

MOHO REFLECTIONS FROM STRONG NEAR QUARRY BLASTS: AN EXAMPLE FOR THE CENTRAL ORE MOUNTAINS, CZECH REPUBLIC

Hana KAMPFOVÁ^{1)*}, Jiří MÁLEK¹⁾ and Oldřich NOVOTNÝ²⁾

¹⁾ *Institute of Rock Structure and Mechanics, Academy of Sciences of the Czech Republic, v.v.i., V Holešovičkách 41, 182 09 Prague 8, Czech Republic*

²⁾ *Department of Geophysics, Faculty of Mathematics and Physics, Charles University in Prague, V Holešovičkách 2, 180 00 Prague 8, Czech Republic*

*Corresponding author's e-mail: kampfova@irms.cas.cz

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ABSTRACT

The present paper describes a method for identification of reflected waves on the seismograms from a cluster of quarry blasts. These reflections are used for determination of the Moho depth. Only one seismic station is sufficient, but a cluster of seismic sources is needed. To increase the signal-to-noise ratio of reflected waves, several techniques are applied, such as filtering, polarisation analysis and stacking of seismograms. The method was tested on seismic data from the central part of the Ore Mountains region, Czech Republic. Seismic waves were generated by strong quarry blasts at the Tušimice open-pit coal mine, and recorded at the Přísečnice (PRI) temporal seismic station at an epicentral distance of about 16 km. As the station was equipped with a three-component seismograph, also S-wave onsets could be determined. Although Pg, Sg and surface waves dominate the seismograms, weak Moho reflections of P and S waves could also be recognized at travel times of 9.7 s and 17.3 s, respectively. From these times we found the mean ratio of the P- to S-wave velocities in the crust to be 1.78. Considering P-wave velocity model of Beránek (1971), the observed travel times of the reflections yield a crustal thickness of 29.5 – 31.5 km, which agrees with recent receiver function studies. These agreements indicate that the proposed method of reflected seismic waves, generated by quarry blasts, could represent a simple way for mapping the Moho discontinuity.

KEYWORDS: Moho reflection, crustal thickness, quarry blast, Ore Mountains

1. INTRODUCTION

The Eger Rift (ER) in the northwestern part of the Bohemian Massif belongs to the European Cenozoic rift system. The ER tends generally NE – SW along SE margin of the Ore Mountains in the Czech – German border region. The rift attracts attention of many investigators due to several extraordinary geological phenomena on a relatively small area (Plomerová et al., 2007; Babuška et al., 2007). Among them, one should mention contacts of several geological units in the basement, deep faults, granitic massifs, extensive Tertiary sedimentary basins with lignite deposits, Tertiary and Quaternary volcanism, mineral and thermal springs, dry gas vents (mofettes), contrast gravity anomalies, and earthquake swarms in the western part of the rift (Horálek et al., 2000). These remarkable phenomena call for detailed studies of the crustal and upper mantle structure of the region.

The first deep seismic soundings (DSS) in the Bohemian Massif, carried out in the 1960s and 1970s, revealed a relatively thin Earth's crust in the Ore Mts. block (Beránek, 1971; Beránek et al., 1975). Subsequent areal mapping of the Moho discontinuity depth using seismic waves generated by industrial explosions confirmed the unusually thin crust of the Ore Mts. block (Mayerová et al., 1994). Similar

results have recently been obtained using the receiver function technique by Heuer (2006) in the scope of the BOHEMA project and by Wilde-Piórko et al. (2005) for permanent stations. The present paper supplements these studies by detailed measurements at a locality in the central part of the Ore Mts. region.

The seismic reflection measurement is a basic, widely used method in exploration geophysics (e.g. Shearer, 1999). The main idea of the presented method is to find Moho reflections on quarry blast seismograms at near epicentral distances. These reflections are very weak and they cannot be identified by standard readings of seismogram. Therefore, we apply filtering and stacking to amplify them.

In the present study, we have used a series of industrial quarry blasts at the quarry Tušimice recorded at the nearby seismic station Přísečnice (PRI) at an epicentral distance of about 16 km. We attempted to find reflections from the Moho discontinuity. The main motivation for this study was the fact that seismograms from quarry blasts are recorded at short epicentral distances at many stations in the Czech Republic, where a dense network of quarries exists (Málek and Žanda, 2004). The records can be used for mapping the Moho if the reflections are extracted from them. This method of Moho

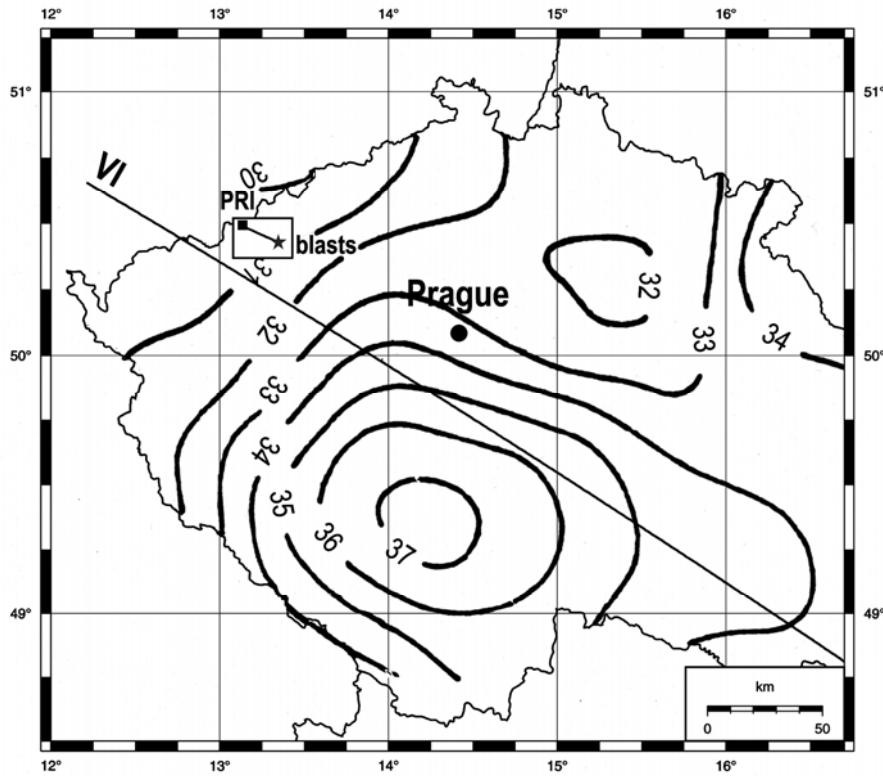


Fig. 1 Moho depths (in kilometres) on the territory of Czech Republic (after Mayerová et al., 1994). The straight lines show profile VI of the deep seismic sounding (Beránek, 1971) and the studied profile (the short one).

Table 1 Coordinates of the blasts and station PRI (with respect to the WGS-84 reference ellipsoid).

| Name | Latitude [°] | Longitude [°] | Altitude [m] | Distance to PRI [m] |
|------|-----------------|------------------|-----------------|------------------------|
| A1 | 13.3441 | 50.4297 | 280 | 16 263 |
| A2 | 13.3440 | 50.4299 | 280 | 16 249 |
| A3 | 13.3420 | 50.4306 | 280 | 16 090 |
| A4 | 13.3395 | 50.4308 | 280 | 15 914 |
| B1 | 13.3391 | 50.4275 | 280 | 16 045 |
| B2 | 13.3371 | 50.4279 | 280 | 15 898 |
| B3 | 13.3276 | 50.4282 | 280 | 15 275 |
| B4 | 13.3419 | 50.4275 | 280 | 16 227 |
| C1 | 13.3481 | 50.4269 | 260 | 16 648 |
| C2 | 13.3461 | 50.4275 | 260 | 16 491 |
| C3 | 13.3490 | 50.4270 | 260 | 16 705 |
| C4 | 13.3446 | 50.4276 | 260 | 16 394 |
| PRI | 13.1355 | 50.4903 | 718 | |

mapping does not require special blasts, which are necessary in the conventional seismic reflection experiments.

The raypath between Tušimice and Přisečnice crosses two main geological units: Chomutov sedimentary basin and Ore Mts. Crystalline unit (Fig. 2). These units are separated by the Ore Mts. fault. Igneous rocks and sediments, which fell into large depths during the Proterozoic till Palaeozoic, are

generally denoted as the Crystalline unit. They were metamorphosed by high pressure and temperature, and also younger granite rocks leaked into them.

2. EXPERIMENTAL SETTINGS

The Tušimice quarry is a large open-pit coal mine in the NW of the Czech Republic. The geological sketch is shown in Fig. 2 (after Zoubek, 1998). In the last years, the shots were performed

Table 2 Modified DSS model for the Ore Mts. block composed of homogeneous layers: m is the sequential number of the layer, z_m is the depth of the top of the m -th layer in kilometres, v_m is the P -wave velocity in km/s, and d_m is the thickness in kilometres.

| m | z_m | v_m | d_m |
|-----|-------|-------|-------|
| 1 | 0.0 | 5.5 | 2.5 |
| 2 | 2.5 | 5.7 | 1.0 |
| 3 | 3.5 | 5.9 | 0.5 |
| 4 | 4.0 | 6.1 | 1.0 |
| 5 | 5.0 | 6.3 | 9.5 |
| 6 | 14.5 | 6.5 | 3.5 |
| 7 | 18.0 | 6.7 | 11.0 |
| 8 | 29.0 | 6.9 | 2.0 |
| 9 | 31.0 | 7.1 | 1.0 |
| 10 | 32.0 | 8.2 | |

several times a week to disintegrate the roof stone. For this study we selected twelve blasts from January 2003 to June 2003, which can be divided into three clusters, denoted as A, B and C. Clusters A and B were situated at an altitude of 280 m, while cluster C was situated at the lower layer at an altitude of 260 m (Table 1). The charges of the selected blasts ranged from 3600 to 6350 kg of explosive, divided into several tens of boreholes. The boreholes were blasted in several steps with time delay of 23 ms. The accurate shot time was not measured regularly, but only for one shot, which we call master blast. The times for other shots were extrapolated from Pg -wave onsets at PRI (Fig. 5) considering the differences in epicentral distances, see Section 4.1.

All seismograms come from the seismic station PRI (operated by the Institute of Rock Structure and Mechanics), which was established during the BOHEMA experiment (Plomerová et al., 2003). This station is situated inside a concrete water dam. The station is equipped with the seismic sensor GURALP CMG 40T, which has a flat velocity response in the frequency range from 0.03 to 40 Hz. The continuous acquisition system RUP2000 with GPS time synchronization is used. The sampling frequency is 100 Hz.

3. MODEL OF THE CRUSTAL STRUCTURE

Refraction measurements along the Tušimice – Přísečnice profile have not been performed yet. Consequently, for our purposes we have adopted the velocity model for the Ore Mts. block along the nearby DSS profile VI. This P -wave velocity model was proposed by Beránek (1971) and Beránek et al. (1975) as a piecewise linear function of depth. Later, Novotný and Urban (1988) approximated this model by a simpler model composed of homogeneous layers. The velocities and thicknesses of the first two layers

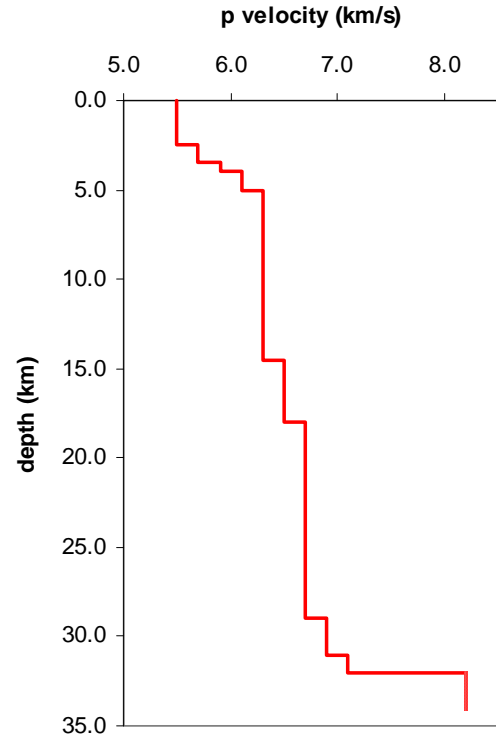


Fig. 3 Modified velocity model of the Ore Mts. crustal block.

were as follows: 5.3 km/s and 1.5 km in the first layer, 5.5 km/s and 1.0 km in the second layer. However, the Pg wave observed at PRI (see below) requires a higher superficial velocity of about 5.5 km/s. Consequently, we have increased the velocity of the first layer from 5.3 km/s to 5.5 km/s and joined the first two layers. The parameters of the resulting model are given in Table 2 and Fig. 3.

4. METHOD OF AMPLIFYING THE MOHO REFLECTIONS

A typical seismogram used in this study is shown in Fig. 4. The first onset, which is formed by the Pg wave, is quite clear with pronounced signal-to-noise ratio. The Sg wave can also be easily identified especially on the transversal component T . The seismogram is characterized by intensive surface waves, which arrive at the same travel times as the Moho reflection, but with much lower frequencies. The Moho reflection cannot be identified directly from the single seismogram. The goal of our analysis is to amplify the Moho reflection using frequency and polarization filters and stacking the groups of seismograms. We proceeded in several steps, the descriptions of which follow.

4.1. DATA PREPARATION

The Moho reflections of the longitudinal waves, PmP , are polarized nearly at the vertical direction, while the reflections of shear waves, SmS , are

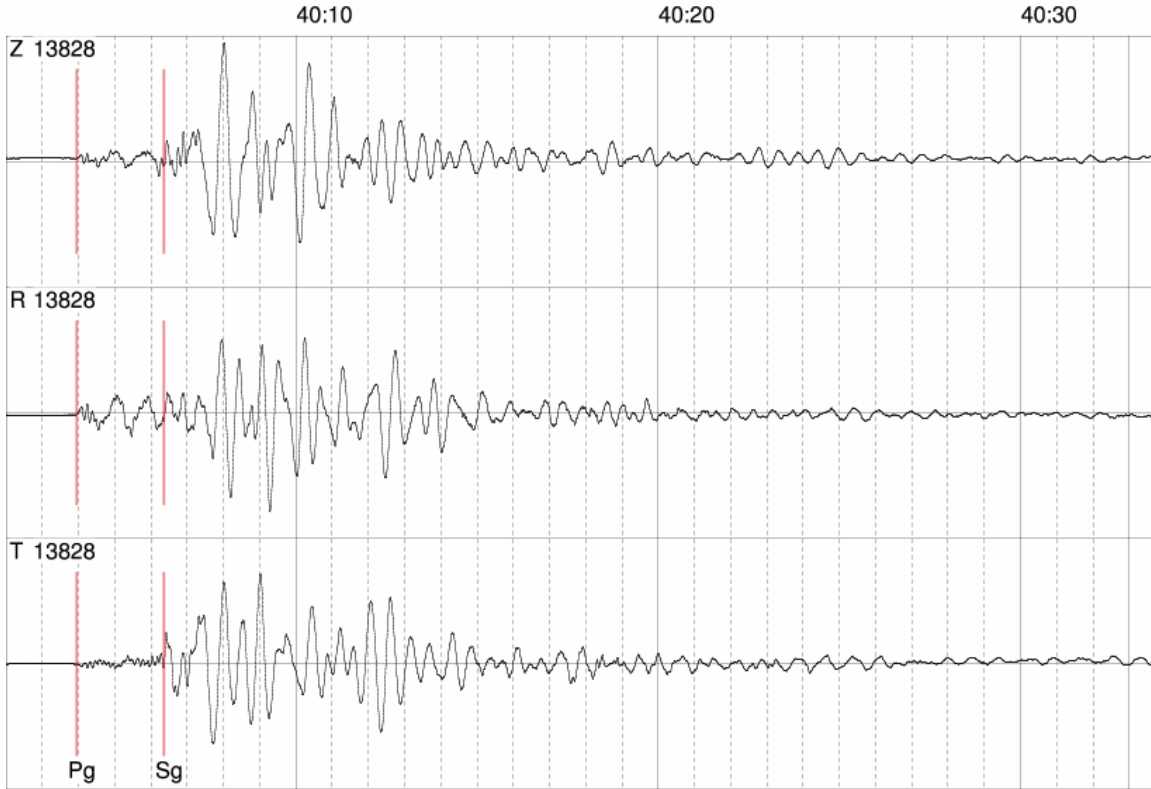


Fig. 4 Typical seismogram recorded on June 18, 2003. Pg: 08:40:03.940, Sg: 08:40:06.350.

polarized nearly in the horizontal plane. To amplify these reflections in the seismograms we performed four preparatory steps. First, we rotated the horizontal components to obtain the radial and transverse components. After that we computed Pg onsets. We shifted seismograms relatively to obtain the best correlation as shown in Fig. 5. To obtain high correlation, it is necessary to select blasts with similar source function, which determine the shape of the Pg pulse (that is the reason, why we selected just four blasts in each group from 95 registered blasts). Finally, we determined the origin times for all blasts. Since only one origin time was measured (for "master blast"), the remained origin times were calculated using this master event with corrections computed from the differences of epicentral distances. The apparent Pg -wave velocity of 5.5 km/s was used for this purpose.

4.2. TIME-FREQUENCY ANALYSIS

The time-frequency analysis (Fig. 6) showed that in the frequency band of about 8 – 22 Hz, the seismic signal continues more than 10 s after the explosion. This signal represents the reflections from the Moho depths which are hidden in the seismic coda. Consequently, a cosine shaped band-pass filter with flat response between 8 and 22 Hz was applied.

4.3. ENVELOPES

For further amplification of the reflections a directional filter was applied. First, the envelopes of all components (vertical Z , radial R and transverse T) were computed. We used the Hilbert transformation for that. To obtain the filtered signals of P - and S -reflections we applied the formulae:

$$\begin{aligned} Z_{ampl} &= Z * \sqrt{\frac{Env^2(Z)}{Env^2(Z) + Env^2(R) + Env^2(T)}}, \\ R_{ampl} &= R * \sqrt{\frac{Env^2(R)}{Env^2(Z) + Env^2(R) + Env^2(T)}}, \\ T_{ampl} &= T * \sqrt{\frac{Env^2(T)}{Env^2(Z) + Env^2(R) + Env^2(T)}}, \end{aligned} \quad (1)$$

where Env denotes the envelop of the signal. We proposed these formulae in order to amplify the waves impinging from the directions close to the vertical. In our model the incidence angle at the surface is about 12 degree.

4.4. LINEAR SUMMATION

Finally, to amplify the reflections, all seismograms in the individual groups A, B, C were

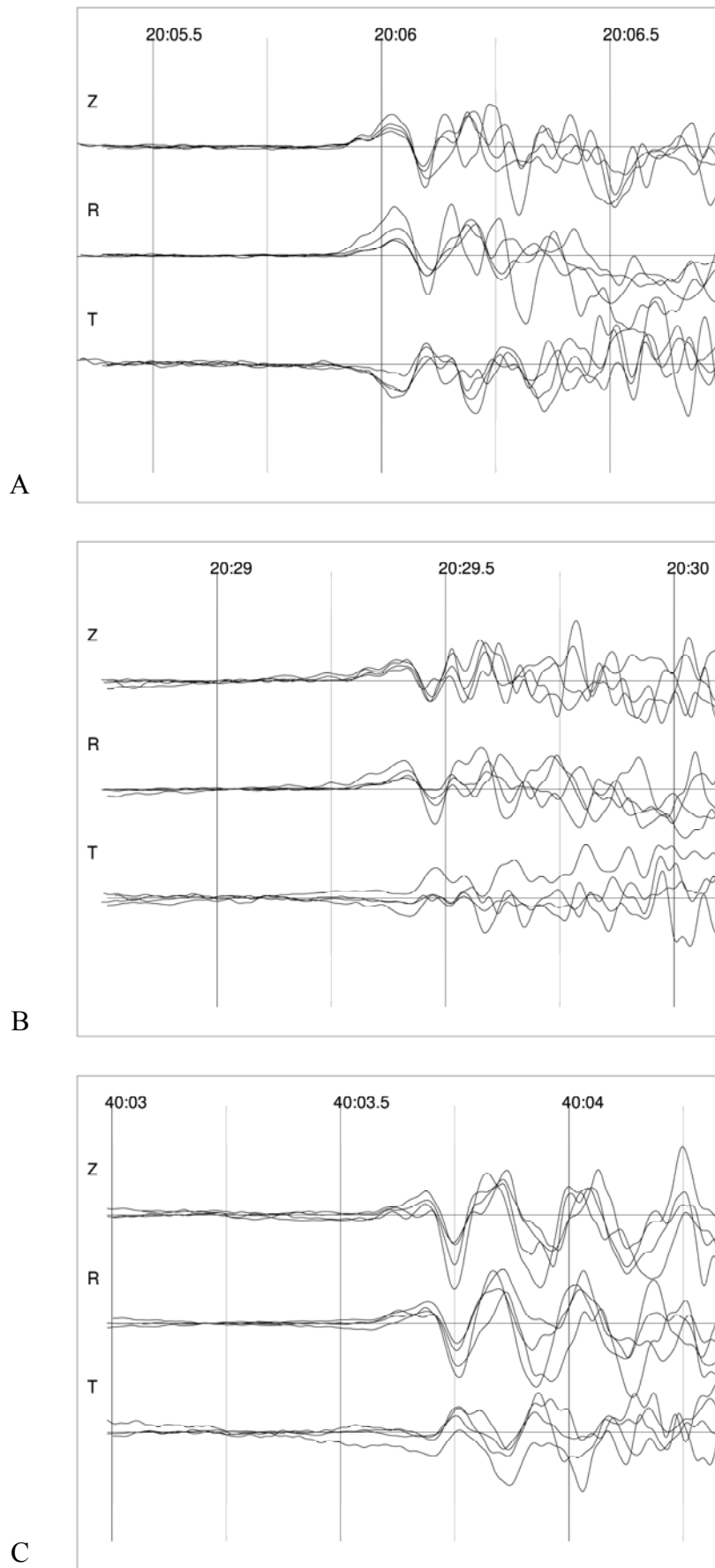


Fig. 5 Correlation of all seismograms in groups A, B, and C.

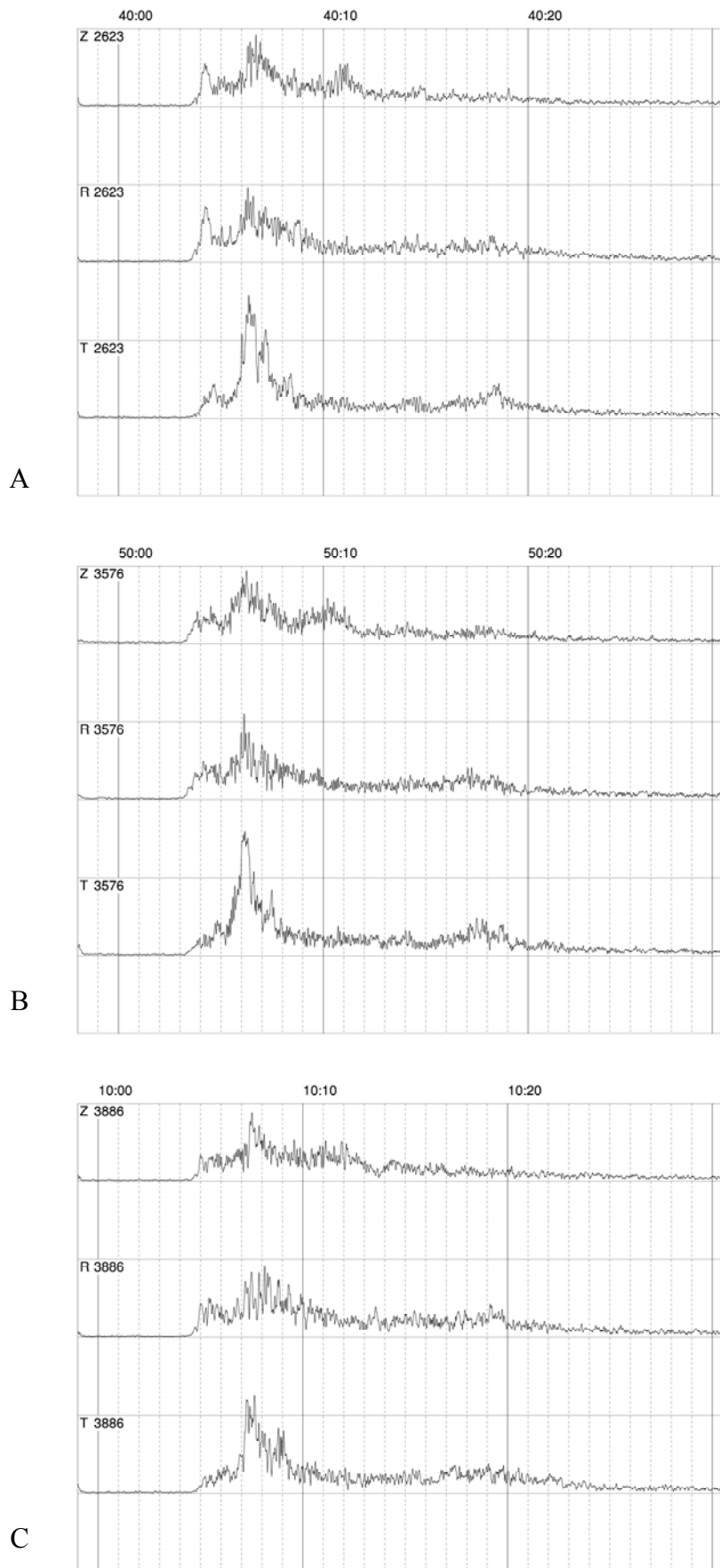


Fig. 7 Summation of seismograms (groups A, B, C).

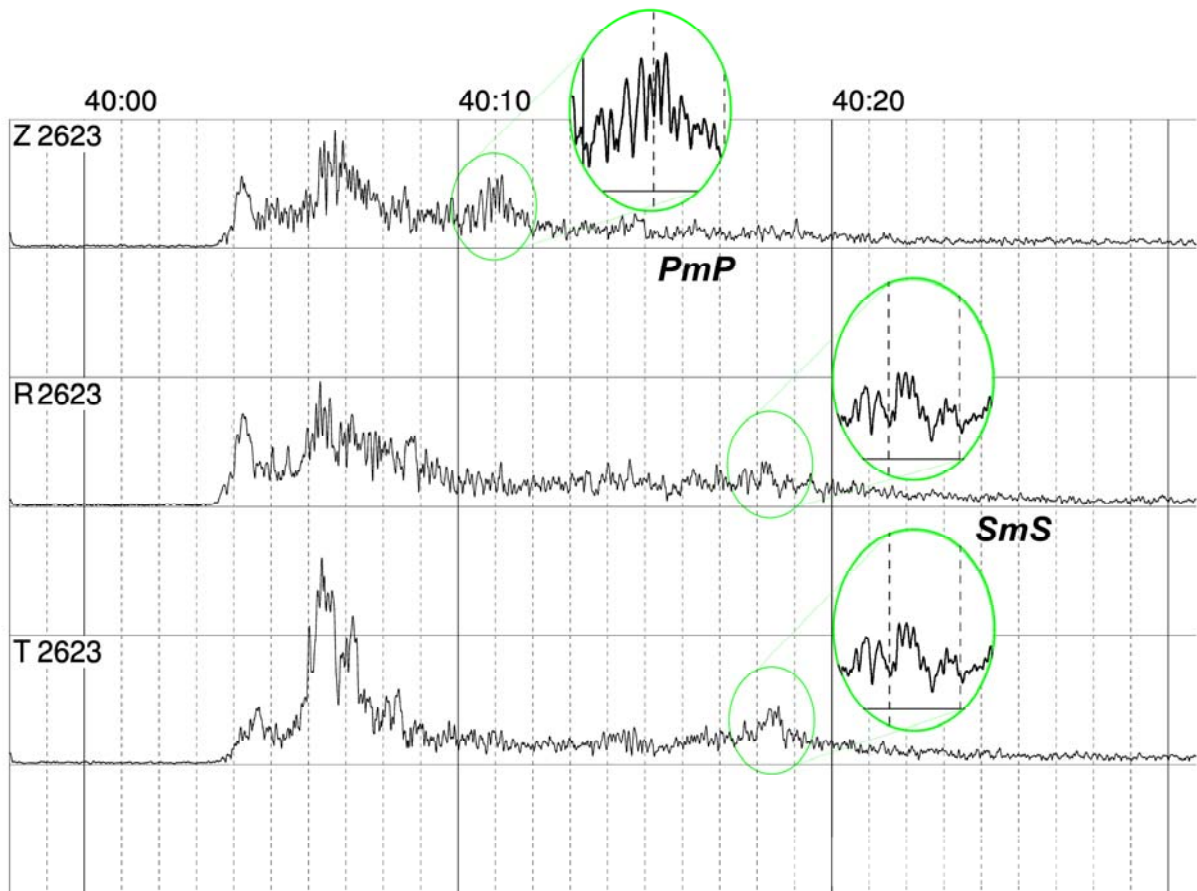


Fig. 8 Details of the seismogram.

Table 3 Travel times of seismic waves: r is the epicentral distance in kilometres, the other columns contain the travel times of the individual waves in seconds (for notations, see the text).

| Group | r | Pg | PmP_1 | SmS_1 | PmP_2 | SmS_2 | PmP_3 |
|-------|-------|------|---------|---------|---------|---------|---------|
| A | 16.09 | 2.93 | 9.82 | 17.34 | 10.04 | 17.48 | 10.16 |
| B | 16.23 | 2.95 | 9.63 | 17.22 | 9.94 | 17.50 | – |
| C | 16.71 | 3.03 | 9.73 | 17.39 | 10.11 | 17.68 | – |

summed together, considering time delays between seismograms according to travel time curves of reflected waves (Fig. 7). The reflections in Fig. 8 are amplified by constructive interference, while the other phases are reduced. After this procedure amplified reflections have become comparable with the direct Pg wave. The amplification could be successful only if the wave form of the Pg wave was similar for all blasts in the group and therefore, it was necessary to select just only seismograms with similar focal mechanisms.

5. MEASURED TRAVEL TIMES

We have found three PmP reflections for group A and two PmP reflections for groups B and C. Moreover, we found two SmS reflections for all groups (Table 3).

6. MOHO DEPTH DETERMINATION

The depths of the interfaces corresponding to times in Table 3 were computed using the homogeneous model and the layered model whose parameters are given in Table 2. Let us mention briefly the basic formulae for the forward problem.

Consider a medium composed of homogeneous layers, and assume the source and receiver to be placed at the surface. Introduce a fictitious interface in the model coinciding with the assumed Moho discontinuity, and consider only the medium above this interface. Denote by n the sequential number of the layer where this Moho interface is situated. Further, denote by v_m and d_m the velocity (the corresponding P - or S -wave velocity) and thickness of the m -th layer, respectively, where $m=1,2,\dots,n$. Note that d_n is the thickness of the fictitious upper part of

Table 4 Moho depths determined from travel times of the reflected waves given in Table 3. A homogeneous crustal model with $v_P = 6.3$ km/s and $v_P/v_S = 1.78$ km/s is considered. The Moho depths are given in kilometres. The last row contains mean values

| Group | PmP ₁ | SmS ₁ | PmP ₂ | SmS ₂ | PmP ₃ |
|-------|------------------|------------------|------------------|------------------|------------------|
| A | 29.9 | 29.6 | 30.6 | 29.9 | 31.0 |
| B | 29.2 | 29.4 | 30.2 | 29.9 | – |
| C | 29.5 | 29.6 | 30.7 | 30.2 | – |
| Mean | 29.53 | 29.53 | 30.50 | 30.00 | 31.00 |

Table 5 Moho depths for the layered crustal model of Ore Mts. block, given in Table 2. The Moho depths are given in kilometres. The last row contains mean values.

| Group | PmP ₁ | SmS ₁ | PmP ₂ | SmS ₂ | PmP ₃ |
|-------|------------------|------------------|------------------|------------------|------------------|
| A | 30.2 | 29.9 | 31.0 | 30.2 | 31.5 |
| B | 29.5 | 29.7 | 30.6 | 30.3 | – |
| C | 29.8 | 30.0 | 31.2 | 30.5 | – |
| Mean | 29.83 | 29.87 | 30.93 | 30.33 | 31.50 |

the n -th layer only, i.e. the part above the assumed Moho.

In the m -th layer, let us denote by α_m the incidence angle, $p = (\sin \alpha_m)/v_m$ the ray parameter (identical in all layers),

$$s_m = \frac{d_m}{\cos \alpha_m} = \frac{d_m}{\sqrt{1 - p^2 v_m^2}} \quad (2)$$

the length of the ray in the layer,

$$\xi_m = s_m \sin \alpha_m = s_m p v_m \quad (3)$$

the increment of the epicentral distance, and by

$$\tau_m = \frac{s_m}{v_m} \quad (4)$$

the increment of the travel time. The arrival time, t , at a given epicentral distance r cannot be expressed analytically (if $n > 1$), but only in a parametric form:

$$r = 2 \sum_{m=1}^n \xi_m, \quad (5)$$

$$t = 2 \sum_{m=1}^n \tau_m. \quad (6)$$

The ray tracing represents a numerical solution of Eq. (5) to determine the implicit function $p = p(r, v_m, d_m)$. If the ray parameter p is found, the arrival time t can be determined from Eqs. (2), (4) and (6).

In solving the inverse problem to determine the Moho depth, we applied the method of conjugate gradients where the required partial derivative of the travel time with respect to the Moho depth was

calculated analytically (Novotný, 1980; Novotný et al., 2007).

7. RESULTS

The error of the determination of the travel times is estimated to be better than 0.05 s (5 samples) in all cases. The depths of the interfaces were computed using a homogeneous crustal model (Table 4) and the slightly modified layered velocity model (Table 5) derived by Beránek (1971) for the Ore Mountains block.

All reflections come from depths between 29.5 and 31.5 km (Fig. 9). This agrees well with the position of the Moho discontinuity in the previous studies of the Ore Mts. region (30 – 31 km) from DSS (Beránek, 1971) and from receiver functions technique (Wilde-Piorko, 2005; Heuer, 2006).

8. CONCLUSIONS

A method of amplifying the Moho (or low crust) reflections has been developed. The method can be applied to seismograms from cluster of quarry blasts recorded at single seismic station at short epicentral distances of about 10 to 20 km. According to our results at distance of 16 km, the signal-to-noise ratio is sufficient to obtain reliable results. The reflections from the Moho could be distinguished from other waves at frequencies of about 20 Hz. The advantage of this method is that measurement of only one shot time is necessary. The summation of the seismograms and the application of a directional filter improve the results considerably. The application of this method to blasts at open-pit coal mine Tušimice confirmed that the Moho in the central Ore Mts. region is relatively shallow. Since we found the reflections of both P and S waves we calculated directly the mean crustal value of $v_P/v_S = 1.78$. The crust-mantle boundary is not

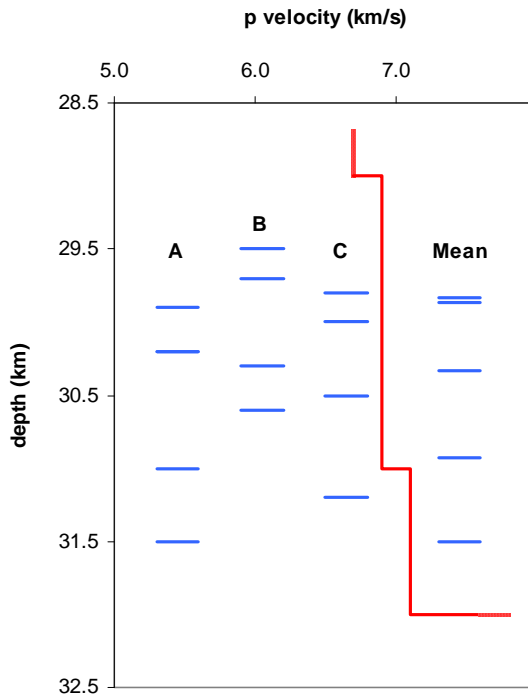


Fig. 9 Location of the Moho determined from different data.

probably formed by a single interface. Four reflections from depths between 29.5 and 31.5 km were detected. This agrees well with the position of the Moho discontinuity in the previous studies of the Ore Mts. region (30 – 31 km) from DSS and from the receiver functions technique.

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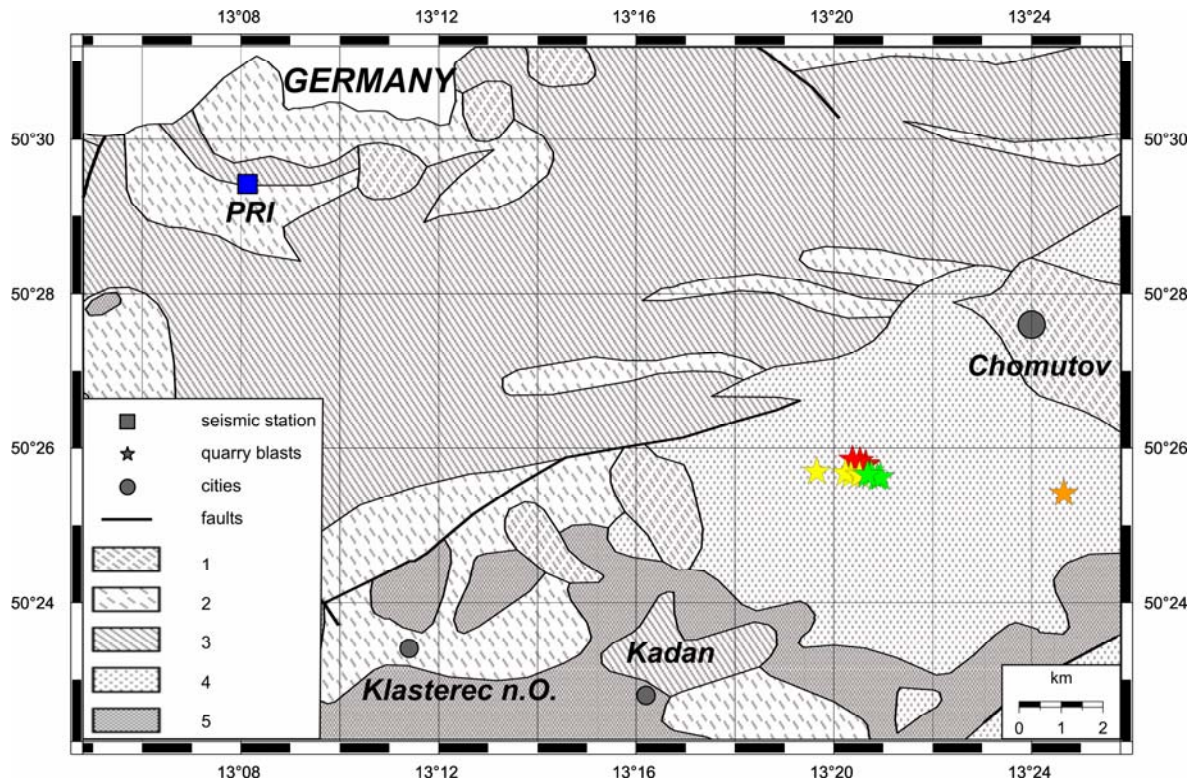


Fig. 2 Geological map of the studied region. 1 – Quaternary (loams, loess, sands, gravels), 2 – orthogneisses, granulites, 3 – Proterozoic rocks faulted by Cadomian orogeny with differently strong Variscan faulting (shales, phyllites, mica shists up to paragneisses), 4 – Tertiary rocks (sands, clays), 5 – Tertiary volcanic rocks (basalts, phonolites and tuffs), ★ – group A, ☆ – group B, ☆ – group C, ☆ – master blast.

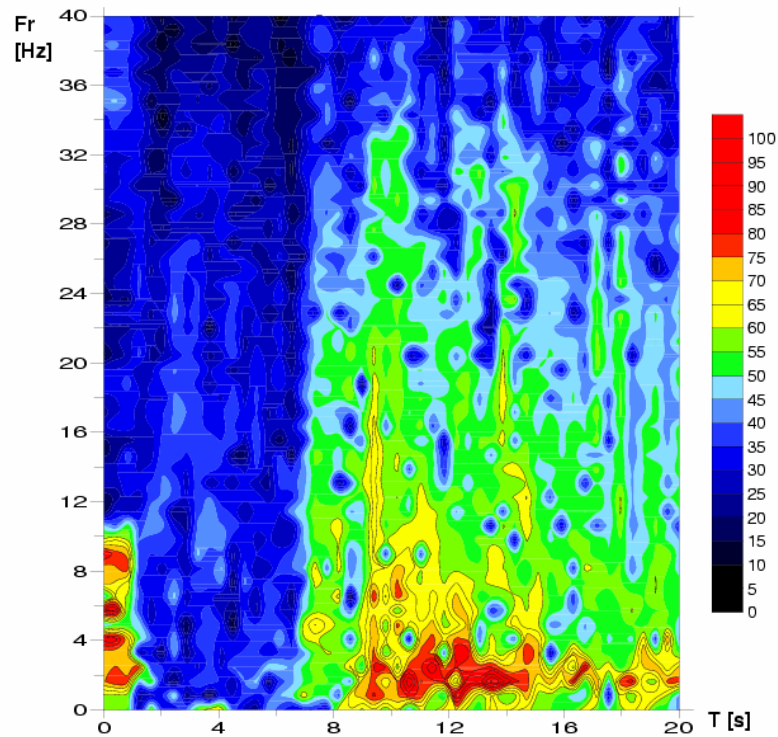


Fig. 6 A sonogram of the time-frequency analysis: Z-component of the seismogram in Fig. 4.