the contribution from the last term in Eq. (5) as well as the correlations among the harmonic coefficients

in Eq. (6) one obtains:

$$\sigma_D^2(P) = \left(1 + \frac{2D_1(P)}{R}\right)^2 \sum_{n=0}^{\infty} \sum_{m=-n}^n \left[\frac{2n+1}{n+1} Y_{nm}(P)\right]^2 \sigma_{b_{nm}}^2 \quad (15)$$

The variances of the spectral solutions of the coefficient matrix b is usually available along with the solution for b , and, if in addition the full variance-covariance matrix is available, Eq. (15) can be extended for it. In addition, it is possible that the omitted, 2nd-order, term in Eq. (6) contributes significantly to the variance of D , but such an investigation is beyond our present study.

The bias can be then expressed:

$$\text{bias}(D) = \frac{1}{4\pi G \Delta \rho} \sum_{n=0}^{n_{\max}} \left(2 - \frac{1}{n+1}\right) \sum_{m=-n}^n Y_{nm}(P) c_{nm}^{g^{NI}} \quad (16)$$

Here g^{NI} is the NIEs on gravity with its coefficients $c_{nm}^{g^{NI}}$ as:

$$c_{nm}^{g^{NI}} = \frac{1}{4\pi} \iint g^{NI} Y_{nm}(P) d\sigma, \quad (17)$$

where g^{NI} was originally formulated by Bagherbandi and Sjöberg [8] as follows:

$$g^{NI} \approx \delta g_{DSNSC08}^{R(TBISN)}(P) + A_{C0} + 2\pi G \Delta \rho^{c/m} T_S(P) \quad (18)$$

where T_S is the known value of the MD determined from the seismic model, and the term A_{C0} was already defined in Eq. (4).

Similar to uncertainties in the MD, the aforementioned errors can be also propagated to the MDC. Accordingly, the variance error of the MDC ($\sigma_{\Delta \rho}^2$) can be estimated by (cf. Abrehdary et al. [1]):

$$\sigma_{\Delta \rho}^2 = \frac{\sigma_{D\Delta \rho}^2}{D_0^2} + \frac{\sigma_D^2(D\Delta \rho)^2}{D_0^4} \quad (19)$$

and, the variance error of $D\Delta \rho(\sigma_{D\Delta \rho}^2)$ can be approximated by the following formula:

$$\begin{aligned} \sigma_{D\Delta \rho}^2 \approx & \left(\frac{\gamma}{4\pi G}\right)^2 \sum_{n,m} N_{nm}^2 \sigma_{nm}^2 \\ & + 2\left(\frac{\gamma}{4\pi G}\right)^2 \sum_{n,m} \sum_{k,l \neq n,m} N_{nm} N_{kl} \sigma_{nmkl}, \end{aligned} \quad (20)$$

where γ is normal gravity, $N_{nm} = (2n+1)$, σ_{nm}^2 , and σ_{nmkl} are the potential coefficient error degree and order variances and covariances, respectively. The latter quantities are usually available from the least-squares solution of the potential coefficients [2]. It deserves to be mentioned that the MD uncertainties are also due to omission error (or truncation error) as the harmonic series in Eq. (16) is limited to degree and order $n_{\max}(\bar{n})$. This error can be described by the limited resolution of the result, being of order $1^\circ \times 1^\circ$ for $n_{\max} = 180$ (see Sjöberg [36]).

3 Description of the data and numerical realization

3.1 Description of the data

In construction of the MOHV19 model for the European plate and surrounding oceans, bounded by latitudes (30 °N–82 °N) and longitudes (40 °W–70 °E), different types of data sets were used. To do so, in section 2.1.1 the MDC is assumed to be known, i. e., from seismic survey (e. g., CRUST1.0) and then the MD is estimated under assumption the Earth is in isostatic equilibrium and finally in section 2.1.2 we alter the VMM problem by assuming that the MD is known (e. g., from seismic data analysis) and the MDC is the sought constitute. The main input data utilized in this study are the free-air gravity disturbance observations (DSNSC08) together with data from topography (Earth2014; Hirt and Rexer [20]) and seismological model (CRUST1.0). The DSNSC08 gravity model is created by two models of EGM2008 [31] and DNSC08GRA [7] as grids of 1 arc-minute resolution, where the offshore free-air gravity data, provided by DNSC08GRA, and the onshore ones are delivered by the EGM2008 model. The DNSC08GRA model is a satellite-based gravity field, which uses data mainly from ERS-1 and GEOSAT altimetric missions. In addition to data from these missions, altimetry data from other available satellite missions were included in the derivation of the DNSC08GRA model.

3.2 Crust density variation corrections

As observed gravity data contains disturbing signals from the topography and density heterogeneities associated to bathymetry, ice, and sediments, therefore, in order to isolate the gravity data caused only by the geometry of the Moho, aforementioned signal contributors to the gravity data were tried to be suppressed by applying the stripping gravity corrections (see; Tenzer et al. [40]; Tenzer et al. [41]). This result in the refined gravity disturbances $\delta g_{DSNSC08}^{R(TBISN)}(P)$ used in Eq. (2).

3.3 Non-isostatic effects (NIEs)

It is important to remind that always after correcting the intra-crustal density anomalies such as those for water, ice and sediment, there are still some density anomalies left in the upper and lower mantle that leads to NIEs, which must also be removed (see Bagherbandi and Sjöberg [8]).

In order to compute the refined Bouguer gravity disturbances, free-air gravity disturbances were corrected for

the gravitational contributions of mass density variation due in different layers of the Earth's crust (i. e. stripping gravity corrections) and for the gravity contribution from deeper masses below the crust (i. e. NIEs). The corrections were calculated using CRUST1.0 model.

The statistics of the free-air gravity disturbance and refined Bouguer gravity disturbance are presented in Table 1. One can see that the two types of anomalies differ considerably with the free-air anomalies being much smoother than the refined/Bouguer anomalies.

Table 1: Statistics of the free-air and refined Bouguer gravity disturbances derived from DSNCO8 model to a resolution of $1^\circ \times 1^\circ$. STD is the standard deviation of the estimated quantity.

Unit	Quantities	Max.	Mean	Min.	STD
mGal	$\delta g_{DSNCO8}^{free-air}$	238.83	10.06	-192.47	31.11
	$\delta g_{DSNCO8}^{R(TBSN)}$	423.42	106.25	-302.35	144.44

3.4 Numerical realization

As already mentioned, the main objective of this study is to determine a new European Moho model with its uncertainties, which comprises both the MD and MDC using compilation of free-air gravity disturbances from the DSNCO8 model together with seismic-based crustal model and Earth's topographic/bathymetric data (Earth2014) in a resolution of $1^\circ \times 1^\circ$. In this context, Eqs. (6) and (13) were applied for the refined Bouguer gravity disturbance and the Earth2014 topographic model to produce the MOHV19 model.

The statistics of the MD, MDC and their uncertainties are presented in Table 2.

Table 2: Statistics of estimates of MOHV19 for $1^\circ \times 1^\circ$ block data. D^{MOHV19} and σ_D^{MOHV19} are MD and its standard error estimated by MOHV19 model. STD is the standard deviation of the estimated quantities. $\Delta\rho^{MOHV19}$ and $\sigma_{\Delta\rho}^{MOHV19}$ are MDC and its standard error computed from MOHV19 model, respectively.

Unit	Quantities	Max.	Mean	Min.	STD
km	D^{MOHV19}	57.85	30.94	7.49	12.29
	σ_D^{MOHV19}	7.10	1.50	0.05	0.70
kg/m ³	$\Delta\rho^{MOHV19}$	565.80	350.30	60.21	91.53
	$\sigma_{\Delta\rho}^{MOHV19}$	102	25.29	0.41	11.59

4 Analysis of the results

4.1 General analysis

In this section, we plot the free-air gravity disturbance (Fig. 1), the NIE (Fig. 2), the refined Bouguer gravity disturbance (Fig. 3), and the MD and its uncertainty (Fig. 4) as well as the MDC and its uncertainty (Fig. 5) estimated by MOHV19 model.

Figure 1 shows the free-air gravity disturbances obtained from DSNCO8 model for the European block. Its maximum, minimum and mean standard deviations are 238.83, -192.47, 10.06, and 31.11 mGal, respectively. The gravity disturbances are generally rather small, but grow to large negative values in some parts of Mediterranean and Caspian seas.

Figure 1: The free-air gravity disturbances derived from the DSNCO8 (in mGal).

The NIE on gravity disturbance is depicted in Fig. 2, showing variations from -416.7 to 180.4 mGal with a mean value of -147.62 ± 81.3 mGal. As can be seen, large positive NIEs are found in Iceland, whereas the most pronounced negative NIEs are closely related with the post-glacial rebound region in Fennoscandia and with the thickening/thinning of the Earth's crust in central Finland (see Elo [14]; Bagherbandi and Sjöberg [8]).

Figure 3 shows the refined Bouguer gravity disturbances corrected by removing the effects of the ocean/bathymetry, ice, sediment variations and the NIEs, respectively. As can be seen, these features drastically change the refined Bouguer gravity disturbances from the free-air disturbances (cf., Fig. 1) over oceans due to the application of the bathymetric stripping gravity correction. They also change in central Greenland due to application of the ice density variation stripping gravity correction but change less remarkable by the sediment density variation

Figure 2: The NIE on gravity disturbance (in mGal).

Figure 3: The refined Bouguer gravity disturbances (in mGal).

stripping gravity correction in offshore areas with a significant change in Fennoscandia and along the northeast Greenland.

Figure 4 (top) depicts the MOHV19 MD estimated from the refined spherical Bouguer gravity disturbance. Its maximum, minimum, mean and standard deviation are 57.8, 7.5, 30.9, and 12.3 km, respectively. As one would expect, small MDs, down to about 10 km in the deep sea, are generally seen in the oceanic areas and along the oceanic ridges, increasing with topographic elevation in continental areas. In central Finland, there is a notable deepening of the MD down to a maximum of 57 km (not related with the former ice sheet load with its centre in the Gulf of Bothnia), and this sink is also observed in other models like CRUST1.0, MDN07, GRAD09 and MD19, where it reach to 57.4, 53, 58 and 58.10 km, respectively (see Meier et al. [27]; Grad and Tiira 2012; Laske et al. [23] and Szwilius et al. [39]).

Figure 4 (bottom) maps the MOHV19 MD standard errors. One can observe that the standard errors in oceanic regions are smaller than 3 km, but they reach to more significant values under Iceland, parts of Gulf of Bothnia and

along the Kvitoya Island. The large standard errors in Iceland and along the mid-Atlantic ocean ridge, i. e. all along the mid-Atlantic continental plate divider that experience seafloor spreading and oceanic ridging due to mantle convection (thermal expansion), are likely caused by lacking modelling of this effect (see e. g., Van der Pluijm and Marshak [43], Ch. 16). In some areas, such as parts of Gulf of Bothnia, these large values are likely an effect of the ongoing of Glacial Isostatic Adjustment (GIA), showing that the separation of the GIA gravity signal from the gravity field was unsuccessful and it is indeed impossible completely to strip the observed gravity field from the GIA signal with a sufficient accuracy (see Root et al. [34] and Abrehdary et al. [1]).

Figure 5 (top) images the MDC estimated by MOHV19 model. Its maximum, minimum, mean and standard deviation are 565.8, 60.2, 350.3, and 91.5 km, respectively. Although, it is not easy to compute precise value for the MDC, as it is highly dependent on the properties of the crust and upper mantle of the study area, the largest MDCs are concentrated in mountainous continental areas, whereas the lowest MDCs are seen in ocean areas, in particular along the mid-Atlantic ocean ridge. Ocean ridges are special ar-

Figure 5: (top) The European MDC estimated from MOHV19 and (bottom) the standard errors of the estimated MDC (in kg/m^3).

as due to the presence of hot spots and up-welling light materials very close to the surface of the crust, as well as the thinning of the oceanic crust, modifying the normal MDC between the crust and the mantle. Hence, it is natural to gain shallow MDC values along the ocean ridges. As can be seen from the figure, moving away from the ridge, the MDC progressively increases to considerable amounts in some specific areas. As the ocean ridges have young lithospheric age, large MDCs found in such regions are likely

due to lacking modelling of the mantle convection (see Meier et al. [27]).

Figure 5 (bottom) shows that the standard error varies from 0.4 to 102 kg/m^3 , with the largest values in Iceland, parts of Gulf of Bothnia and along the Kvitoya Island, located in much the same areas where the MD is uncertain.

4.2 Geological and geophysical overview

The main focus of this section is to interpret the MOHV19 model in terms of geological and geophysical structures and processes in view of the maps in Figs. 6 and 7.

Here the ocean and continental Moho features will be treated separately. This is necessary due to their different nature and evolution. The structure of oceanic crust mainly depends on the conditions at the mid-ocean ridge, where it was formed. In contrary, the properties of continental crust are the result of a much longer evolution and different processes.

First we study Fig. 6, the USGS geological province map compiled in 1995, which is classified as one of the eight main crustal types such as oceanic crust, basin, large igneous province, orogen, shield, platform, extended crust and ocean ridges (see Exxon [15] and Table 3). The map helps us to understand the relationship between tectonic history and crustal structure. All tectonic processes and geological structures mentioned above have their images in the MOHV19 map. In order to make a first validation of the MOHV19 model the simplest way is to compare it with the USGS map (Fig. 6) for the six regions. As for the continental crust, the MOHV19 MD model shows that the Moho is at 35–57 km depth beneath Sweden and Finland, which correspond to the Fennoscandia Shield, which contains the oldest of rocks, at 2500–3100 Myr (million years)

Figure 6: Map of geological provinces enhanced with mid the mid-Atlantic ridge (USGS).

Table 3: Geologic provinces by origin.

Province	Definition
Basin	A low area in the Earth's crust, in which sediments are accumulated.
Large igneous province	Accumulation of igneous rocks, including liquid rock (intrusive) or volcanic rock formations (extrusive).
Orogenic crust	Linear or arc-shaped formation where continental crust has been folded, deformed and uplifted to form mountain ranges.
Shield	Exposed Precambrian crystalline igneous and metamorphic rocks that form tectonically stable areas.
Platform	Horizontal or gently-lying sedimentary strata covering a basement of igneous or metamorphic rocks.
Extended crust	Continental crust thinned due to extensional strain.

old. The Moho beneath the Ural Mountains, Norway, Novaya Zemlya and northeast Greenland is at an intermediate level ca. 30–40 km, which is due to the orogenic belt, where the continental crust is folded, deformed and uplifted to form mountain ranges. On the east coast of Greenland, in SW Iceland and along the mid-Atlantic ridge, the MD is within 24–26 km, and these features are defined as large igneous province formations. Beneath Svalbard, Franz Josef Land, Ireland, France, Germany and United Kingdom, which are related to extended crust areas, where the continental crust is thinned due to extensional strain, the MD is in the range of 30–35 km. In some regions, as in the Caspian Sea, the MD is found at depths of 35–40 km under sediment basins. On the western part of Russia, the Moho is at depths of 40–45 km, being evidently associated with the areas known as the Platform.

Taking a closer look at Figs. 5 and 6, one can see that the MDC map of Fig. 5 (top) approximately matches the geological provinces in Fig. 6.

As a second step in our attempt to assess the MOHV19 MDC, we use the OLA08 oceanic lithosphere age model (Fig. 7), obtained from the National Geophysical Data Centre (NGDC), by the Marine Geology and Geophysics Division of the National Oceanic and Atmospheric Administration (NOAA). The compilation of the digital models of the age, age uncertainty, spreading rates and spreading asymmetries of the crusts of world's ocean basins based on measured marine magnetic anomalies and additional geophysical and geological evidences are described in detail by Müller et al. [29]. The data grids include data from all the major ocean basins as well as detailed reconstructions of back-arc basins. The map exhibits major features of the sea-floor spreading with new oceanic lithosphere formed along the mid-ocean ridges and an increasing age towards the deep sea floor basins. Here the age of the oceanic lithosphere is up to 180 Myr. The oldest lithosphere (between 231.1 and 278.4 Myr) is beneath the Mediterranean Sea, where a piece of the Tethys Oceanic crust captured by continental convergence is found [35].

Figure 7: Oceanic lithosphere age (OLA08) in millions of years (in Myr).

In order to argue why the MDCs are small on oceanic areas, it is worthwhile to compare the estimated MOHV19 MDC model with the OLA08 oceanic lithosphere age model. By comparing Figs. 5 and 7 one can observe that the MOHV19 MDC and the OLA08 model are correlated, revealing that the small MDC values occur in the youngest oceanic lithosphere while for increasing age of the lithosphere the MDC becomes larger. Taking a closer look at Fig. 5, we can see the most notable of the large MDC values are along many shallow coastal zones and parts of mid-Atlantic ridge. However, in some of the coastal zones, such as in the Nordic Skagerrak region, the MDCs are quite large, which may be an artifact caused by corrupted altimeter data from loss of track of the sea surface near to the coast.

As for the continental crust, it can be seen as both MOHV19 MD and OLA08 model clearly show a correlation between MD and age.

4.3 Relation between the MDC and MD

In Fig. 8 the relation between MDs and MDCs are plotted in ocean region (left) and continental region (right) to-

Figure 8: Circles are MD and MDC; (left) oceans, (right) continents and the red regression lines represent the relationship between MD and MDC.

gether with the fitted (regression) lines. As can be seen, in both regions the regression lines show a positive correlation between the Moho constituents. The slope of the line is eight times steeper ($0.08 \pm 0.002 \text{ kg/m}^3/\text{km}$) for the oceanic Moho vs. for the continental Moho ($0.01 \pm 0.001 \text{ kg/m}^3/\text{km}$). In both regimes the slopes are statistically very significant.

In ocean areas, the MD and MDC are to large extent related with a thermal-pressure effect driven by mantle convection that results in changes in the MDC and MD with aging, whereby regional variations occur along with variations in the lithosphere temperature (e. g., Parson and Richter [30], Bai et al. [10, 11]). Although we have not specifically corrected for this phenomenon, it is obviously largely adjusted for by the applied NIE (see Sect. 3.3).

4.4 Validation of results

It is instructive to evaluate the quality of the MOHV19 model by comparing it with some other seismic models (i. e. CRUST1.0, MDN07, GRAD09 and MD19), in order to numerically assess the possible improvements achieved in our model vs. others.

Analysis of the results are given in Figs. 9–15 as well as Table 4.

Figure 9: Differences between the MDs estimated from MOHV19 and the CRUST1.0 model (in km).

Figure 9 maps the difference between the MD derived by the MOHV19 and that by the CRUST1.0 model. As seen from this comparison, our results closely correspond with the CRUST1.0 MDs in most areas (differences are mainly within $\pm 3 \text{ km}$), suggesting that the MOHV19 MD model works fairly well.

As seen in Figure 10, the differences between the MDs of MOHV19 and MDN07 are generally large, being within $\pm 15 \text{ km}$. In particular, one can observe that the largest negative discrepancies occur near to Svalbard in the Arctic Ocean, which might be due to the failure of properly modelling the sediment thickness in the CRUST1.0 model, which causes the Bouguer gravity disturbance not to be properly corrected (see Abrehdary et al. [4, 5]).

In Fig. 11 one can see that the two models MOHV19 and GRD09 are almost compatible. However, there are some disagreements concentrated in a few regions, which might be due to different types of data and different seismic techniques used in the GRAD09 model.

Figure 12 shows the difference between the MOHV19 and MD19 models. The MD19 is a global crustal model based on a USGS database of crustal seismic studies (see Szwilius et al. [39]). Generally one can see that the differ-

Table 4: Statistics of the differences between the MOHV19 and other models. STD is the standard deviation. RMS is Root Mean Square.

Unit	Quantities	Max.	Mean	Min.	STD	RMS
kg/m^3	$\Delta\rho^{\text{MOHV19}} - \Delta\rho^{\text{CRUST1.0}}$	115.88	-7.78	-131.10	40.81	41.54
km	$D^{\text{MOHV19}} - D^{\text{CRUST1.0}}$	5.95	0.96	-3.58	1.88	2.11
	$D^{\text{MOHV19}} - D^{\text{MDN07}}$	24.10	3.12	-19.60	6.09	6.30
	$D^{\text{MOHV19}} - D^{\text{GRAD09}}$	14.25	0.91	-16.03	4.43	4.53
	$D^{\text{MOHV19}} - D^{\text{MD19}}$	13.79	1.21	-12.13	3.49	3.74

Figure 10: Differences between the MDs estimated from MOHV19 and the MDN07 model (in km).

Figure 12: Differences between the MDs estimated from MOHV19 and the MD19 model (in km).

Figure 11: Differences between the MDs estimated from MOHV19 and the GRD09 model (in km).

Figure 13: Differences between the MDCs estimated from MOHV19 and the CRUST1.0 model (in kg/m^3).

ences between the two models are typically ± 5 km in many regions. However, our results differ substantially for the different places on continents and tend to be higher than 10 km, which could be result of the interpolation of MD19 in these areas. In the oceans there is qualitative agreement between the two models in many areas, substantial large-scale differences mostly occur where no data are available in MD19 database.

Figure 13 compares the MDCs of the new model and those of CRUST1.0, characterized by mainly small differences. This can be explained by the more recent and complete data set used in the MOHV19 model.

The inset in Figs. 9–13 shows a scatterplot of misfits between MOHV19 on the horizontal axis and CRUST1.0, MDN07, GRAD09, MD19 on the vertical. As can be seen from the figures, in order to infer the relationship between pairs of the models, a line that best fits all the data (a regression line) has also been plotted (i. e. the middle line).

In addition to this line, the top and bottom lines have been drawn as prediction bands, that is, $\pm$ twice the RMS difference between the models (i. e. middle line ± 2 RMS differences) to assess the variation between the two models. Note the linear correlation of the models in all four plots indicating the overall agreements between these models. One can also see outliers in these plots, which might be attributed to the differences in data resolution, and weighting of the different contributes in MDN07, GRAD09 and MD19 and to the improvements expected in MOHV19.

In Fig. 14 the four models, CRUST1.0, MDN07, GRAD09, MD19 and the MOHV19 model are compared. To do so, the difference between MD derived by CRUST1.0, MDN07, GRAD09, MD19 and that derived by the MOHV19 model are divided by the standard deviation of MOHV19 model. This allows to localize specific regions where the disagreement with CRUST1.0, MDN07 and GRAD09 is smaller than $\pm 1\sigma$.

From Fig. 14, one can see that almost everywhere our estimates are within $\pm 1\sigma$ of the four other models; however, in specific regions such as Skagerrak region and coastal re-

Figure 14: The differences between MOHV19 MD and those from (a) CRUST1.0, (b) MDN07, (c) GRAD09, and (d) MD19 model.

gions according to our model the MD seems thinner than proposed by CRUST1.0, MDN07 and GRAD09 models. In this region, there is good agreement of the MD between our results and MD19. The probable reasons for this discrepancy in the Skagerrak region can be explained partly, due to the lack of coverage of altimetric tracks in the region, being very close to the coastlines and therefore the altimeter starts to lose track and subsequently the coverage of altimetric observations is problematic for gravity field modelling and also for the MD recovery. For coastal regions it could be attributed to errors in the DSNOSC08 model based on altimeter data. For example, the adjustment process used to remove systematic errors from the altimeter data may be in error caused by orbit error and altimeter bias, poor data coverage and/or malfunctioning prediction procedure used [33, 6, 3].

In Fig. 15 the MDC estimated from the MOHV19 is plotted versus CRUST1.0 model. From Fig. 15, one can observe that the resulting fit is rather good almost everywhere except for the few regions, which could be due to CRUST1.0 uncertainties in these areas.

Figure 15: The differences between MDC of MOHV19 and CRUST1.0.

5 Conclusions

As a final product, we have derived a solution to Vening Meinesz–Moritz inverse problem for the MDC as well as for the MD beneath Europe and surrounding oceans with a resolution of $1^\circ \times 1^\circ$ by using the DSNOSC08 gravity distur-

bance data set, the Earth2014 solid Earth topographic and CRUST1.0 crustal models. In order to assess the accuracy of the Moho constituents, several factors such as the stochastic errors in the gravity, topographic models, ice, and sediment datasets as well as systematic biases due to unmodelled mantle features including core-mantle boundary and other geophysical processes have been considered.

Our numerical results show a correlation between Moho constituents and tectonic provinces, revealing that all tectonic processes and geological structures have their images in the MOHV19 map. As can be seen from the numerical results, the MDC is to a large extent correlated with the MD, implying the MDC almost proportionally increases with increasing values of the MD. However, this result may to some extent be an artifact from our way of determining MD and MDC, which could possibly be eliminated by iterating the two procedures. Also, we already emphasized that for ocean areas the thermal pressure effect related with mantle convection was not directly corrected for.

We have demonstrated that the new MOHV19 model has some advantages over the previous models in that: (1) it contains both the MD and MDC with corresponding uncertainties; (2) the model covers the whole European plate including the surrounding oceans, bounded by latitudes (30 °N–82 °N) and longitudes (40 °W–70 °E), which is much wider than the areas covered by previous Moho maps of Europe; (3) it is available in digital form.

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