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Gravity-derived Moho map for Latvia

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Abstract. A precise understanding of crustal structure is essential to the fields of geodynamics, seismology and certain branches of geophysics. A boundary between the crust and the mantle is known as the Mohorovičić discontinuity, simply referred to as the 'Moho'. Moho geometry and depth have been extensively studied in Europe, but there are still regions with little information about it. One such area is the northern Baltics, Latvia in particular. So far, only one seismic refraction profile, spanning from Sovetsk (Kaliningrad) to Kohtla-Järve (Estonia), has been used to study the deep structure of the Earth in Latvia. We propose gravity inversion (Parker–Oldenburg algorithm) to gain more insight into the Moho depth of Latvia. Multiple gravity sources are combined into a single dataset with the regression-kriging method. Gravity data are then iteratively filtered with various wavelength low-pass filters. We use different combinations of these filtered datasets and varying input parameters – mean depth to the Moho and density contrast between the crust and the mantle – to carry out multiple iterations of the inversion, validating the results by seismic refraction profiles available for Latvia. The calculated Moho depth varies from 41.5 km in the southern and northeastern parts of Latvia to 46.5 km in the northern part of Latvia and the Gulf of Riga. We conclude that gravity inversion with the Parker–Oldenburg algorithm can be used as an alternative to the seismic exploration of the Moho, especially in places where there is a shortage of earlier seismic data. The obtained results also show that it is necessary to create multiple models with various combinations of input values when using the Parker–Oldenburg inversion algorithm.

Key words: Latvia, Parker–Oldenburg inversion, gravity data, Mohorovičić discontinuity, crustal thickness.

INTRODUCTION

Historically there have been various opinions about the structure of the Earth. Some authors insisted on the rather simple composition of the Earth, while others predicted a much more complex structure (Hrvoje 2017). Since the beginning of global seismic observations, our understanding of the deep Earth has improved significantly (Agnew 2002; Shearer 2009). By summarizing data gathered up to that point in time, Dziewonski & Anderson (1981) created the first model that showed the variation in seismic wave propagation speed, density and viscosity in a radial direction of the Earth. Later various improved models have been published (Kennett & Engdahl 1991; Morelli & Dziewonski 1993; Kennett et al. 1995). The boundaries of the inner structure of the Earth are depicted in those models. One such boundary is the Mohorovičić discontinuity (Moho), which separates the Earth's crust from deeper layers. The Moho was discovered by the pioneering work of Andrija Mohorovičić already in 1909 by analysing seismic signals of the earthquake located in Croatia (Mohorovičić 1910). This study was followed by many more, confirming that such a boundary is distributed globally (for a review of Moho studies see Prodehl et al. 2013).

Various papers have been published where a significant amount of mainly seismic data of previous studies is compiled to create a single Moho depth map of a large part or the whole Europe (Tesauro et al. 2008; Grad et al. 2009; Molinari & Morelli 2011; Artemieva & Thybo 2013). All models contain areas where information about the Moho is sparse. One of such regions is Latvia. In addition, several more local models for Northern Europe have been created (Jensen et al. 2002), however, the territory of Latvia is not included in any of them.

Multiple seismic profiles are located close to Latvia, but unfortunately, only one of them crosses the country (Artemieva & Thybo 2013). It has been possible to study the deep structure of the Earth in the territory of

Latvia by using one refraction seismic profile spanning from Sovetsk (Kaliningrad) to Kohtla-Järve (Estonia) (Ankudinov et al. 1994). However, some authors suggest that the results of this study should be treated with caution because the crustal depth parameters were examined only by using pressure wave reflections off the Moho (PmP) (Yliniemi et al. 2001).

As limited refraction seismic data are available regarding the territory of Latvia, other sources of information for defining the Moho depth should be considered. The Moho depth can also be determined using different methods, such as surface wave tomography, seismic reflection surveys, receiver function analyses from broadband seismographs and gravity data inversion (Grad et al. 2009). It has been shown that gravity measurements can be successfully implemented in the construction of a Moho depth model (Braitenberg et al. 2000; Gómez-Ortiz et al. 2005; Grad et al. 2009; Prasanna et al. 2013), and as extensive gravity surveying has been conducted in Latvia since the early 2000s, these data are an obvious choice.

When performing studies of the crustal structure of the Earth, seismological observations or geodynamical modelling, it is important to have reliable information about the Moho depth. As such, Moho models are of utmost importance for the aforementioned research and industries. In this study, we use satellite-derived and on-ground collected gravity measurements in combination with the available seismic information to construct a new Moho depth map of Latvia.

DESCRIPTION OF THE STUDY AREA

The territory of Latvia is a part of the Eurasian plate and is considered as part of the Baltica palaeocontinent (Cocks & Torsvik 2005). The Baltica palaeocontinent formed 1.8–1.7 Ga ago in the southern hemisphere (Torsvik & Cocks 2005; Bogdanova et al. 2008; Li et al. 2008), most likely as several microcontinents assembled (Bogdanova et al. 2015). After its formation, the general trend of movement of Baltica was to its present position in the northern hemisphere (Torsvik & Cocks 2005). During the Phanerozoic Eon, Baltica was involved in several collisions but as the territory of Latvia is located in the middle part of the palaeocontinent, Latvia was never directly involved in those tectonic processes and experienced relatively stable conditions throughout its history (Cocks & Torsvik 2005; Torsvik & Cocks 2005; Nance et al. 2014).

The crustal structure in the territory of Latvia has been studied along the Sovetsk–Kohtla-Järve seismic refraction profile only (Ankudinov et al 1994; Fig. 1). The data show that the Conrad discontinuity is approximately at a depth of 18 km while the Moho surface is at a depth between 40 and 60 km. As within nearby territories (Belarus, Estonia, Lithuania and Poland), the Precambrian rock layers have a block-wise structure (Bogdanova et al. 2015). According to seismic data, the blocks are separated by deep faults that are oriented approximately in the NW–SE direction. Nonetheless, except the Leba ridge–Riga–Pskov fault zone, the topography of the crystalline bedrock surface does not show any prominent steps (Brangulis & Kaņevs 2002; Tuuling 2019).

In general, the geological cross section of Latvia consists of two parts. The upper layer includes sedimentary rocks that are underlain by crystalline rocks. The thickness of the sedimentary rock layer varies from approximately 600 m in the NE part of Latvia to 2 km in the SW (Brangulis et al. 1998).

Boreholes reaching the basement in the territory of Latvia (altogether 207) show that the crystalline basement consists of various magmatic and metamorphic rocks (for a detailed summary of the composition of crystalline rocks see Bogdanova et al. 2015). Unfortunately, out of those 207 boreholes, only 14 expose the crystalline basement

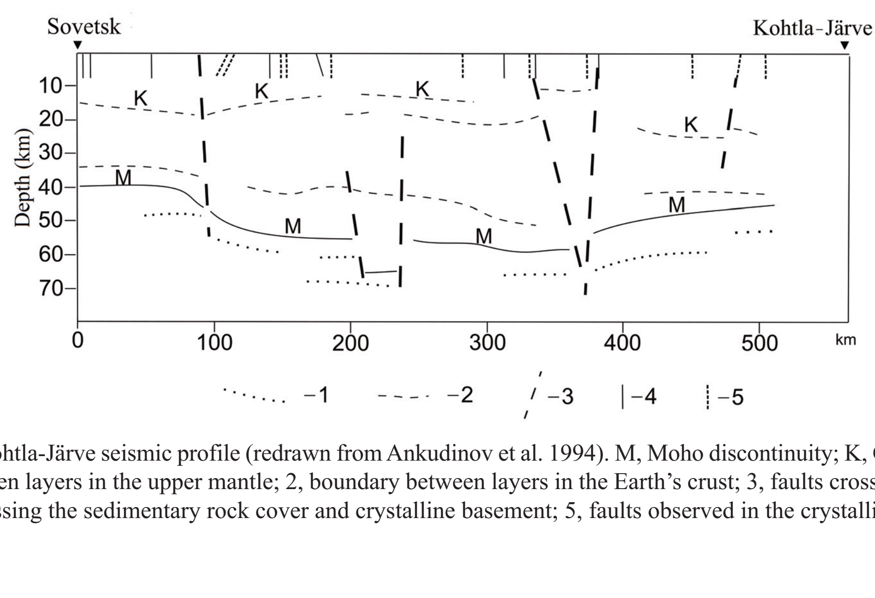

Fig. 1. Sovetsk–Kohtla-Järve seismic profile (redrawn from Ankudinov et al. 1994). M, Moho discontinuity; K, Conrad discontinuity; 1, boundary between layers in the upper mantle; 2, boundary between layers in the Earth's crust; 3, faults crossing the entire Earth's crust; 4, faults crossing the sedimentary rock cover and crystalline basement; 5, faults observed in the crystalline basement.

for more than 100 m. As a result, direct information about the lithology of the crystalline basement is available only for its upper part (Brangulis & Kaņevs 2002). There are some intrusive structures, the most prominent of which is the Kurzeme batholite (in older literature also referred to as the Riga batholite), that cover almost all of the western part of Latvia (Bogdanova et al. 2015).

Up to now, 20 samples for age determination have been taken from crystalline rocks. Analyses show that the rocks were formed between 2450 and 595 Ma (Bogatikov & Birkis 1973). These ages fit well also with the more recent reconstructions of the formation of the Baltic craton (Bogdanova et al. 2008, 2015).

The deposition of sediments in the territory of Baltica began in the late Proterozoic. In Latvia, mainly siliciclastic and carbonate rocks make up the sedimentary cover that was formed in the Cambrian to Cretaceous period. During the Palaeogene and Neogene, the terrestrial environment dominated in the territory of Latvia (Scotese 2001; Gibbard & Lewin 2016). Numerous faults, mostly oriented in the SW–NE direction, have been recorded in the sedimentary rock cover by using seismic exploration data. The upper part of the geological section of Latvia is made of Quaternary sediments formed during the last glaciation (Brangulis et al. 1998).

MATERIAL AND METHODS

Combination of gravity data from different sources

For Moho modelling we have used multiple gravity data sources because no single high-resolution gravity dataset for the territory of Latvia existed. The first task was to combine three historical measurement sets in a single, easy to use gravity dataset (Fig. 2). First, terrestrial relative gravity measurements from a geophysical mapping of the USSR-era from the years 1963–1981 were used. This gravity dataset consists of about 12 000 measurements over the entire territory of Latvia spaced in an irregular grid of 2–3 km between points. The accuracy of the measurements is about 0.1 mGal (Brio & Shtehman 1967). All the data have been digitized from geophysical maps, recalculated to International Gravity Standardization Net 1971 (IGSN71) and reduced by Kaminskis (2010). In this research, we used Bouguer anomalies of the same dataset.

Second, we used terrestrial relative gravity measurements, made by the Geodetic Survey of Latvia (GSL) and the State Land Service in the years 1998–2011 (Zandersons et al. 2018). In total, 4886 relative measurements have been made during this period in an irregular grid with the average distance between points being 3 km. The territorial distribution of the points is not even: most of the measurements are located in the western and central parts of the country, while the areas in the far east and west are not well covered. The relative accuracy (standard error) is about ±0.055 mGal, which makes these measurements the most accurate of three datasets. However, the low and uneven spatial resolution makes it hard to use these data as a single gravity dataset. In this study, Bouguer anomalies were calculated using the 2.67 g cm^{-3} value for density.

Third, the EIGEN-6S4 satellite model by Förste et al. (2016) was used to extend gravity data outwards from the territory of Latvia to account for the so-called ‘edge effect’, when the inversion algorithm calculates erroneous values near the model edges. This model was selected as it is one of the most recent and accurate in the low-frequency spectra satellite-only global gravity datasets. The model Bouguer anomaly data for Latvia and the surrounding territories were downloaded from the International Centre for Global Earth Models (ICGEM) homepage on a 0.6° grid with a reduction density of 2.67 g cm^{-3} on land and 1.65 g cm^{-3} at sea.

To combine gravity measurements from different sources, while taking their mutual differences into account, we used a regression kriging (Hengl 2009), sometimes also called kriging with external drift (Hengl et al. 2007). This method works by creating a regression model between gravity data and auxiliary covariables (here: different gravity data sources) and afterwards fitting the residuals of the model with ordinary kriging (Hengl et al. 2003). It allows the incorporation of the changes observed in all three gravity datasets into one gridded dataset of finer resolution. Similar geostatistical methods are commonly used in environmental and atmospheric sciences with various parameters (e.g., elevation or groundwater level) to better estimate the value of some natural variable, such as carbon concentration in soil (Mondal et al. 2017; Zhang et al. 2020). The method also enables combining different measurements of the same variable if (1) measurement sources are independent, (2) residuals of the underlying regression model are normally distributed and (3) measurements are mutually correlated (Hengl et al. 2003, 2007).

Regression kriging requires auxiliary information to be available at every grid node. As this is not the case (see Fig. 2A–C), the gravity data were pre-processed before the regression kriging was performed. The whole gravity interpolation process was done sequentially. First, we determined the ‘target variable’ for regression modelling. We chose this to be the GSL measurements within the years 1998–2011, as this dataset is most accurate and represents the gravity field of Latvia in the most precise way. Second, we determined the target grid size and resolution. Data were chosen to be gridded on a 2 km × 2 km grid, following the guidelines of Hengl (2006). Third, the USSR-era and

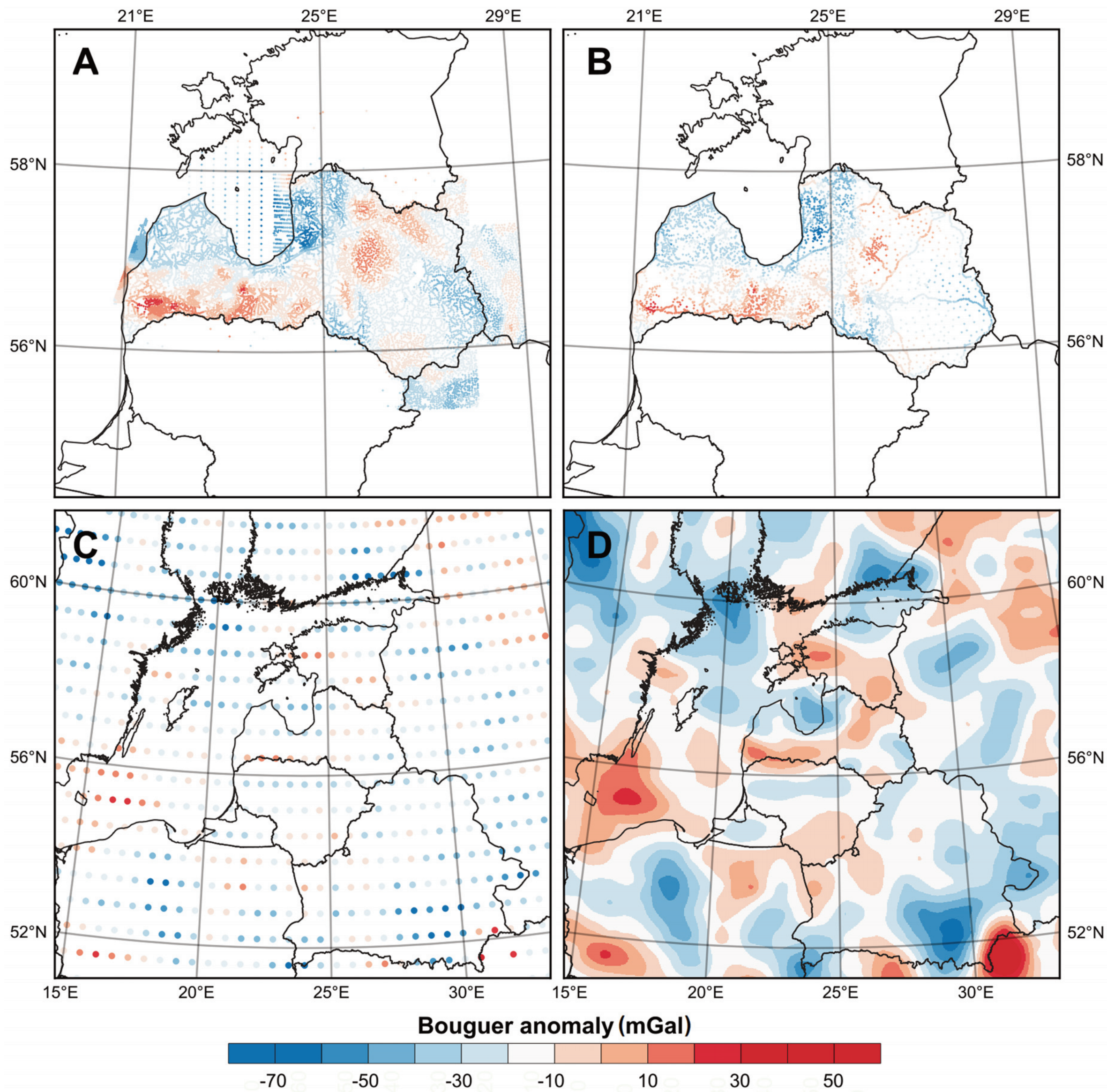

Fig. 2. Overview of gravity measurements in Latvia. **A**, dots represent calculated Bouguer anomaly from the geophysical mapping measurements from of the USSR-era (Kaminskis 2010); **B**, Bouguer anomaly from the gravity measurements by the Geodetic Survey of Latvia (Zandersons et al. 2018); **C**, Bouguer anomaly sampled from the EIGEN-6S4 satellite model (Förste et al. 2016); **D**, gridded and combined gravity data.

EIGEN-6S4 satellite model anomaly data were resampled at the locations of the GSL measurements as well as on-target grid nodes. For this purpose, we used ordinary kriging included in the R open-source statistical software, version 3.5.1 (R Core Team 2019) and its external library *gstat* (Gräler et al. 2016). It is important to note that this step may create some uncertainty in the final dataset, however, without it the following regression modelling could not be performed. Fourth, we created a linear regression model between the GSL, USSR-era and EIGEN-6S4 data. This model was used to predict the Bouguer anomaly at the newly chosen grid nodes over the territory of Latvia. Fifth, we used ordinary kriging to interpolate regression model residuals. These were summed with previous regression model predictions, creating a single interpolated Bouguer anomaly dataset.

The gravity data mostly cover the terrestrial part of Latvia (Fig. 2A, B). A proper Moho model of Latvia would need to consider the inversion edge effect. To deal with this issue, we significantly extended the gravity data outside the territory of Latvia, so that the edge effect would not affect the results. This was done by appending the EIGEN-6S4 model data to the outer border of interpolated gravity data in Latvia (Fig. 2D). The two datasets can have differences of up to 20 mGal because of different spatial resolutions and measurement accuracies. Differences can be seen near the border of Latvia at the Baltic Sea. These differences, however, are not regarded as significant because of the later processing of the gravity data (specifically, low-pass filtering), and as far as the Moho is considered, did not influence the modelling result notably.

Moho modelling

Moho modelling was devised iteratively, by changing input parameters to obtain multiple possible results. Each iteration consisted of three steps.

First, we performed gravity data filtering by using the open-source programming language Python (vers. 3.6.1) and its extension *numpy* (Python Software Foundation 2019). Gravity data were filtered to extract low-frequency information only, which is commonly associated with regional geological structures such as the Moho. Data were filtered with a low-pass cut-off filter. This was done with an underlying assumption that filtered gravity data would only contain a signal for the Moho interface, a method similar to previous research in this field (Lefort & Agarwal 2000). With each iteration, low-pass filter wavelengths were changed. Overall, we used 10 different cut-off wavelengths: 1360, 680, 453, 340, 272, 226, 194, 170, 151 and 134 km. To remove the so-called 'ringing-effect', which sometimes leaves unwanted artifacts in the filtered dataset instead of a sharp frequency cut-off, we used a Butterworth filter with the order parameter of 50 to smoothen out the low-pass cut-off (Wu et al. 2008). The filtered gravity dataset used in the calculation of the best performing validated Moho depth model is seen in Fig. 3.

Second, we used the Parker–Oldenburg algorithm (Parker 1973; Oldenburg 1974) to calculate the Moho depth. The algorithm is a rearranged form of the Parker gravity anomaly equation in the frequency domain, and it calculates the geometry of the interface between two media of different density. In one-dimensional form (Equation (1)),

$$F[h(x)] = \frac{F[\Delta g(x)]e^{-kz_0}}{2\pi G\rho} - \sum_{n=2}^{\infty}\frac{k^{n-1}}{n!}F[h^n(x)], \quad (1)$$

where $F[\Delta g]$ is the Fourier transform of gravity anomaly, $h(x)$ is the calculated mean depth to the interface (in this case – Moho), k is the wavenumber, z_0 is the input mean depth to the interface, ρ is density contrast between the two media and G is the universal gravitational constant.

We used the implementation of the algorithm in MATLAB environment by Gómez-Ortiz & Agarwal (2005).

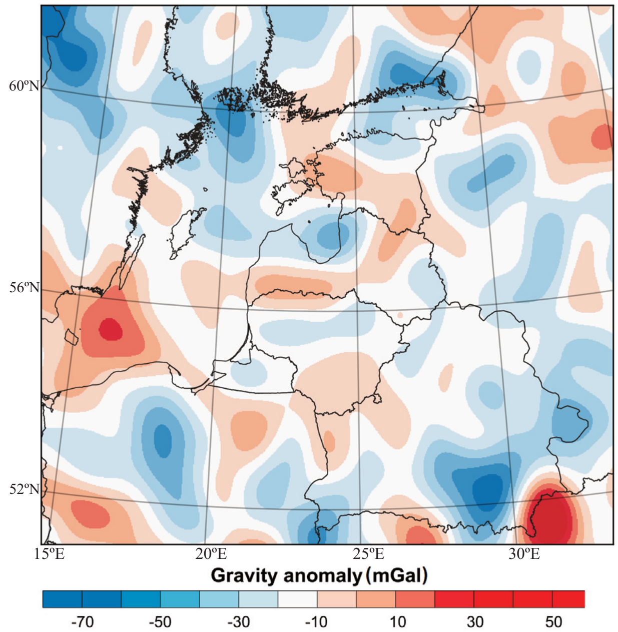

Fig. 3. The low-pass filtered gravity data of Fig. 2D, used in the calculation of the best performing model. The filter cut-off wavelength is 134 km.

The calculation of a single model is iterative: in the first iteration, only the first term of the equation is calculated, obtaining the approximation for $h(x)$. This approximation is then used as an input for the second iteration. After the second iteration is complete, the root mean squared error (RMSE) between the two results is obtained. If it is larger than the specified convergence criterion, 0.001 km in this case, the calculation continues up to $n = 10$ times (Gómez-Ortiz & Agarwal 2005).

With each algorithm implementation, we changed the input parameters – z_0, ρ and $[\Delta g]$. When accounting for all the possible input-parameter combinations, we obtained 25 110 different Moho topography models. The input parameters, as well as gravity low-pass filter wavelengths, can be seen in Table 1. We use various realistic input depth values from 30 to 70 km with 0.5 km steps to observe changes that the input depth parameter would have on the resulting Moho model. Each of the models is created for the entire land territory of Latvia and its

Table 1. Parameters used in Moho calculation

Parameter	Parameter value and unit
Low-pass filter of the gravity dataset	1360, 680, 453, 340, 272, 226, 194, 170, 151, 134 km
Density contrast between the mantle and the crust	0.1, 0.12, 0.14 … 0.7 g cm^{-3} with a 20 step
Mean depth to the Moho	30, 30.5, 40 … 70 km with a 0.5 step

immediate surroundings (see Fig. 4A, extent marked with a dashed border) with a 2 km × 2 km spatial resolution similar to the input data.

Third, models were validated with refraction seismic measurements of Latvia and the surrounding territories (Fig. 4A). Refraction profiles were digitized by hand and afterwards sampled in 2 km intervals to match the spatial resolution of the models. The multiple refraction seismic studies of the area were conducted in a period of two decades – from 1984 to 2000 (Sadov & Penzina 1986; Ostrovsky et al. 1994; Bogdanova et al. 2006; Grad et al. 2006), resulting in various measurement and interpretation methodologies and precision. To take this into account, we used the Moho uncertainty map provided by Grad et al. (2009) as a guideline to assign weight to each refraction seismic profile. The European Moho model by Grad et al (2009) had been interpolated using the same seismic refraction profiles as in this research. Thus, the uncertainty of the European model should provide proportionally accurate uncertainty information for the profiles. The weights assigned to the seismic profiles can be seen in Table 2.

We used two validation metrics for the model, the RMSE and Pearson correlation coefficient. With individual profile RMSE values we calculated the weighted average

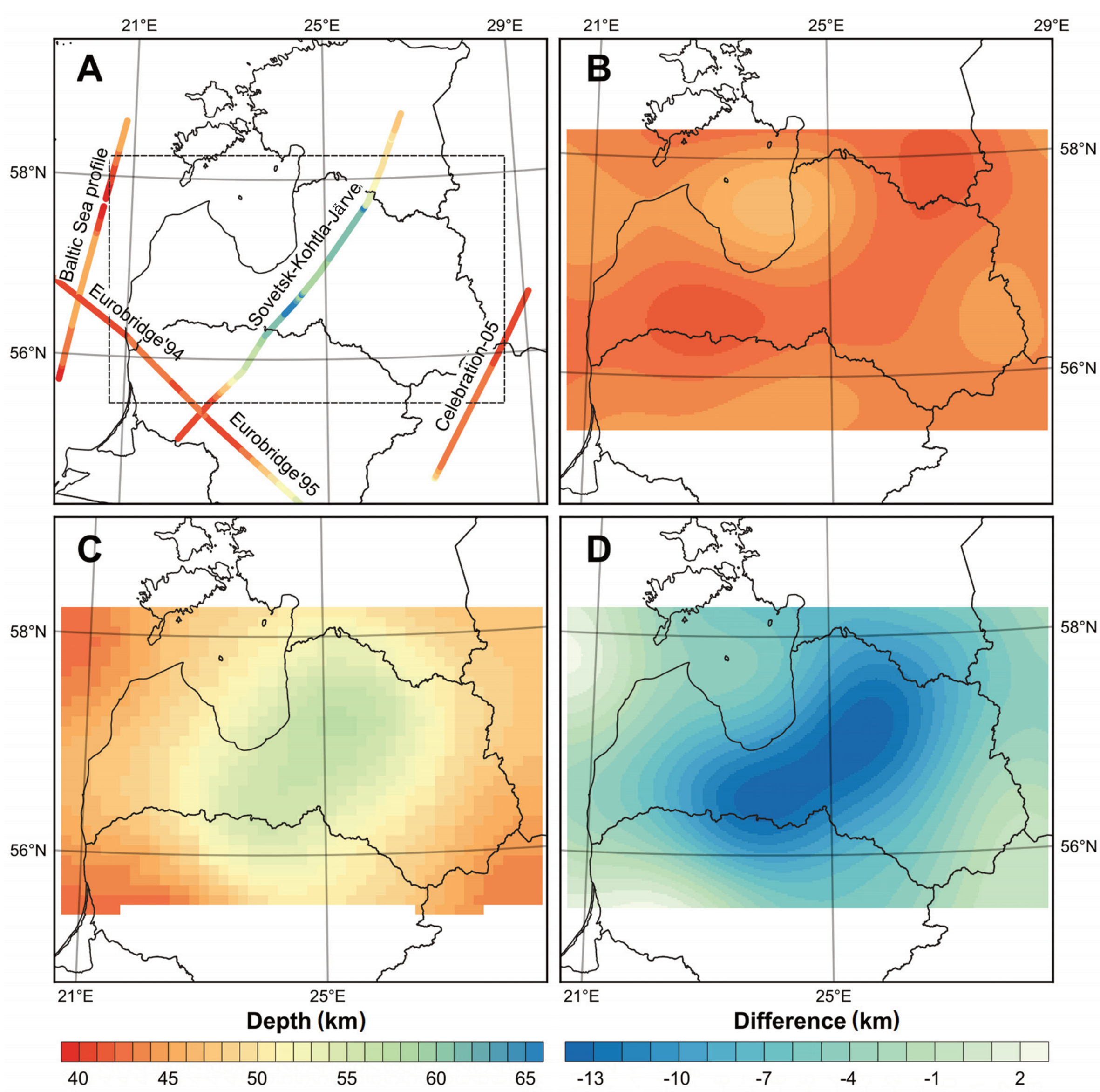

Fig. 4. A, refraction seismic surveys and their respective calculated Moho interface depths in the vicinity of Latvia (digitized from Sadov & Penzina 1986; Ostrovsky et al. 1994; Bogdanova et al. 2006; Grad et al. 2006); **B**, Moho depth, calculated from the gravity measurements using iterative modelling (the present work); **C**, subset of the European Moho depth map from Grad et al. (2009); **D**, difference between the calculated Moho depth and the European Moho depth map from Grad et al. (2009) shown in Fig. 4C.

Table 2. Weights assigned to each of the seismic studies in the area

Seismic profile	Weight
Part of EUROBRIDGE'95 which crosses the study area (marked by the dashed rectangle in Fig. 4A)	0.25
CELEBRATION-05	0.25
EUROBRIDGE'95	0.2
EUROBRIDGE'94	0.2
Baltic Sea profile	0.05
Sovetsk–Kohtla-Järve	0.05

Table 3. Validation results of the best performing Moho model

Seismic survey	RMSE (km)	Pearson's correlation
Part of EUROBRIDGE'95 which crosses the study area (marked by the dashed rectangle in Fig. 4A)	0.87	0.18
CELEBRATION-05	0.86	0.22
EUROBRIDGE'95	6.81	–0.72
EUROBRIDGE'94	3.71	0.98
Baltic Sea profile	2.61	–0.33
Sovetsk–Kohtla-Järve	11.50	–0.41
Weighted average	**3.24**	–

RMSE for every Moho model. All these metrics were used to select the best performing model (Fig. 4B). Uncertainties of the best performing model are provided in Table 3.

We compared our best performing model with the European Moho model by Grad et al. (2009), to consider the differences with previous research in this area. The European Moho model was resampled to the resolution of our research using bilinear interpolation and cropped to fit our model (Fig. 4C). The comparison of both models is found in Fig. 4D.

RESULTS AND DISCUSSION

The relationships between the weighted RMSE and modelling parameters are shown in Fig. 5. Various density contrast values result in similar RMSE values (Fig. 5A), with the lowest median values with density contrast of 0.7 g cm^{-3}. All the density values over 0.4 g cm^{-3} show a similar distribution of the weighted RMSE, and the lower density contrast values of 0.1–0.38 g cm^{-3} have almost the same RMSE range as larger values. For these two reasons the density contrast between the mantle and the crust was not the determining factor in the selection of the appropriate Moho depth model.

On the contrary, the input depth has the largest impact on the weighted RMSE (Fig. 5B). The smallest weighted RMSE of about 3.2–3.4 km can be acquired with an input depth of 43.5, 44 or 44.5 km. Changing the input depth beyond these values significantly decreases the RMSE. It shows that the Parker–Oldenburg algorithm is sensitive regarding the input depth parameter and the choice of incorrect modelling values makes it possible to end up with a model that is not representing the actual geological situation. It also shows the importance of carrying out the calculations iteratively while changing the algorithm input parameters.

Changes in gravity low-pass filter wavelength adjust the weighted RMSE by approximately 1 km. The lowest weighted RMSE can be acquired from strict filters of wavelengths of 1360, 680 and 453 km, however, reasonable results can also be gained with not-so-strict filters of wavelengths of 131 and 194 km. Wavelengths of about 150–200 km have been used in similar research before (Lefort & Agarwal 2000; Corchete et al. 2010). Higher frequencies may also represent shallower structures of the crust, while low-frequency filters with wavelengths higher than 500 km would likely represent deeper structures in the upper mantle. Therefore, after the validation of results, we chose the best performing model from models which were acquired with higher gravity filter wavelengths than 500 km.

The resulting Moho model (Fig. 5B) had the following input parameters: density contrast between the mantle and the crust of 0.7 g cm^{-3}, input depth of 43.5 km and low-pass filter wavelength of 131 km. The model did not have the lowest weighted RMSE, but it still was reasonably low (3.24 km). We chose this model based on other criteria: despite a comparatively large error relative to the seismic profile Sovetsk–Kohtla-Järve (11.5 km), it had a very small error (0.86 km) relative to CELEBRATION-05, a rather small error in regard to EUROBRIDGE'94 (3.71 km with 0.98 correlation) and a very small error in relation to the part of the EUROBRIDGE'95 profile which crossed the southwestern corner of the study area (0.87 km) (see Fig. 4A). When excluding the models acquired with long-wavelength gravity filters, our selected model had one of the lowest weighted RMSEs and the lowest CELEBRATION-05 and the previously discussed part of the EUROBRIDGE'95 RSME values.

The Moho topography of our model (Fig. 4D) varies in depth from 41.5 km in the southern and northeastern parts of Latvia to 46.5 km in the northern part of Latvia and the Gulf of Riga. The Moho map clearly resembles the low-pass filtered gravity anomaly values in Fig. 3, with shallower depth values in the middle and northeastern parts of Latvia and deeper values in the northern and eastern parts of Latvia, reminding of a saddle-like structure. Most of the seismic profile RMSE in the study area is relatively small, in the range of 4 km.

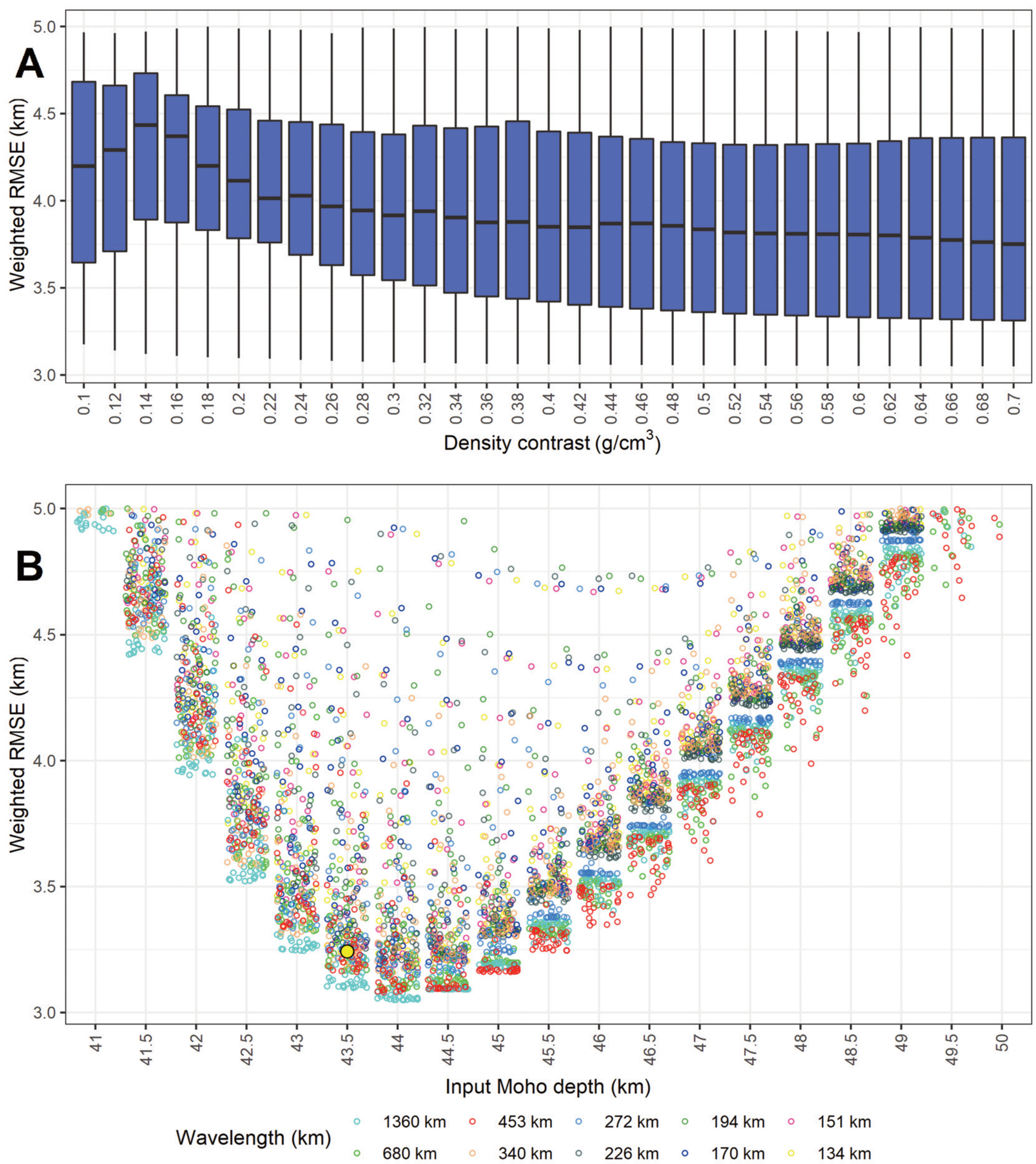

Fig. 5. Weighted RMSE in relation to modelling parameters. **A**, density contrast; **B**, filter wavelength and input depth. The large yellow dot marks the selected model. All models with weighted RSME ≥5 km are not shown.

The Moho model correlates with the Sovetsk–Kohtla-Järve profile poorly, as well as with previous regional models (Artemieva & Thybo 2013; Grad et al. 2009). The RMSE between the Moho model and the Sovetsk–Kohtla-Järve profile is about 13 km at the largest (±31% of the calculated Moho depth). This error can be seen in the comparison with the European Moho map of Grad et al. (2009) (Fig. 4D), which, in the territory of Latvia, was mainly based on the Sovetsk–Kohtla-Järve profile. The largest error can be seen in the central part of Latvia.

The Sovetsk–Kohtla-Järve seismic survey suggests that the Moho depth in the central part of Latvia reaches 50–60 km. However, Yliniemi et al. (2001) have suggested that the crustal thickness from the Sovetsk–Kohtla-Järve seismic profile should be investigated carefully, as this value was determined only using PmP Moho reflection. To further study the difference, we performed a simple modelling experiment (Fig. 6) – we modelled the theoretical gravity anomaly amplitude associated with such high Moho depths. We approximated the crust in the research area as multiple 3-dimensional prisms with a mean density contrast value of –0.4 g cm^{-3}. The choice of density values was in line with previous research (Kozlovskaya et al. 2002), but we chose smaller

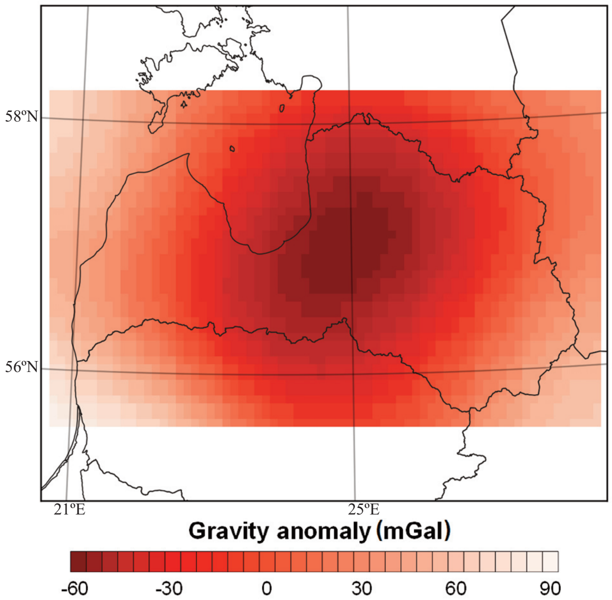

Fig. 6. Modelled gravity response of the European Moho map (Grad et al. 2009). The amplitude of the negative anomaly in the territory of Latvia reaches 142 mGal.

values than the areal average to generate a lower-gravity anomaly amplitude, so that differences in regard to our dataset would be emphasized. The geometry of the prisms was acquired from the cells of the European Moho map (Grad et al. 2009), which, as previously mentioned, approximates the geometry of the Moho in the research area based on the Sovetsk–Kohtla-Järve profile.

The gravity anomaly amplitudes of the European Moho map reach around 142 mGal (from 83 mGal in the corners of the research area to –59 mGal in the central part of Latvia). In reality, the measured amplitudes of gravity anomalies in Latvia vary about 90 mGal (from –60 mGal in the northern part of Latvia and Gulf of Riga to around 30 mGal in southern–southwestern Latvia). Thus, we observed a significant difference of around 55 mGal between the theoretically modelled and measured anomaly amplitudes. While a part of this difference can be explained by heterogeneities in density within the crust, we suggest that this mismatch is large enough to raise questions regarding the Sovetsk–Kohtla-Järve profile results. We encourage a new seismic survey in Latvia or in its surroundings to further validate these crustal structure peculiarities. The observed mismatch might also be validated by extending further research areas to the territories of Lithuania and Estonia.

Even if we claim for a need to validate the Sovetsk–Kohtla-Järve seismic results, the Moho model presented here can be imprecise. First, there are digitalization errors. All the seismic survey data were georeferenced manually and digitized from figures in various publications (Sadov & Penzina 1986; Ostrovsky et al. 1994; Bogdanova et al. 2006; Grad et al. 2006), which inevitably leads to a digitalization error. Such errors could significantly affect small-scale data, but we believe that the effect on large-scale models, such as the Moho, is minor. It is also difficult to quantify digitalization errors, as every profile is georeferenced separately. Therefore, we followed the assumption that the digitized data are reasonably correct and can be used as a benchmark.

Second, when considering the devised Moho surface and modelling parameters, one of them stands out. The density contrast of 0.7 g cm^{-3} between the mantle and the crust can be considered as large, especially when taking into account previous research conducted in the area, suggesting a density contrast between the lower crust and the upper mantle of about 0.3–0.4 g cm^{-3} (Kozlovskaya et al. 2001, 2002). We provide the following two possible explanations for the large density contrast.

When considering the simple Parker–Oldenburg inversion algorithm, the density contrast controls the maximum possible amplitude of the inverted surface – larger density difference creates a more rugged interface between the two layers. Our test metrics, such as the RMSE and correlation, favours models with larger amplitudes (because they can better 'adapt' to the seismic profiles), which is probably the reason why the median model RMSE decreases slightly with the increase in density contrast (see Fig. 5A). This problem is similar to statistical model overfitting in machine learning and has to be considered as a side effect of the chosen methodology.

The Parker–Oldenburg algorithm models the interface between two layers only. This leads to an assumption of a simple crustal model – one which must be approximated with a single density value. The average density of the crust would also take the less dense upper crustal layers into account. This brings the overall density contrast between the crust and the mantle up. When comparing the 0.7 g cm^{-3} density contrast with other studies, we cannot only compare the values between the lower crust and the upper mantle; we also have to consider the mantle and the crust as two homogeneous layers. This means that 0.7 g cm^{-3} is comparable with previous studies in the area, which, when approximating, shows average values of about 0.5–0.6 g cm^{-3} (Kozlovskaya et al. 2001, 2002).

Third, as mentioned, the Parker–Oldenburg algorithm assumes a simplified crust–mantle structure, which in turn affects the results. More algorithms for crustal thickness calculations, such as those reviewed by Bagherbandi (2012), could be considered before we try to better understand the errors associated with our method. We also believe that acquiring more seismic data and conducting detailed joint inversion in combination with forward modelling would improve the accuracy of our model.

The simple structure of the crust and mantle modelled by the Parker–Oldenburg algorithm is both a weakness and strength of the method. It allows easy experimentation and iterative calculation, but, at the same time, there is a possibility that the calculated interface is too general and might miss important information regarding the Moho topography.

CONCLUSIONS

Gravity inversion with the Parker–Oldenburg algorithm can be used as an alternative to the seismic exploration of the Moho or crustal structure modelling, especially in locations where there is a shortage of seismic data. However, gravity data still need to be pre-processed and inversion must be constrained with seismic data.

While using the Parker–Oldenburg algorithm, it is necessary to create multiple models with various combinations of input values. Further, via using statistical methods, the most appropriate model can be chosen. Limiting the number of different calculation iterations increases the chance that the obtained model could be erroneous.

The Moho depth calculated by the Parker–Oldenburg algorithm varies between 41.5 and 46.5 km. A significant mismatch of about 13 km was observed between our calculated model and the Sovetsk–Kohtla-Järve seismic profile. The comparison of the observed gravity anomalies and calculated gravity anomalies in accordance with the Sovetsk–Kohtla-Järve profile also shows a mismatch of about to 55 mGal.

Considering the relatively simple structure of our crustal model, we encourage further research of our results. These should be verified and possibly compared with new data sources and inversion algorithms to better understand the errors associated with the Parker–Oldenburg inversion method.

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Supplementary data

The supplementary materials to this article can be found at https://drive.google.com/open?id=1QvRQ0orx5j-Np0tf_f7AdOLHTZI-Z4V4.

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Moho piirpinna sügavuse kaardistamine Lätis raskusjõu kiirenduse andmetel

Viesturs Zandersons ja Janis Karušs

Maakoore struktuurse ehituse tundmine on oluline alusteadmine erinevate geodünaamiliste protsesside mõistmiseks ja Maa siseehituse tundmaõppimiseks. Üks tähtsamaid küsimusi on maakoore paksus, mida määratletakse Mohorovičići piirpinna ehk lihtsamalt "Moho" sügavusega, mis markeerib piirpinda maakoore ja vahevöö vahel. Moho geomeetria ja sügavus on Euroopas reeglina hästi tuntud, kuid selle täpsem sügavus ning pindalaline varieeruvus on Baltikumis, iseäranis Läti alal, siiani ebaselge. Läti ala läbib ainult üks süvaseismiliste uuringute profiil, mis ulatub Sovetskist Kaliningradis kuni Kohtla-Järveni Eestis. Käesolevas töös analüüsiti varasemaid Läti alal teostatud raskusjõu kiirenduse mõõtmiste andmeid muudetavate sisendparameetritega Parkeri-Oldenburgi meetodiga, et selgitada Moho sügavuste pindalaline varieeruvus. Saadud tulemused näitavad, et modelleeritud Moho sügavus varieerub 41,5 km-st Läti lõuna- ja kirdeosas kuni 46,5 km-ni Läti põhjaosas ja Riia lahes, mis on heas kooskõlas süvaseismilistelt profiilidelt interpreteeritud Moho piirpinna sügavustega.