Journal of Geosciences, 67 (2022), 1–17 DOI: 10.3190/jgeosci.339

Original paper

Geological interpretation of a seismic reflection profile in the eastern part of the Bohemian Cretaceous Basin

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A seismic reflection profile was realized in the eastern part of the Bohemian Cretaceous Basin in the years 2013–2015. Seismic research was supported by a detailed gravity and geoelectric survey. The profile crossed three significant hydrogeological structures or districts: Vysoké Mýto, Ústí and Kyšperk synclines. Interpretation of geophysical data enabled a determination of the Cretaceous sediments with a thickness of up to 250 m and Permian sediments even with a thickness of 2000 m. The seismic reflectors and gravity effect, together with the boreholes and geological mapping, were used to compile the uncovered geological map.

Keywords: Bohemian Cretaceous Basin, reflection seismic, gravity, basement, tectonics, hydrogeological structures
Received: 14 April 2020; accepted: 3 February 2022; handling editor: J. Žák

1. Introduction

The Bohemian Cretaceous Basin (BCB) is the largest intracontinental basin in the Czech Republic (Fig. 1). The eastern part of the BCB has a unique morphotectonic character within the whole Cretaceous platform cover of the Bohemian Massif. New geological mapping in this area (Čech 2002; Valigurský and Čech 2003; Čech et al. 2011), tectonic and morphostructure analyses (Uličný et al. 2015; Burda and Grundloch, eds. 2020a, b) present a system of grabens and horsts, which were interpreted as anticlines and synclines in the traditional view (Zahálka 1918; Malkovský et al. 1974; Herčík et al. 1999) and which are still used in hydrogeological nomenclature (Olmer et al. 2006). These morphological horsts or half-horsts are usually deformed by faults, forced folds, and flexures on their eastern flanks. Cretaceous deposits are lithologically characterized by the development of several nearshore sandstone wedges in the marlstone or "*opuka*" facies. Together with the unique morphotectonic character of the Cretaceous deposits, these sandstone wedges form an important hydrogeological multi-aquifer basin system of eastern Bohemia and western Moravia.

Cretaceous strata overlie the basement of Proterozoic to Early Paleozoic ages. The area between the Kozlov Ridge and graben, called as Kyšperk Syncline, is occupied by the Permian deposits of the Orlice Basin (Pešek et al. 2001). The thickness of the Permian fill of the Orlice basin is estimated at over 1 km (Malkovský 1987; Pospíšil et al. 2009).

The present general knowledge of the crystalline basement in this area (Fig. 1) is based on papers discussing the geodynamic evolution of the Bohemian Massif (e.g., Mazur et al. 2005; Schulmann et al. 2005, 2009). The evolution of the boundary between the Teplá–Barrandian (TBU) and Lugicum units is difficult to describe using only surface outcrops. The crystalline basement is known only from boreholes in the Vysoké Mýto Syncline and the Kozlov Ridge near Semanín. More recent papers attempting to describe complex relationships of the regional units in this area are based on geochemistry, geochronology and petrology of outcrops in the broader surroundings (e.g., Buriánek et al. 2003; Verner et al. 2009; Buriánek 2010).

Regional geophysical research in the study area was until recently very limited. Regional gravity measurements at a scale of 1 : 200 000 in this territory were taken from 1953–1961 (Ibrmajer 1963). The seismic refraction survey, undertaken in the 1960s (Hrách 1970), yielded the first information about the depth of the crystalline basement. Electrical vertical sounding (Šafránek 1974) identified the thickness of the aquifers in the Cretaceous deposits only in the Vysoké Mýto area. The first regional airborne geophysical surveys (magnetic and radiometric) were made in 1963–1964 (Šalanský et al. 1965) and subsequently at a detailed scale of 1 : 50 000 in 1986 (Dědáček et al. 1987). None of these geophysical methods clearly explained the morphotectonic evolution of this area (whether the Cretaceous deposits represent syncline or graben). Therefore, a seismic reflection survey was realized in the eastern part of the BCB in 2013–2015 within the "*Review of groundwater resources in the Czech*

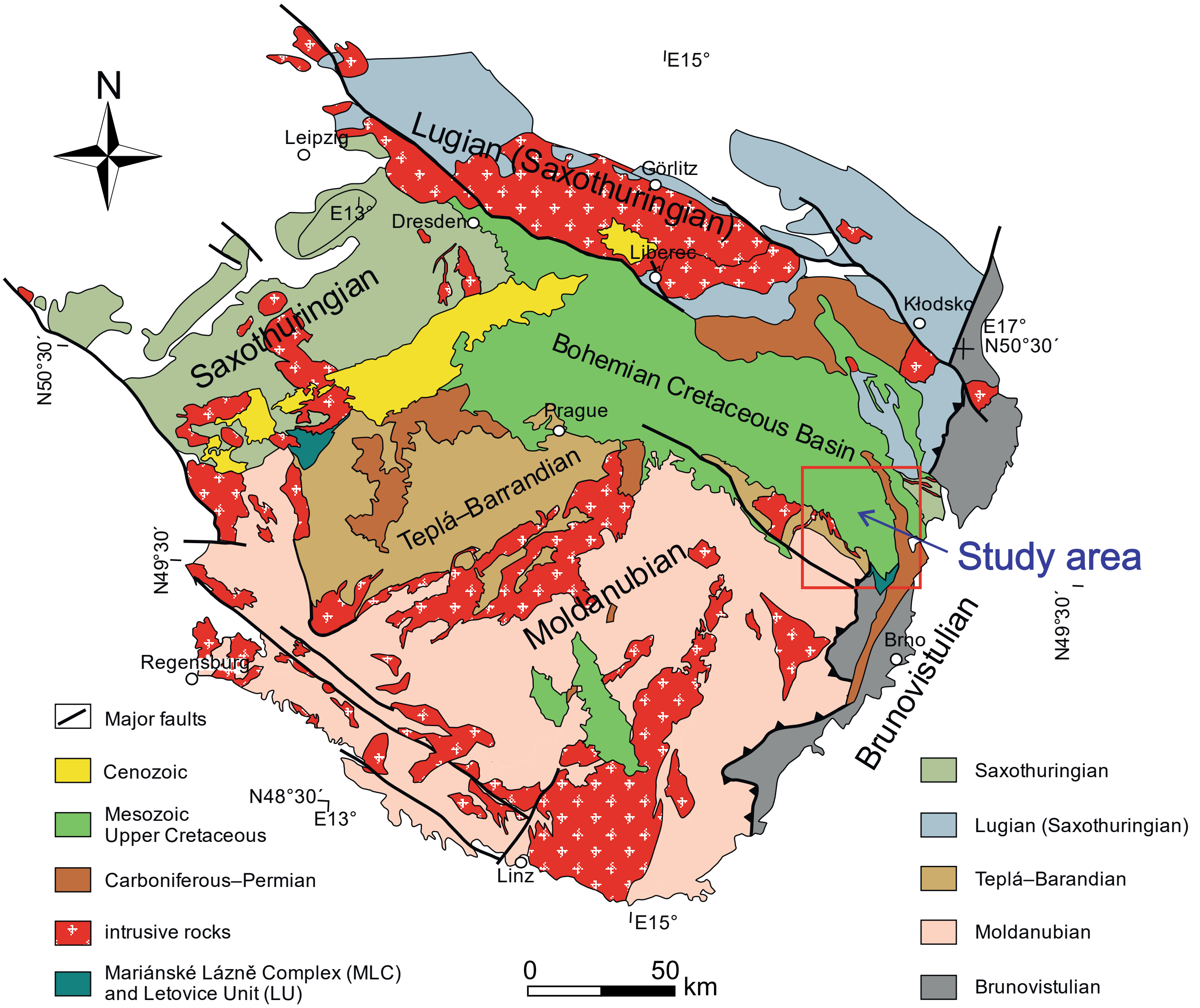


Fig. 1 A simplified geological map of the Bohemian Massif with marking of the study area.

Republic" project led by the Czech Geological Survey. The main task was to specify the geometry of critical hydrogeological structures, geological boundaries, and their tectonics concerning the position of groundwater aquifers and confining layers. The seismic reflection method is a powerful non-destructive sensing technique that can image the subsurface over depths. The acoustic wavefield locates the reflectors at a certain depth where the acoustic properties change. A detailed gravity survey supported seismic research in the studied area (Sedlák et al. 2015). The submitted geological interpretation of seismic profile RBSP/2011 is based on these two geophysical methods combined with archive borehole data.

Based on the results of new geophysical measurements, a cross-section of Cretaceous deposits and the basement and a tectonic and geological scheme of the crystalline basement were compiled. This scheme respects regional geological units exposed to the broader area.

2. Geological settings

History of geological studies in this region has been reviewed by Svoboda ed. (1962), Malkovský et al. (1974) and Herčík et al. (1999). First, an isopach map of Cretaceous deposits has been compiled by Vachtl (1965) and a map of the basement by Chaloupský (1973). Tectonics, stratigraphy and paleontology of Cretaceous deposits have been summarized by Soukup *in* Svoboda ed. (1962) and more recently by Burda and Grundloch eds. (2020a, b).

Cretaceous deposits overlie the crystalline basement and Permian fill of the Orlice Basin with a sharp unconformity. Transgressive sequences of continental, estuarine and shallow marine clastics (mudstones, coal seams, glauconitic and quartzose sandstones of the Peruc-Korycany Formation) on the basal unconformity surface were deposited during the Cenomanian. Nearshore and

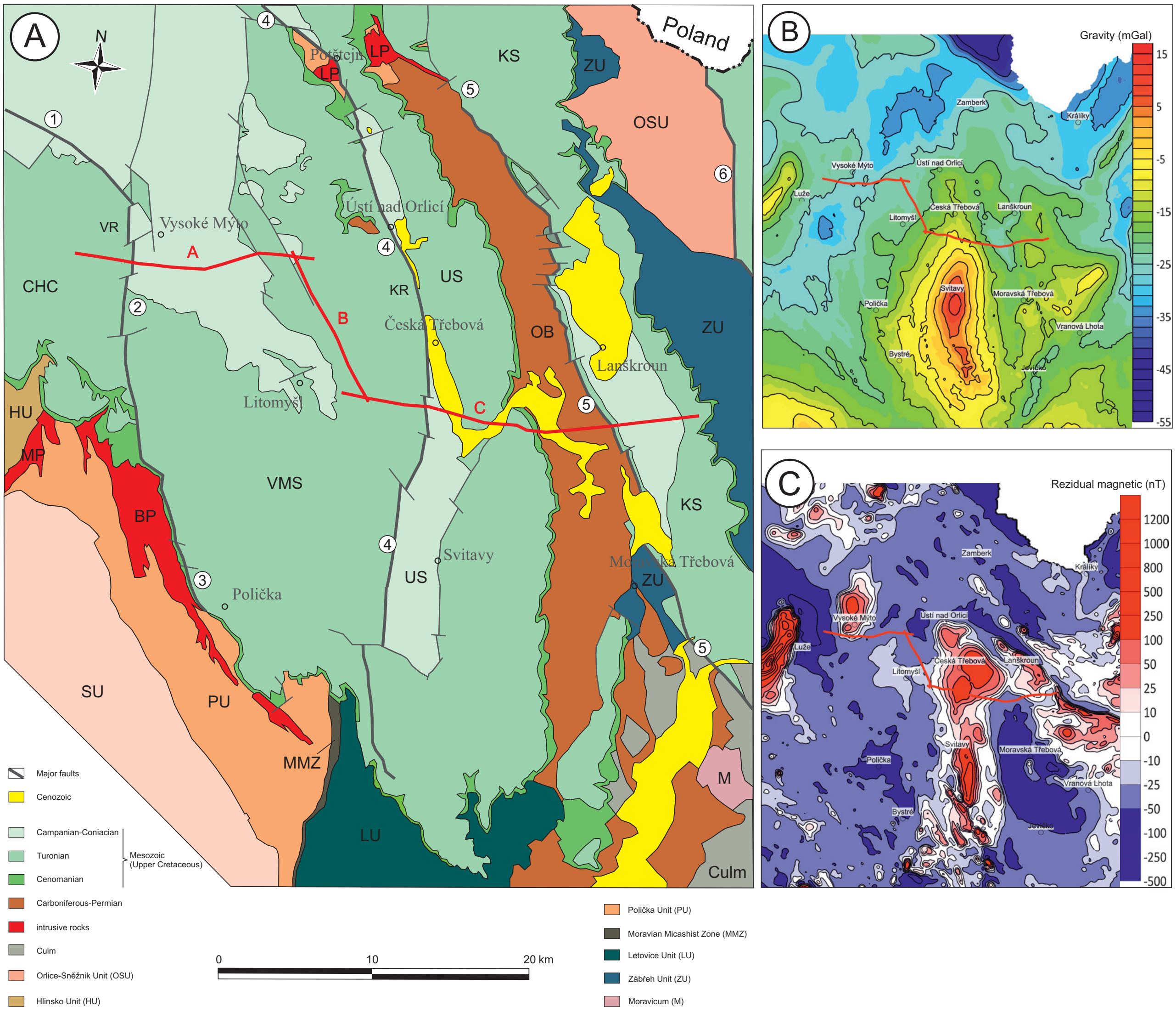


Fig. 2 A – geological map of the eastern part of the Bohemian Cretaceous Basin. Units: SU – Svratka Unit, PU – Polička Unit, MP – Miřetín pluton, BP – Budislav pluton, HU – Hlinsko Unit, LP –Litice pluton, MMZ – Moravian Mica-schist Zone, LU – Letovice Unit, ZU – Zábřeh Unit, OSU – Orlice–Sněžník Unit; CHC – „Chrudim Cretaceous" ; VMS – „Vysoké Mýto Syncline"; US –„Ústí Syncline"; KS – „Kyšperk Syncline"; VR – Vraclav Ridge; KR – Kozlov Ridge; OB – Orlice Basin. Faults: 1 – Malejov Flexure; 2 – Vanice Fault; 3 – Polička Fault; 4 – Semanín Fault Zone; 5 – Kyšperk Fault. Red line A, B, C – seismic profile. **B –** map of the refined Bouguer gravity anomaly. **C –** residual magnetic map.

open marine deposits (marlstones, spiculitic calcareous siltstones and calcareous sandstones) arranged into several upward coarsening sedimentary cycles are regarded to the Bílá Hora and Jizera formations of the Early and Late Turonian. Calcareous mudstones characterize hemipelagic deposits of the Teplice and Březno formations of the Late Turonian and Early Coniacian ages. The eastern part of the BCB involves morphotectonic structures (synclines and horsts) as well as hydrogeological units (Olmer et al. 2006): "Chrudim Cretaceous" (CHC), "Vysoké Mýto Syncline" (VMS), "Ústí Syncline" (US) and "Kyšperk Syncline" (KS) (Fig. 2A). In the west, the asymmetrical horst of the Vraclav Ridge (VR) separates the Chrudim Cretaceous and the Vysoké Mýto Syncline (VMS) units. In the east, this horst is limited by the Vanice Fault and Polička Fault (Fig. 2A), which represent the hydrogeological boundary between CHC and VMS. According to borehole data, the VMS forms a 20 km wide depression with the maximum estimated thickness of Cretaceous deposits of 330 m. In the central part of the VMS, the local Choceň Flexure is bounded by a fault reported by Soukup (1948) and Coubal (1989) in the west. In the east, the VMS is terminated by the asymmetrical horst of the Kozlov Ridge. The Kozlov Ridge (KR) separates the VMS in the west from the half-graben, formerly called Ústí Syncline (US) in the east. The prominent Semanín

Fault Zone is situated on the steep eastern slope of the KR and forms a hydrogeological boundary between VMS and US (Fig. 2A). In the east, the relatively narrow depression of the NNW–SSE-elongated US is bounded by a marginal cuesta of Cenomanian and Turonian sandstones and marlstones and by Permian deposits.

Permian deposits of the Orlice Basin (Pešek et al. 2001) represent an exhumed core of the horst structure (formerly anticline) which separates Cretaceous sediments of the US in the west and the half-graben of the Kyšperk Syncline (KS) in the east. The eastern margin of this horst is limited by a reverse fault known as the Kyšperk Fault (Fig. 2A). The Cretaceous fill of the KS reaches 600 m in thickness.

As was documented by several boreholes, the axis of the US hosts a narrow valley deeply incised into the Cretaceous deposits (down to the Bílá Hora Formation) and in Permian deposits of the Orlice Basin, filled with Neogene marine sediments hundreds of meters thick.

The seismic research was situated between several principal crystalline units, the Hlinsko (HU) and Polička units (PU) in the west and the Zábřeh Unit (ZU) in the east (Fig. 2A). They are exposed in opposite limbs of a large synclinal structure of the eastern part of BCB, of the VMS and US. Their relevant regional classification and their mutual relationship gradually produced controversial views. The PU and ZU are two parts of a single geological unit situated in the NE part of the Bohemian Massif (e.g., Kodym and Svoboda 1950). In the classical concept of Mísař et al. (1983), the PU is a unit related to the Bohemicum (TBU) and the ZU is related to the Lugicum (Fig. 1). Buriánek et al. (2003) inclined to the opinion of Mísař and Dudek (1993) that all these units belong to the Bohemicum (TBU). Cháb et al. (2008) related both units with the Lugicum, including the HU (Hlinsko–Skuteč Unit in their concept). Buriánek and Pertoldová (2009) pointed out the lithological similarity of the low-grade metamorphosed rocks between the HU, PU and ZU. Many papers have been recently published containing detailed characteristics, a comparison from different aspects, and the regional position of these units (Buriánek et al. 2003; Buriánek and Pertoldová 2009; Verner et al. 2009; Pertoldová et al. 2010; Žák et al. 2014).

Variscan intrusions of the Budislav pluton (Fig. 2A), concordant with the NNW–SSE-elongated outcropping part of the PU, have been described in detail by Buriánek et al. (2003) and Buriánek (2010). In addition, another plutonic body situated along the HU boundary at a tectonic contact with the HU – the Miřetín pluton – has become the subject of study of Vondrovic et al. (2011).

The Letovice Unit (LU) exposed S of the VMS and US (Fig. 2A) was associated with the Svitavy Unit (Cháb at al. 2008), previously known as the Svitavy gravity and magnetic anomaly (Čuta et al. 1964; Mátl 1969; Mottlová 1985). The Svitavy Unit (SA) is knowns only from the geophysical survey and borehole HSV-1 (803.6 m) near Svitavy (Kopecký jr. 1992). It was accepted as the border between the Bohemicum (TBU) and Lugicum (Mísař et al. 1983; Kopecký Jr 1992).

The complex LU represents an oceanic relic according to Mísař et al. (1983), Höck et al. (1997), and Finger et al. (1998). This was confirmed by Soejono et al. (2010) based on whole-rock geochemistry and Nd isotopic signatures. However, it was probably only an incipient oceanic basin developing on the attenuated continental crust (Soejono et al. 2010). Such setting corresponds to other contemporaneous metabasic complexes in the western Bohemian Massif, such as the Mariánské Lázně Complex (Bowes and Aftalion 1991; Timmermann et al. 2004). Metabasic complexes distributed along the eastern margin of the Bohemian Massif were interpreted as relics marking possible remnants of the Rheic Ocean (Finger and Steyrer 1995; Finger et al. 1998; Linnemann et al. 2008).

The uncovered map of the crystalline basement of the study area was printed within the edition of structural geological maps at scale 1 : 200 000 ("Sheet 14 Šumperk"; Kumpera and Blažek 1987). Subsequently, the map of the basement 1 : 200 000 for the western part of the study area was attached to an unpublished summary manuscript report of the Diamo Company (Rutšek et al. 1995). Since then, only a few boreholes contributing significantly to the knowledge of the crystalline basement have been drilled.

3. Methodology

3.1. Seismic survey

Regional seismic reflection profile RBSP/2011 (consisting of parts A, B and C) traverses the eastern part of the BCB in the direction W–E (Fig. 2). The acquisition and processing of 2D seismic reflection data from this profile were contracted to Geophysik GGD mbH. The profile stretches across a 55 km line from the village of Domoradice near Vysoke Mýto in the west to Tatenice near Lanškroun in the east.

Individual steps were made within the seismic works: permit, geodetic survey, short refractions, seismic reflection survey, ppv (peak particle velocity) measurements, field data control and processing. Test altitude measurements were taken at selected trigonometric points of the official geodetic network of the Czech Republic. Data from the individual profiles A, B and C were obtained using one seismic vibrator of type *IVI EnviroVibe*. The maximum force of this vibrator is 66 kN. The vibrator was controlled by a *SeismicSource Force II / Universal Encoder* (version 2) electronic system. The number (2) and length (12 s) of the vibrator signal (sweep) per source location was defined in the contract; the frequency range was 14–120 Hz (linear). The sweep frequencies and types were tested before the onset of acquisition to obtain optimum values. The energy source used for the acquisition of the high-resolution profiles of the detailed survey was an accelerated weight drop *BISON EWG-III*. This heavy hammer generates output energy of 9.8 kN·m. Two to four hammer drops were done per source point, depending on the ambient noise level.

2D seismic reflection data at profiles A, B and C were collected with an active geophone (digital single geophones 10 Hz) spread of up to 240 channels for each source point nominal fold (60). The source point distance was 20 m and the step of registration 10 m.

The observer monitored the quality of collected data on the screen in the recording car. Additionally, field processing was performed in the crew office, including the check for correct geometry. The first result of the field processing was a brute stack. Fifty-eight short refraction measurements were performed to determine the thickness of the near-surface layer and its particularly low seismic velocity (low-velocity layer, LVL).

Seismic data processing was performed using ProMAX 2D (Landmark Graphics Corporation, USA) on a Linux server. The final objective was to enhance seismic resolution and to achieve an optimum image of the geological structure. For static corrections of data, a one-layer refraction static solution was calculated, including the results of the short refraction measurements. Smoothing of the refractor velocities was performed before the calculation of the refractor depths with the diminishing residual matrices method. Refraction statics were calculated for each profile individually. Variable replacement velocities derived from the refractor velocity and the last datum of 250 m a. s. l. were used.

In the first step, seismic reflection data were processed to two-way travel time without depth conversion. The conversion to depth was realized by the Seismic Data Processing Centre of Moravian Petroleum Mines (MND Group Companies) by seismic system Geocloster (CGG Veritas) using a velocity model describing the spatial distribution of velocities. Knowledge of seismic wave velocities in the rocks is needed for depth conversion. A check-up of the conversion was applied at the intersections of the profiles.

For the interpretation of profiles, the methodology of the seismic stratigraphy was used (Vail et al. 1977; Van Wagoner et al. 1988). The seismic reflections generating along surfaces of unconformity, which represented hiatuses in the deposition of sediments, were correlated with the lithostratigraphy and lithology of the Cretaceous deposits in Eastern Bohemia (Fig. 3).

3.2. Well logging

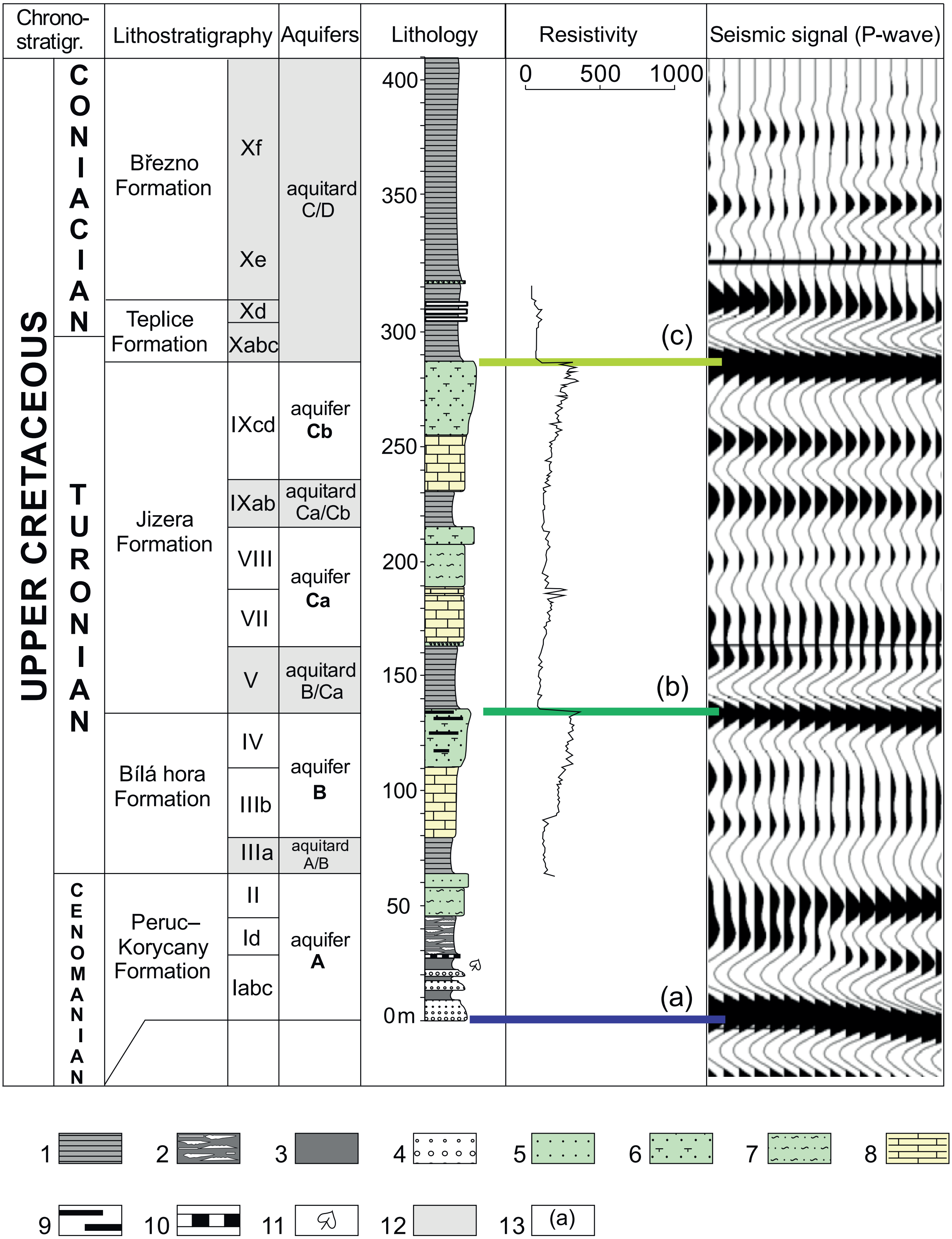
The distribution of P- and S-wave velocities in Cretaceous deposits and basement rocks was obtained from acoustic and seismic well logging in 6 boreholes near seismic profiles. The borehole-geophysical acoustic technique was used to measure the travel time of elastic waves through the individual strata. The full wave-form sonic tool registered acoustic signal on three receivers with a depth interval of 5 cm. The correlation analysis and processing by the WellCAD software of all signals enabled the determination of the time of the first arrival, the velocities of the P and S waves, and the Poisson's Ratio. Acoustic well-logging was realized in 2 new boreholes, 4270_07W Vanice and 4232_A Vítějeves, by the Geotest company. Seismic well-logging determined the velocity using two geophones in the borehole and a source point at the collar of a borehole. The measurements were undertaken in the boreholes 4270_02B Janov, 4270_03B Radhošť, 4231_01B Dolní Libchavy and 4270_06A Lubná by the SIHAYA company.

3.3. Gravity modeling

The gravity modeling method enables the test of the conformity between the calculated gravity response of modeled bodies (interpreted in a vertical geological cross-section based on seismic reflection survey) and the gravity effect of the ground measurements. The gravity data were acquired by a detailed gravity survey at a scale 1 : 25 000 (Sedlák et al. 2015). The gravity 2.5D model was verified at all seismic profiles (A, B and C) by using Geosoft software. Results of the laboratory rock density measurements and data from boreholes (situated near the cross-section line) were respected to minimize the risk of non-realistic models.

3.4. Laboratory measurements

Moreover, P-wave velocities of the crystalline rocks and sediments were measured on drill-core samples and samples from outcrops (unpublished technical reports of the project). Laboratory measurements of the physical properties (density, porosity and seismic velocities) were taken to interpret seismic and gravity surveys. The samples were taken from rocks on the surface and from drill cores which represent the rock background in the study area. Rock porosity, bulk and grain densities were measured using three weighings by the GEORADIS company. The velocity was determined by the ARENAL com-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Lithostratigraphy
Aquifers
Lithology
Resistivity
Seismic signal (P-wave)
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TURONIAN
CENOMANIAN
Březno Formation
Teplice Formation
Jizera Formation
Bílá hora Formation
Peruc–Korycany Formation
Xf
Xe
Xd
Xabc
IXcd
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V
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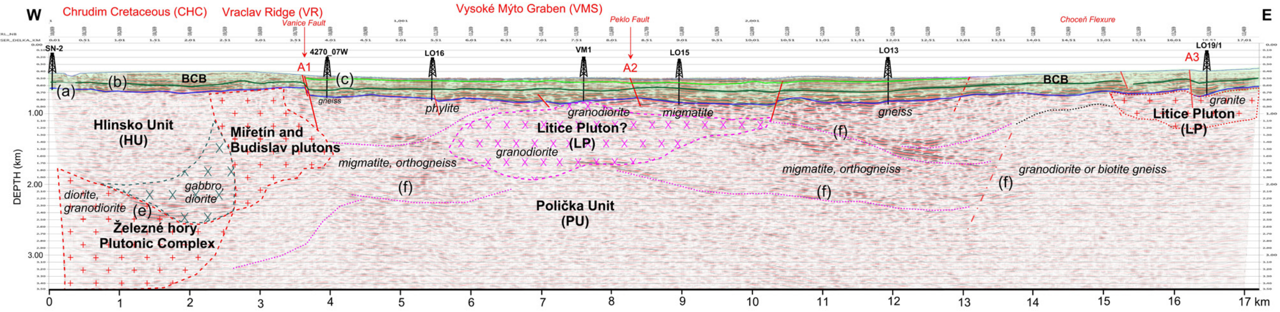

Fig. 4 A 2D gravity model along profile RBSP/2011, part A (D – density used in model).

pany using a sonic method generally used to determine anisotropy in rocks (Pros et al. 1998; Brož et al. 2009).

3.5. Geological data

All archive borehole data, as well as geological maps 1 : 50 000, were used for geological interpretation. Only a few rock samples and thin sections of magmatic and metamorphic rocks of the original drill core were available for research. Four new boreholes have been drilled down to the crystalline basement within the project "Review of groundwater resources in the Czech Republic" in eastern Bohemia.

4. Results and interpretation

The new seismic reflection survey results, gravity modeling and geological data (boreholes, geological mapping) enabled the interpretation of the thickness of sedimentary fill in the individual Cretaceous grabens and, eventually, indicated fault systems and deformation patterns in the pre-Cretaceous basement.

4.1. 2D gravity model

The gravity modeling aimed to support the seismic results. The initial gravity model was constructed based on the seismic depth cross-section with the supposed geological interpretation. The final gravity models at profiles A and C (Figs. 4 and 5 D = used rock density in the model) respect the gravity field as well as seismic reflectors.

The western part of the study area (central part on profile A) is characterized by low gravity, caused by the low densities of granitic rocks (Fig. 4). Towards the east, gravity increases to reach the maximum of the "Svitavy gravity high" on profile C (Fig. 5), representing high-density ultramafic rocks. On the eastern edge of this anomaly, sediments of the Orlice Basin likely contribute to the gravity minimum. High-density metamorphic rocks cause the subsequent increase in gravity towards the end of profile C. The central part of the "Svitavy gravity high" shows distinct narrow local negative anomaly coinciding with the young paleovalley filled with sediments several tens to hundreds of meters thick. At the end of profile C, the mafic rocks are the source of the gravity high. The gravity model on profile B is not presented in this article. The monotonous trend of the increasing gravity values to the SSE is shown in the data, most probably the effect of the "Svitavy gravity high".

4.2. Seismic interpretation

Seismic data provided valuable information for structural interpretation of the sedimentary basins (Neogene, Cretaceous, Permian) and also the crystalline basement. The Cretaceous synclines and horst structure of the Vysoké Mýto, Ústí and Kyšperk is documented by an interruption of the reflector (a) representing top of the crystalline basement or top of Permian sediments (d). A large number of reflections were recorded in crystalline rocks at a depth of more than 0.5 km. In some favorable cases, important shear zones and granitic bodies can be identified in the crystalline basement. The seismic profiles transect the supposed contact between the TBU and the Lugicum. High-amplitude reflectors possibly indicate thrust sheets in the basement, especially the shear zone of thrusting on the western margin of profile A.

4.2.1. Profile A

Profile A 17.3 km in length (Fig. 6) transects two Cretaceous morphostructures: the "Chrudim Cretaceous" (between boreholes SN-2 and 4270_07W, see Fig. 6) and

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Fig. 3 Lithostratigraphy, lithology, hydrogeological units of the Cretaceous deposits in Eastern Bohemia and correlation with the resistivity log and reflection seismic data. 1 – calcareous claystone and marlstone; 2 – estuarine heterolithic facies; 3 – organic-rich claystone; 4 – quartz sandstone and conglomerate; 5 – glauconitic quartz sandstone; 6 – glauconitic carbonate sandstone; 7 – glauconitic clayey sandstones; 8 – spiculitic marlstone („opuka"); 9 – chert; 10 – coal seam; 11 – fossil flora; 12 – hydrogeological insulator; 13 – reflector.

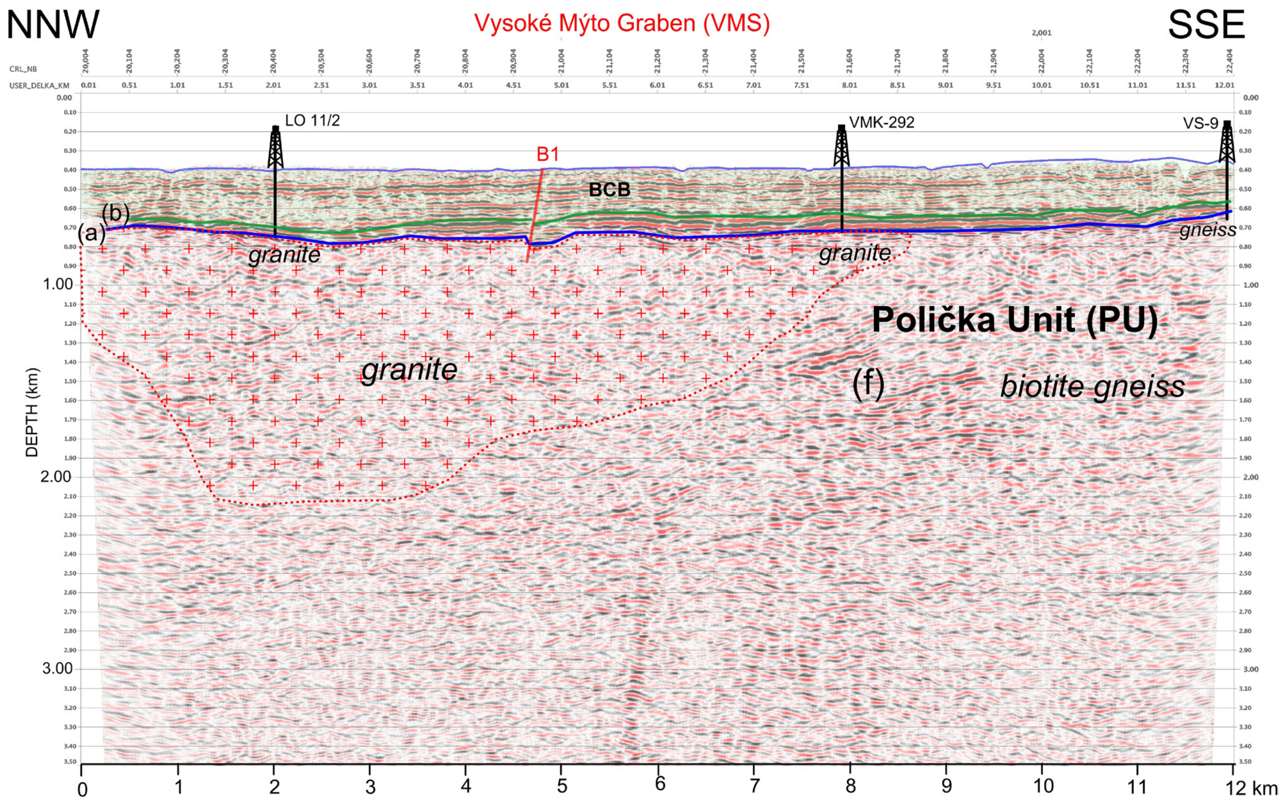

Fig. 5 A 2D gravity model along profile RBSP/2011, part C (D – density used in model).

the VMS (between boreholes 4270_07W and Lo-19) in the W–E direction (Fig. 2A). Three prominent reflectors (a, b and c) can be recognized in the Cretaceous deposits of the CHC and VMS (Fig. 3). Reflectors (a) and (b) are continuous across the whole profile A, and reflector (c) is present only in the central part of the VMS. The course of the reflectors in the Cretaceous deposits is nearly subhorizontal, except the eastern part of profile A where the reflectors gently dip to the central part of the VMS. According to boreholes, Cenomanian deposits are missing along whole profile A (or reduced to bodies having only a few metres in thickness) due to a pre-Cenomanian paleo-elevation in this part of the BCB. This means that reflector (a) corresponds to the top of the crystalline basement and also the base of Lower Turonian marlstones of the Bílá Hora Formation. Reflector (b) indicates the top of the sandstones (aquifer B) of the Bílá Hora Fm. Reflector (c) marks the top of calcareous sandstones of the Middle–Upper Turonian Jizera Fm. (aquifer C). Reflector (c) becomes less prominent in the westernmost

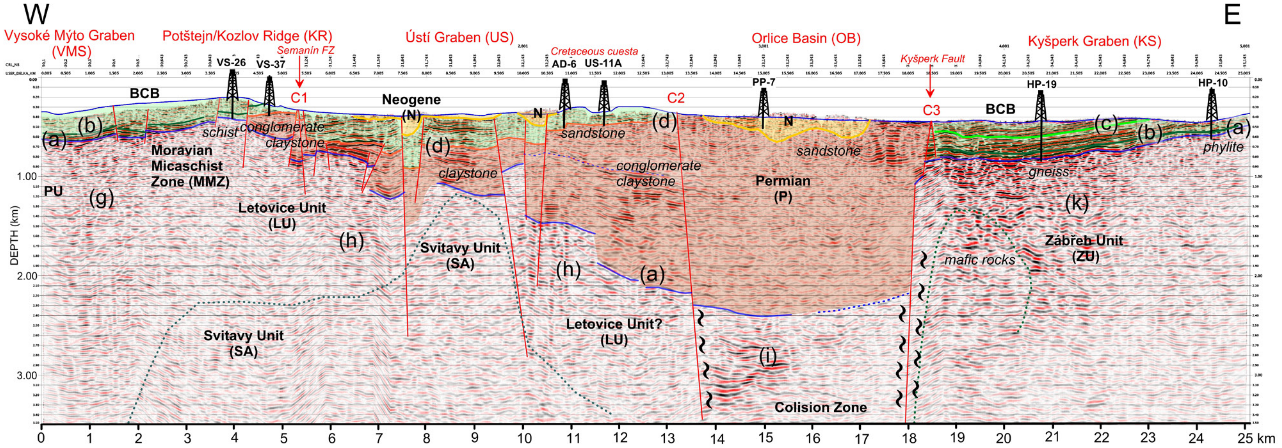

Fig. 6. A depth-converted seismic cross-section with geological interpretation along the profile RBSP/2011, part A (a, b, c, e, f, – individual reflectors described in the text).

part of profile A (at borehole SN-2) due to a change of regional facies from calcareous sandstones to marlstones. The deposits above reflector (c) belong to mudstones of the Teplice and Březno formations (Upper Turonian to Coniacian). These mudstones fill the central part of the VMS (Fig. 2A).

In the western part of profile A (between boreholes SN-2 and 4270_04W), a part of a horst structure is developed, monoclinally dipping to the north. Inclined reflections between 3.5 km and 4 km of the profile are observed at 180 to 50 m a. s. l. This steep slope corresponds to the Vanice Fault (A1 on Fig. 6) of the N–S direction which was found on the surface (Fig. 2A). A detailed geophysical survey at Vanice revealed that this fault consists of at least two parallel faults and probably forms a "flower structure" of the sinistral shear zone (Burda and Grundloch, eds. 2020b). This fault is associated with the so-called Malejov Flexure (a forced fold) dipping ca. 35° to the E, as described by Soukup (Svoboda ed. 1962) from surface outcrops north of profile A. Along the fault, sandstones of the Jizera Fm. are in contact with mudstones of the Teplice and Březno formations. The supposed vertical displacement along this fault is 120 m. This is the difference between the top of the Jizera Fm (reflector c) on the surface of the Vraclav Ridge (profile length 3.5 km) and in borehole 4270_07W Vanice (Fig. 6). The fault forms a boundary between hydrogeological units of the CHC and the VMS.

Prominent reflectors show subhorizontal dips of Cretaceous strata in the central part of the VMS filled with the youngest deposits of the Teplice and Březno fms. Borehole Lo-15 is situated in a small graben (Fig. 6) which is bounded by the Peklo Fault (A2) in the west at position 8.5 km on the profile. This fault, also recognized in geological map 1 : 50 000 (Čech ed. 1996), plays a prime role in the hydrogeology of this area.

Supposed fault on the geological map 1 : 50 000 (Čech ed. 1996) located near the borehole Lo-13 (at the position 13.0–13.5 km on Fig. 6) is not visible in profile A as well as inclined Cretaceous strata of so-called Choceň Flexure. But this fault is marked by a series of springs on the surface. It is also indicated by a detailed geoelectric survey at the Vračovice locality, where a prominent boundary separates low-resistivity mudstones in the west from high-resistivity calcareous sandstones in the east (see Fig. 4–20 in Burda and Grundloch 2020b).

Based on interrupted reflectors (a) and (b), two reverse faults (A3) are interpreted at the position 16.2 km and at the location of borehole Lo-19/1 associated with narrow graben/or half-graben (Fig. 6).

In the basement, the seismic profile transects beneath Cretaceous sediments the TBU (Fig. 1). In the west, the seismic profile shows less conspicuous, flat reflections at a depth of 1 km. Nevertheless, at a depth of 2 to 2.5 km the strong reflection (e) is registered, which represents probably folded structure. This deeper structure, characterized by high reflectivity, can be interpreted as a shear zone indicated by the mylonitic rocks along a thrust fault. According to gravity modeling (Fig. 4), the upper layer with horizontal reflections and relatively high densities represent the Upper Proterozoic and Lower Paleozoic low-grade metamorphosed rocks of the HU. The mafic igneous rocks (granodiorite, diorite and gabbro) are located under them. The HU continues from the outcrop area to the Vysoké Mýto area and farther to the north, according to borehole data. The gravity high (near Zámrsk; after Sedlák et al. 2015) and magnetic anomaly near Vysoké Mýto (Fig. 2B and 2C) reflects basic rocks (diorite, gabbro) probably deeply lying at the contact between the HU and the PU. The character of seismic reflections changes near the Vraclav Ridge (Fig. 6). Many easterly dipping reflections (f) can likely represent a deformation zone beneath VMS (Fig. 6), probably folded structures in the metamorphic crystalline complex. The crystalline basement in the remaining part of seismic profile A represents a complex rock suite of the PU. According to boreholes (VM-1, Lo-10, Lo-5, Po-30), weak reflected energy indicates intrusive granitic rocks in the central and eastern parts of the seismic profile. Their position has been published in previous maps (Chaloupský 1973, 1974; Kumpera and Blažek 1987). The complete absence of reflectivity characteristic of plutons was not registered, probably because the granitoids are weakly deformed and seismic energy generates short and low-amplitude reflections. The eastern part of seismic profile A (13–17 km) transects the faulted limb of the Choceň Flexure, limiting the VMS in the east. According to gravity data, a local high-gravity anomaly occurs in this area near Voděrady (Fig. 2B and 4). It is explained by the presence of high-density rocks. Dolerites would induce a high anomaly in the magnetic field, but such anomaly is missing here (Fig. 2C). The gravity anomaly maybe thus caused by various sources (high-density rocks): granodiorite or biotite gneiss (Fig. 6). The gravity low at the end of the profile indicates granitic rocks of the supposed Litice (LP) pluton in the basement of the Choceň Flexure, which continues farther to the south.

4.2.2. Profile B

Profile B 12 km in length is orientated N–S between the termination of profile A and the onset of profile C, and it is situated on the eastern flank of the VMS (Fig. 2A). Cretaceous strata lie relatively flat on the basement and reach a thickness of about 250–400 m (Fig. 7). Reflector (a) represents the top of the crystalline basement and reflector (b) represents the top of calcareous sandstones of the Bílá Hora Fm. Hydrogeological aquifers of the two

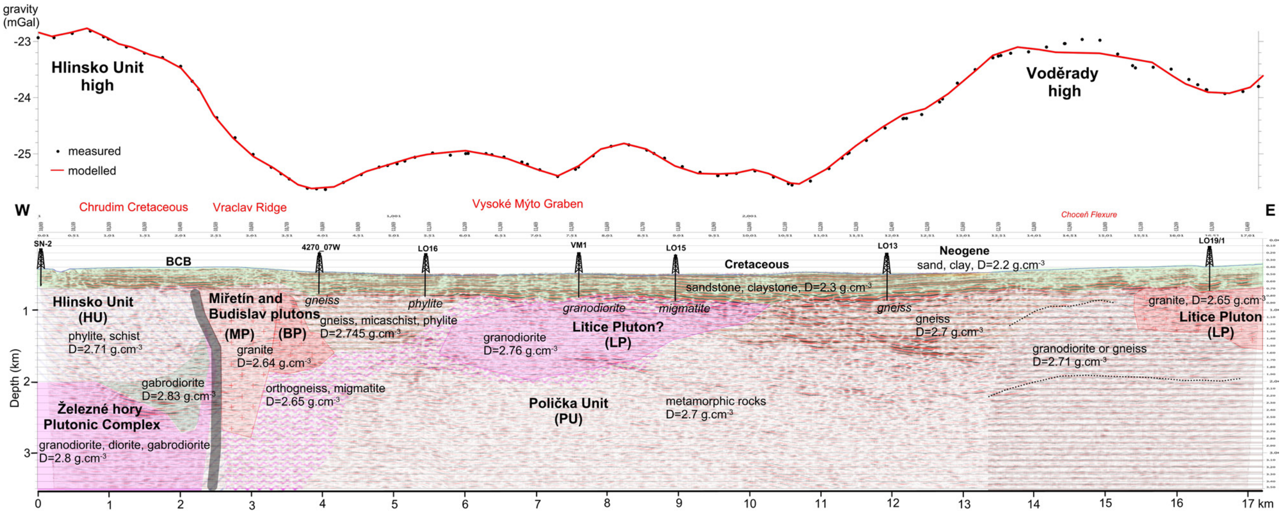

Fig. 7 A depth-converted seismic cross-section with geological interpretation along the profile RBSP/2011, part B (a, b, f, – individual reflectors described in the text).

synclines are probably connected along a fault interpreted at 4.6 km (B1). Cenomanian deposits overlie crystalline basement, reaching a thickness of maximally 20 m in the eastern part of profile B (boreholes VMK-292 and VS-9).

Granitoids of the Choceň Flexure (boreholes Lo-11, Lo-19, Lo-12) form most of the basement in profile B. In its southern part, horizontal or gently dipping reflections to the north (f) indicate a thrust fault in the metamorphic complex, probably gneisses of the PU. In the central part of the profile, granitic rocks are characterized by reduced reflectivity. At the end of the profile, elevated gravity indicates high-density rocks in the basement and the effect of the Svitavy gravity high (Fig. 2B).

4.2.3. Profile C

Profile C 25.1 km in length transects, from the west to the east, the following morphostructures: the KR, US, Permian Orlice Basin and the KS (Fig. 2A). Cretaceous and Permian deposits give a strong seismic response at the beginning and the end of the profile (Fig. 8). The seismic image allows discerning the sediments base (a) and boundaries between Cretaceous strata (b, c) or top of the Permian deposits (d). The basement reflector indicates that the whole area was affected by an extensive tectonic event. Some normal and reverse faults are well visible down to a depth of 1 km. Faults are not frequent at the end of the profile, and the top of the buried crystalline surface slowly and continuously rises. The gentle westerly dips of the reflectors at the beginning of the profile (g) likely represent a banding and schistosity zone. Deformations in the western part of the profile are characterized by subhorizontal reflectors (h) dipping to the east in the central part of the profile. Between 13 km and 18 km of the profile, strong reflections were registered at a depth of about 2 km, representing the crystalline basement. A deeper set of reflections (k) dipping to the west in the eastern part of the profile probably represents a deformed zone in the basement.

On the west, the morphologically prominent KR is now geologically interpreted as a horst (or pop-up structure) (Burda and Grundloch eds. 2020a, b). The topographically highest position of the horst of the KR is the area with boreholes VS-26 and VS-37. The horst separates the VMS from the US, and it also terminates Permian deposits of the Orlice Basin (Fig.8). Here, Cenomanian deposits form a broad riverine and estuarine drainage system with a maximum thickness of 30–60 m. Cenomanian deposits are exposed on the eastern slope of the KR at ca. 5.3 km of the profile. Here, Cenomanian and Lower Turonian deposits are cut by several parallel faults, which comprise the narrow Semanín Fault Zone at 5.3–5.5 km (C1). The fault zone is also recorded in the surface geological map 1 : 50 000 (Adamovič et al. 1996). Cretaceous strata are rather steeply inclined (30–40°) in this zone, and the Cenomanian–Middle Turonian deposits of the KR are at contact with Lower–Middle Coniacian mudstones of the US on the surface. Vertical displacement along the faults is ca. 300 m.

The US is a flat morphostructure except for its eastern part (Fig. 8). It is limited by the Semanín Fault Zone in the west and by an unnamed fault (C2) at the cuesta of Cretaceous rocks in the east, at 13.0–13.5 km of the profile. In the US, reflector (a) is interpreted as the base of Permian deposits or the top of the crystalline basement. An unlabelled orange line marks the base of Cretaceous deposits in Fig. 8. The unconformity between inclined Permian deposits and subhorizontal Cretaceous deposits is visible at position 5.5–7.0 km of profile C (see Fig. 8). The US is filled with Cenomanian–Turonian sandstones, marlstones, and Coniacian mudstones up to 300 m thick. It seems that several faults cut the US. However, reflectors in Cretaceous fill are indistinct in the eastern part of

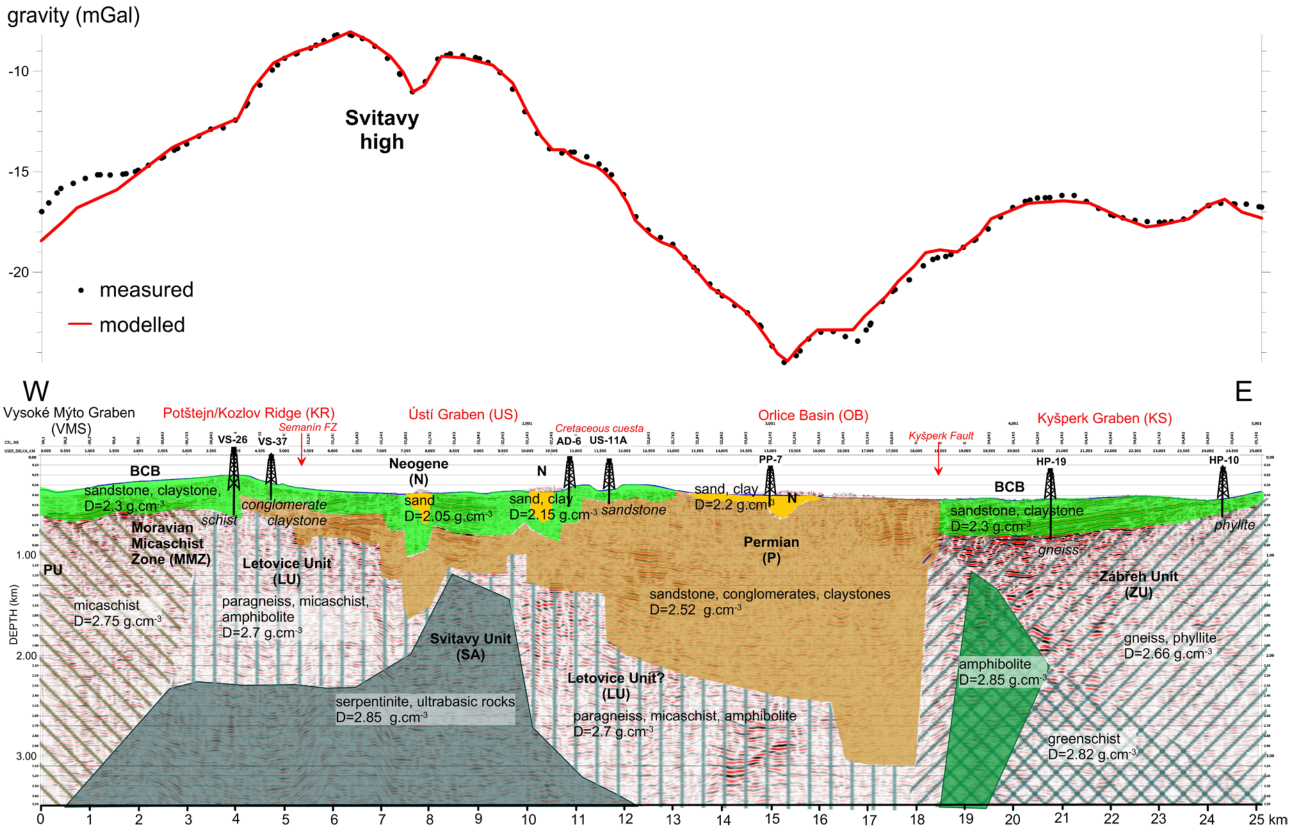

Fig. 8 A depth-converted seismic cross-section with geological interpretation along the profile RBSP/2011, part C (a, b, c, d, g, h, i, k – individual reflectors described in the text).

the US. This, and the lack of deep boreholes, makes the interpretation of the geological setting difficult in this part of the profile.

The subhorizontal reflections of Cretaceous strata are interrupted in areas where Neogene sediments are mapped on the land surface. We interpret these interruptions as narrow paleovalleys deeply incised into Cretaceous mudstones and calcareous sandstones of the Jizera and Bílá Hora Fms. They are filled by Neogene (Lower Badenian) marine and fluvial mudstones and sandstones. According to gravity data (gravity low, see Fig. 2B), a paleovalley forms a broad meander in the US (Česká Třebová–Semanín–Opatov–Damníkov–Trpík), transected by profile C (Fig. 8).

The base of Cretaceous deposits in the KS (now geologically interpreted as a half-graben structure) is marked by a prominent reflector (a). Reflectors (a, b and c) show a monoclinal westerly dip of 3–6°. The Kyšperk Fault (partly reverse fault) limits the KS in the west at 18.5 km (C3) of the profile (Fig. 8). The maximum vertical displacement along the Kyšperk Fault is probably 650 m (Herčík et al. 1999). Recently, tectonic analyses of the Kyšperk Fault are missing.

Permian deposits in the whole range of the Orlice Basin are transected by profile C between the KR in the west and the Kyšperk Fault in the east. The thickness of the deposits along the profile may reach 2 km (south of Lanškroun). None of the boreholes reached the crystalline basement. Previous seismic refraction survey (Hrách 1970) supposed the crystalline basement in-depth more than 1.7 km on the basis of the velocities alone. The detected velocity P-wave at a depth of 1.7 km (4.1 km·s^{-1}) corresponded to the velocity of sedimentary rocks (sandstone, arkose). Based on the new seismic reflection profile and gravity modeling, the thickness of the Permian deposits is calculated at about 2.7 km. Of course, the results of the gravity modeling can be ambiguous because two unknowns are used – the thickness of the Permian deposits and the density of the rocks in the crystalline basement. The seismic image shows strong multiple reflections (i) at a depth of 2.7–3.2 km (1400 ms on the time section), which can be a seismic response of highly reflective interfaces (probably ultramafic body).

In the crystalline basement, the seismic profile transects several major lithotectonic units of the Bohemian Massif (Fig. 8). The starting point of profile C lies on the eastern margin of the VMS and, like in profile B, the basement is formed by gneisses of the PU. To the east, low-grade metamorphic rocks (schist and greenschist) and sporadically diorite were documented from boreholes in the basement. Schistosity is indicated by numerous reflections (g). Father east Cretaceous deposits are underlain by Permian rocks and, beneath them, by ultramafic rocks manifesting

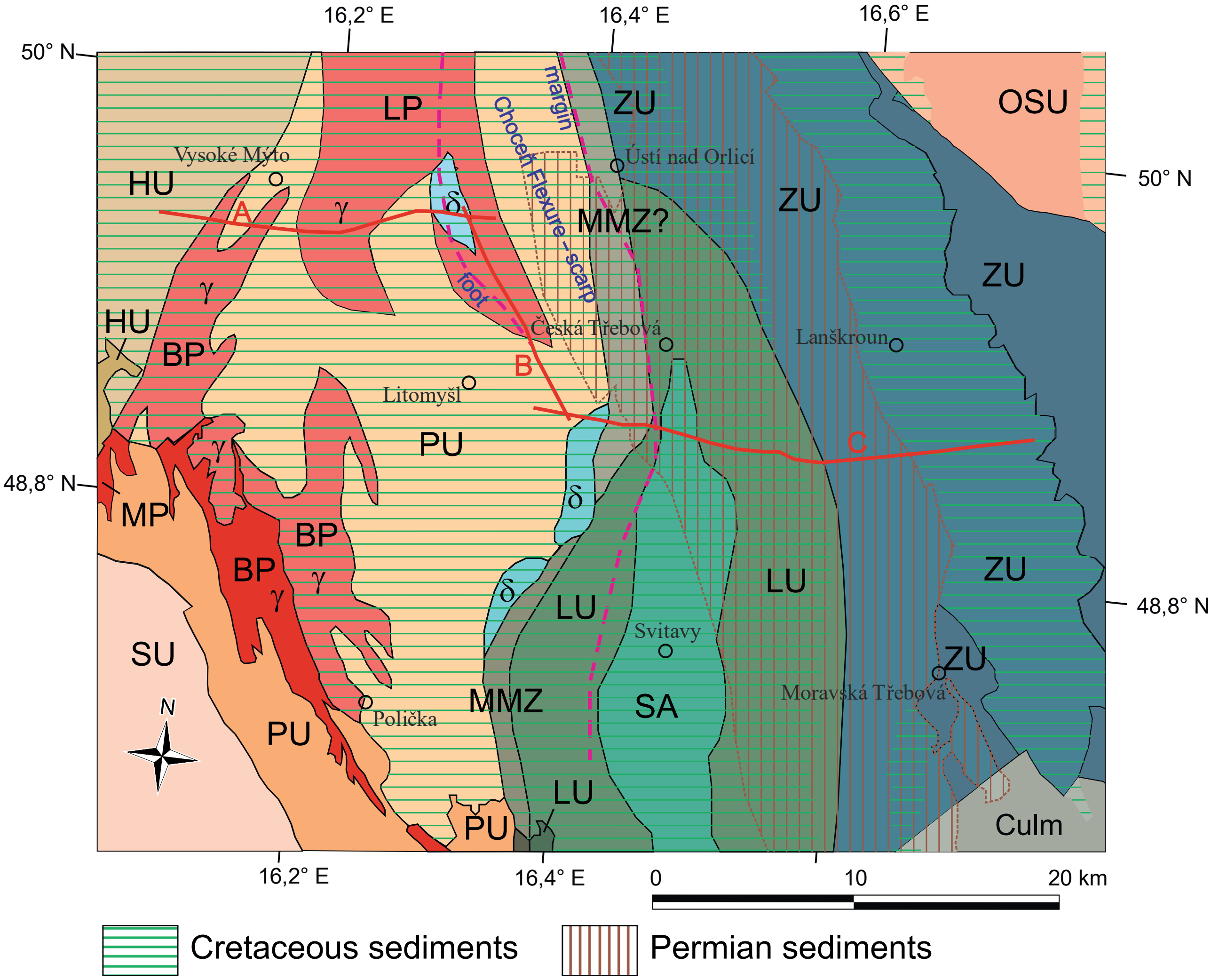

Fig. 9 Interpretation of the geological structure of the crystalline basement below the eastern part of the Bohemian Cretaceous Basin. Legend: SU – Svratka Unit, PU – Polička Unit, MP – Miřetín Pluton, BP – Budislav Pluton, HU – Hlinsko Unit, LP – Litice pluton, δ – presumed dioritic bodies, MMZ – Moravian Micashist Zone, LU – Letovice Unit, SA – Svitavy Ultrabasic Unit, ZU – Zábřeh Unit, OSU – Orlice–Sněžník Unit. Brown vertical raster – the extension of the Permian sediments, green horizontal raster – extension of the Cretaceous sediments, violet dashed line – margin on foot of the Choceň flexure-scarp, red line A, B, C – seismic profile.

as the gravity high (Fig. 5). It is surrounded by metamorphic rock sequences corresponding with reflections (h) slightly dipping to the east. At the end of the profile C reflectors (k), dipping to the west, probably indicate bedding and schistosity of the metamorphic rocks of the ZU represent the basement beneath Cretaceous deposits of the KS. According to gravity and magnetic data (Fig. 2B, 2C), mafic rocks (amphibolite, amphibole-biotite tonalite, granodiorite) are arranged along a line NW–SE to N–S, transversal to the elongation of the ZU surface outcrop.

5. Geology of the crystalline basement

New geophysical research (seismic reflection data and gravity model) from the eastern part of the BCB combined with available borehole data, archive geophysical data (magnetic, seismic reflection surveys) and published geological and tectonic information allowed us to compile the uncovered geological map of the crystalline basement (Fig. 9). Five major units were newly redefined beneath the Cretaceous and Upper Palaeozoic deposits: Hlinsko (HU), Polička (PU), Letovice (LU), Svitavy (SA) and Zábřeh (ZU) and series of igneous intrusions.

In the southwest, outcrops of metamorphic rocks of the PU are elongated NNW–SSE. This unit probably includes gneisses occurring in boreholes and seismic profiles A, B, and the westernmost part of C. The PU is separated from HU by granitoids of the Miřetín pluton (MP), which is interconnected with the Budislav Pluton (BP) beneath Cretaceous deposits in the north. Their continuation as a single body beneath the Cretaceous deposits is indicated by continuous negative gravity (Zderaz anomaly; Sedlák et al. 2015). These granitoid plutons are considered syntectonic intrusions of Variscan age (Verner et al. 2009; Pertoldová et al. 2010). The BP (dated at 350 ± 5 Ma) intruded PU with the NW–SE direction (Vondrovic and Verner 2008). The granitoids MP are dated an age 348 ± 7Ma (Vondrovic and Verner 2008) respectively 346 ± 5Ma (Vondrovic et al. 2011). The MP intruded syntectonically into the NNW–SSE trending normal fault zone between PU and HU (Vondrovic et al. 2011).

In the central and eastern parts of the seismic profile A, beneath Cretaceous sediments of the VMS (Fig. 2A), the presence of intrusive granitic rocks is indicated by geophysical methods (seismic reflection and gravity surveys). In the north, granitoids merge into a single body (Fig. 9), as has been proved by borehole and gravity data (a gravity low near Choceň). These granitoids are unrelated to the Budislav and Miřetín intrusions further south as suggested by borehole and geophysical data (western part of profile A).

The PU is separated from the LU by a narrow belt of mylonitic rocks registered in the west part of profile C (Fig. 9). This may represent the northern part of the mylonite Svojanov Zone (Mísař et al. 1983) or the Moravian Mica-schist Zone (Soejono et al. 2017). After the interpretation of borehole data, it cannot be excluded that the MMZ with some small dioritic bodies extends farther to the north (as far as to Ústí nad Orlicí).

The presence of ultramafic rocks of the Svitavy Unit (SA) together with the LU and MMZ beneath Cretaceous (US) and Permian (OB) deposits is indicated only by geophysical data (Fig. 2B and 2C) and by structural borehole HSV-1, which reached serpentinitized pyroxenites. The SA (Fig. 9) is identical with a "Svitavy gravity high" (Mátl 1969; Mottlová 1985; Sedlák et al. 2015) and also positive magnetic anomaly. This strong regional anomaly between Letovice and Ústí nad Orlicí villages refers to ultramafic rocks of mantle origin (after Cháb et al. 2008) situated between the PU and ZU and separating different regional-geological units of the Bohemian Massif. A similar opinion was reflected by Mísař et al. (1983) and Kopecký jr. (1992). Mísař et al. (1983) and Cháb et al. (2008) assumed that the SA is a continuation of the LU (the Letovice–Roubanice Unit in their concept) beneath the Cretaceous deposits. The deep tectonic contact between the LU and the ZU is probably located beneath the Permian rocks of the Orlice Basin on the eastern part of profile C (Fig. 8).

The supposed existence of a subduction zone at the eastern margin of the Bohemian Massif was considered by some workers at an early stage of Variscan orogeny that culminated by continental collision (e.g., Suess 1912, 1926; Matte et al. 1990; Finger and Steyrer 1995; Konopásek et al. 2002; Finger et al. 2007; Žák et al. 2014). According to this assumption, the continuation of this collision zone to the north in the footwall of Cretaceous deposits separates the PU from the ZU, which is located on opposite sides of the supposed continental collision zone. However, this opinion does not exclude the idea that the ZU is separated from the PU by right-lateral strike-slip shearing (Pertoldová et al. 2010). This is somewhat complicated because granite intrusions with migmatites are found in the northern continuation of the PU around Potštejn (see Fig. 2A). They may represent a deeper level of the PU with different metamorphism. If so, there is no direct relationship with the ZU.

The MMZ represents a boundary between the Brunovistulian and Moldanubian domains of the Bohemian Massif (e.g., Schulmann et al. 2009; Soejono et al. 2010), referred to as the Moldanubian Thrust after Suess (1912). This collision zone between the Brunovistulian Domain and the Lugicum continues to the north as the Staré Město Suture Zone (e.g., Grygar and Vavro 1995; Don et al. 2004; Jastrzebski et al. 2015).

The ZU has a unique position between the southern and northern branches of this thrust zone. Tectonic deformation in the ZU corresponds to the early Variscan nappe shearing in the NNW and the late Variscan ENE–WSW to NE–SW transtension (Grygar and Vavro 1995). A comparison of granitoid geochemistry and ages considered the PU and ZU as the same unit falling within the TBU (Buriánek et al. 2003; Verner et al. 2009; Buriánek 2010; Pertoldová et al. 2010). The contrasting geophysical manifestations of these units were not discussed in these published reports. However, gravity and magnetic data indicate in the ZU the NNW–SSE to NW–SE direction of lithological and tectonic boundaries (Fig. 2B and 2C). A similar striking shear zone is between the Moravo-Silesian Zone and the Lugicum, e.g., to the east the Hoštejn shear zone (Grygar and Vavro 1995). Along the boundary of the ZU with the Orlica–Sněžník Unit (south of the Bušín Fault) in the north, the rocks are analogous with the rocks of the Staré Město Unit (Don et al. 2004). Geochemical characteristics of metabasites along this boundary of the Orlica–Sněžník Unit (in the ZU and the Nové Město Unit/TBU) point to the identical subduction zone activity (Ilnicki et al. 2019).

In the latest, brittle stage of Variscan orogeny, the half-graben of the supposed (from gravity and seismic data) Orlice Basin developed. Its NNW–SSE elongation is perpendicular to the axis of regional transtension.

6. Summary

This paper presents the results of the investigation into the geology of the eastern part of the Bohemian Cretaceous Basin using newly measured reflection seismic profile RBSP/2011, gravity modeling and reprocessed borehole data. A combination of seismic reflection and gravity data was used to obtain a 2D gravity model. The data allowed us to document both stratigraphy and tectonic setting of the Cretaceous basin and faults in the pre-Cretaceous basement.

The interpretation of the seismic depth cross-section yielded the thickness of Cretaceous deposits in the Vysoké Mýto Syncline, Ústí and Kyšperk fault-bounded grabens.

- The grabens in the study area have been previously interpreted as synclines. The term "syncline" is still in use in the present names of hydrogeological units. Reflectors in Cretaceous deposits clearly visualized the top of sandstones of the Bílá Hora Fm., the top of calcareous sandstones of the Middle–Upper Turonian Jizera Fm. In the westernmost part of the Vysoké Mýto Syncline, a facies change from calcareous sandstones to marlstones was detected.
- The Vanice Fault was localized on the western margin of the Vysoké Mýto Syncline. It has the character of a zone consisting of at least two parallel faults with a displacement magnitude of about 120 m in the basement surface.
- The Kozlov Ridge was verified between the Vysoké Mýto Syncline and Ústí graben. It also forms the western limit of the Permian Orlice Basin. On the eastern edge of the Kozlov Ridge, the most significant Semanín Fault Zone represents a vertical displacement of about 300 m.
- The Ústí and Kyšperk grabens are separated by the Permian Orlice Basin. Kyšperk Fault limits the Kyšperk Graben in the west. This fault also represents the eastern limitation of Permian deposits. In the east, the Kyšperk Graben is limited by sedimentary wedges on a margin of the Zábřeh Unit.

  Based on new seismic data, the Permian Orlice Basin represents probably half-graben up to 2.5 km deep. The highest thicknesses of the basin fill were detected on its eastern margin, along the Kyšperk Fault.

  The metamorphic rocks and the felsic and mafic igneous rocks were interpreted in the crystalline basement for each individual part of the profile. The major geological units were identified based on borehole data and the gravity model, and their petrology and geotectonic position were characterized. The seismic interpretation with the geological and area gravity and magnetic data were used for the compilation of the uncovered geological map.
- Seismic and gravity data allowed for a more precise limitation of granitic rocks in the basement. The Miřetín and Budislav plutons form a single body. Granitoids found at the intersection of profiles A and B are separated from this pluton to a depth of 3.5 km.
- A continuation of a narrow belt of mylonitic rocks was identified on the western margin of the Polička Unit based on the gravity model. Further south, this belt was described as underthrusting of the Moravicum beneath the Moldanubicum (*i.e.*, the Moravian Mica-Schist Zone after Suess). This zone with dioritic bodies can be extended to the north as far as to Ústí nad Orlicí as the mylonitic zone separating the PU (TBU) from the Letovice Unit (Brunovistulian Domain). In a regional view, the continuation of the boundary between the Bohemian Massif and the Brunovistulian Domain is represented by the Staré Město Suture Zone in the north. The Zábřeh Unit is wedged between the two, having a unique position in the tectonic pattern of this boundary.
- The significant geophysical anomaly (gravity and magnetic) of the Svitavy Unit lies in the center of the study area. It reflects the presence of ultramafic rocks of mantle origin along the collision zone between the Bohemian Massif and the Brunovistulian Domain. A ridge in the basement, represented by ultramafic rocks of the Svitavy Unit, was indicated beneath the graben formerly called Ústí Syncline.

  According to geophysical manifestation, the Letovice and Zábřeh units have similar physical properties (density, magnetic) to the Polička Unit. The relationships among the Letovice, Zábřeh and Svitavy units cannot be clearly defined based on current geological knowledge.

Acknowledgments. Seismic reflection data and gravity data were collected from 2013–2015 with funding provided by the Ministry of the Environment of the Czech Republic and interpretation of the tectonics and geology of the Bohemian Cretaceous Basin basement was performed within project No 310340. We wish to thank colleagues from Geophysik GGD Leipzig, G Impuls Prague, MND – Center for acquiring and numerical processing seismic data and Miligal s.r.o. Brno for measuring and processing gravity data within the project "Review of groundwater resources in the Czech Republic" led by the Czech Geological Survey. The authors especially thank Assoc. Prof. Ing. R.Grygar, CSc. for professional discussion on the topic and Mgr. J. Adamovič, CSc. for the language correction. Thanks to the reviewers for their helpful comments.

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