# Test of the maximum penetration depth of the Roteg GPR above the Hranice Abyss and in the Moravian Karst

## Test maximální hloubky penetrace georadaru Roteg nad Hranickou propastí a v Moravském krasu

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***Abstract***

*A new kind of Ground Penetrating Radar (GPR), "Roteg", was tested at generally known speleological sites in the Czech Republic. The first examined site – the Hranice Abyss located near the town Hranice – is the deepest underwater cave in the world.*

*This GPR is characterised by much higher pulse power, antennas with rather high voltage (5–15 kV), and, in particular, the special design of the pulse generator.*

*The radar survey near the Hranice Abyss has shown that it is possible to detect reflections of electromagnetic pulses coming from the speleogenic structures of the abyss itself and from lithological boundaries occurring below the water table – something which was not anticipated and was verified for the first time ever. Plausibly detectable reflections were detected from the depths of 580 m below the surface – which is approximately 515 m below the water level – using the longest available 6-metre antennas tuned to the frequency of 25 MHz.*

*The second site tested was the quarry of Malá Dohoda near the municipality of Holštejn, the Moravian Karst, the Czech Republic. The GPR used was the same as above except the power output to the transmitting antenna which produced pulses of 20 kV. The radarogram showed cavities located at the depth of up to 300 m, the layers on the boundary between Lažánky and Vilémovice members of limestone at the depth of 400 m, basement sandstones and conglomerates at the depth of 600–700 m, and granite rocks below this level.*

*Both of the tests mentioned above confirmed the extraordinary big penetration depth of the GPR signal which exceeded 500 m when using the maximum power on transmitting antennas.*

***Abstrakt***

*Na známých speleologických lokalitách v České republice byl testován nový druh georadaru (GPR), „Roteg". První zkoumaná lokalita – Hranická propast u Hranic – je nejhlubší podvodní jeskyní na světě.*

*Tento georadar se vyznačuje mnohem vyšším pulzním výkonem než běžné georadary, velmi vysokým napětím (5–15 kV) na vysílací anténě a zejména speciální konstrukcí generátoru impulzů.*

*Radarový průzkum poblíž Hranické propasti ukázal, že je možné detekovat odrazy elektromagnetických pulzů přicházejících od jeskynních struktur samotné propasti a od litologických hranic vyskytujících se pod hladinou podzemní vody, tedy něco, co se vůbec nepředpokládalo a bylo takto poprvé in-situ ověřeno. Věrohodné odrazy byly detekovány až z hloubek 580 m pod povrchem, což je přibližně 515 m pod hladinou vody, a to za pomocí nejdelších dostupných 6 metrových antén, naladěných na frekvenci 25 MHz.*

*Druhým testovaným místem byl lom Malá Dohoda u obce Holštejn v Moravském krase. Použitý georadar byl stejný jako v předchozím případě, s výjimkou výstupu generátoru pulzů, který generoval impulsy o napětí až 20 kV na vysílací anténě. Na radarogramu byly patrné odrazy signálu od dutin ve vápencích v hloubkách až 300 m, od litologických rozhraní mezi Lažáneckými a Vilémovickými vápenci v hloubce 400 m, bazálními pískovci*

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*a slepenci v hloubce 600–700 m a žulami (Brněnská vyvřelina) pod touto úrovní.*
*Oba výše uvedené testy potvrdily mimořádně velký hloubkový dosah georadaru „Roteg“, který byl při použití maximálního výkonu vysílacích antén v krasových oblastech větší než 500 m.*

## Introduction

The Ground Penetrating Radar (GPR) measurement is one of most effective geophysical measurements in the field. GPR is based on the transmission of high frequency pulses by one antenna and on receiving the reflections of those pulses by another antenna. A delay **t** of the reflections is proportional to the depth **d** of the interface of materials with different permittivities ($\varepsilon_1$, $\varepsilon_2$) that reflects the pulses and indirectly proportional to the velocity **v** following the relationship of t=2d/v. The velocity **v** depends on the permittivity $\varepsilon_1$ of the material following the relationship of $v=c/\sqrt{\varepsilon_r}$, where c is speed of light and $\varepsilon_r$ is relative permittivity. Limestone has relative permittivity of 2.0–2.5 and typical velocity of 12–14 cm/ns. Fresh water has relative permittivity of 9–10 and typical velocity of 3 cm/ns (Annan 2005). Therefore, wet limestone with the porosity of 5% has the velocity of 10–12 cm/ns. The amplitude of reflections is proportional to the ratio of permittivities $\varepsilon_1$ and $\varepsilon_2$ of these materials and decreases exponentially with depth, depending on the electric conductivity of the material (van der Kruk et al. 1999; Gosar 2012).

For commonly used GPR and typical environments in Central Europe with the resistivity of hundreds Ωm, the penetration depth can be a few metres for GPRs with the power output of 300–1 500 W and the centre frequency of 500–1 000 MHz [for example, IRIS GPRs or the ProEx GPR unit (MALA Geoscience, Sweden; Łyskowski et al. 2014)] up to several ten metres for several kW power output and 25–50 MHz centre frequency (Chamberlain et al. 2000). Smith and Jol (1995) experimentally estimated that the penetration depth for a 25 MHz antenna and the Quaternary sedimentary environment (above the surface of mineralised water) is between 52 and 57 metres. For a 100 MHz antenna the penetration depth reduced to 37 m. The results of experimental measurements above the cave of Divaška Jama (Gosar 2012) and above the S-19 Cave on the Kanin massif (Gosar, Čeru 2016) correspond to such estimations.

In 2013, a new type of GPR (Roteg) was developed, one with an extremely high pulse power output of several MW on antenna (Tengler 2013). Two localities were found to test the maximal penetration depth – the Hranice Abyss (HA) (Fig. 1), which is the world‘s deepest flooded cave with a depth of more than 404 m, according to figures recorded so far (Guba 2016; Musil 2017). The next test of the penetration depth of the Roteg GPR was carried out in the quarry of Malá Dohoda, Holštejn near Blansko, and the results were compared with the geological cross-section (Baldík et al. 2017) that was traced in the distance of approx. 1 km from the quarry.

Three Key Points: 1) New kind of Ground Penetrating Radar, 2) Field test of the penetration depth at the Hranice Abyss and in the Moravian Karst, 3) Maximum penetration depth to be more than 500 m in limestones.

## Methodology and methods

Compared with the existing GPRs, the new GPR termed Roteg is characterized by a much higher pulse power, higher voltage of antennas (5–20 kV), and, in particular, the special design of the pulse generator, which bypasses the frequently used semiconductor components of MOS and LDMOS, and makes use of a spark gap. This allows increasing the power output on antenna up to several MW, which is at least 2 orders more than for conventional GPRs. The increasing power output of 2 orders implies increasing maximal penetration depth of at least one order in the same conditions. The spark gap (discharger) produces Dirac pulses of lengths of up to 3 ns by directly discharging capacitors (RTG-Tengler 2013). The predominant frequencies are selected from the continuous spectrum by a special antenna, which is tuned to them. Each antenna has a flat spectrum, i.e., is sensitive to all of the frequencies within the continuous spectrum, but the corner frequency of the spectrum depends on the length of the antenna. The 6-metre antenna is tuned to the predominant frequency of 25 MHz, the 3-metre antenna to 50 MHz, and 1-metre antenna to 150 MHz.

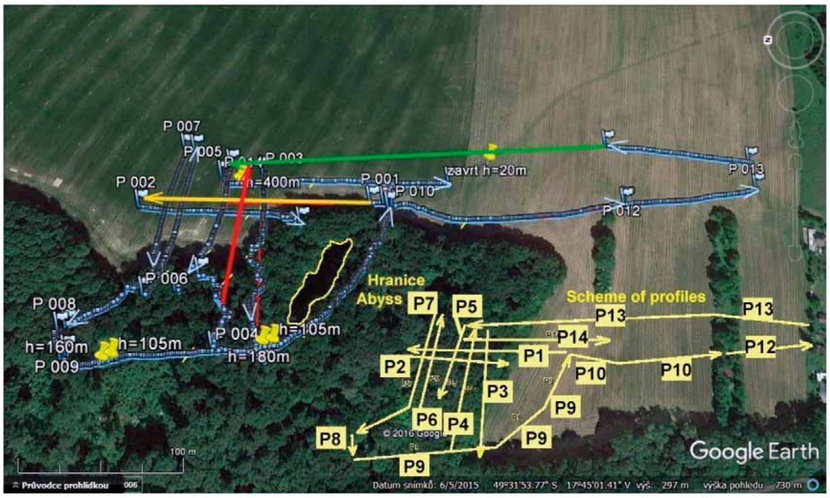

Fig. 1: Profiles P1–P14 around the Hranice Abyss (blue GPS dots), scheme of profiles are in light yellow. The profile name is indicated at the beginning of the profiles. Yellow arrow: profile P1, red arrow: profile P4, green arrow: the second part of profile P13 (GPS was out of operation after the interruption of the measurement). (Credit: Google Earth)

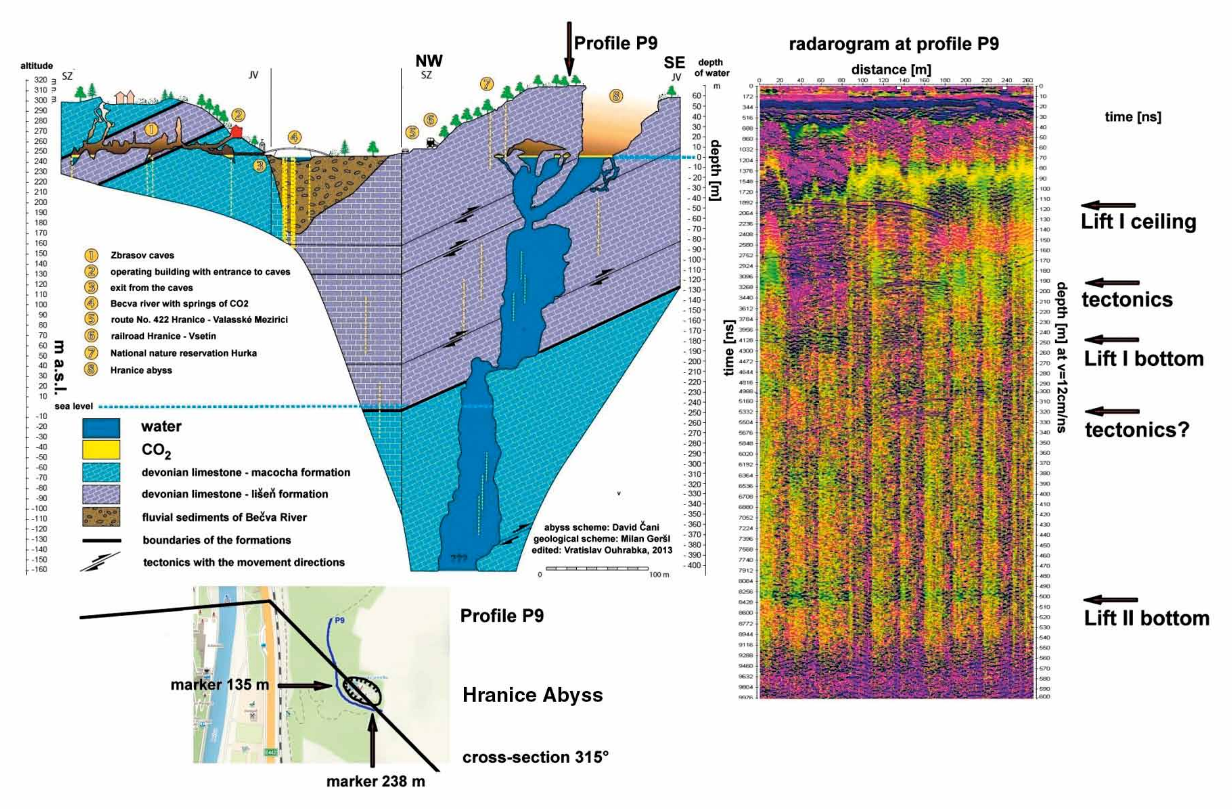

Fig. 2: The geological cross-section of the Hranice Abyss and the radarogram of profile P9. The red arrow marks the intersection of profile P9 and the cross-section of the Hranice Abyss in the position of 135 m on profile P9.

In both cases, i.e., the Hranice Abyss and the quarry of Malá Dohoda, the longest antenna (6 m) was used. The voltage on transmitting antenna was 15 kV in the case of the abyss and 20 kV in the case of the quarry. Approximately 10 pulses (frequency of pulse generation is 120 Hz) were stacked, at the speed of approx. 3 km/h, into one sum, which represented one step of the measurement, i.e. 0.1 m. The accuracy of positioning this measurement point by means of online GPS was approx. 1 m. The sampling frequency was 3.6 GHz (0.277 ns per sample). The total length of records was 38 572 samples in the case of the Hranice Abyss (10 684 ns) and 57 253 samples in the case of the quarry of Malá Dohoda (15 890 ns).

The REFLEXW program (Sandmeier Software, Karlsruhe, Germany) was used for the data analysis and interpretation. The signal was amplified with depth, both x and y axes were averaged at 20 samples (elimination of VF noise), and frequencies below 0.6 MHz and above 12 MHz were reduced (filtered).

We were looking for hyperbolas or lines of reflections that can correspond to linear (2-D) or isometric (3-D) inhomogeneity with high permittivity contrast or contrast between various layers or blocks crossed by faults.

## Geology

The Hranice Abyss is the deepest speleological structure in the Hranice Karst. In 2016, it was identified to be the world's deepest flooded cave (Šráček et al. 2019; Kamenský 2016; Musil 2017). The abyss is filled with mineral water with a high level of carbon dioxide (Šráček et al. 2019).

The Hranice Abyss is a “light hole“ cave with the depth of 70 m down to the water level. The abyss evolved on the tectonics with prevailing direction WNW–ESE (Fig. 2). One of these faults creates one of the walls of the Hranice Abyss as well as Lifts I and II to the north-west from the light hole (Figs. 1 and 2).

Under the water surface, the abyss changes into a tilting wide corridor leading to the depth of 50 m. This space is called Zubatice, which suggests the deeply corroded ceiling of this area. From here, the abyss continues as a nearly vertical shaft that widens to reach a diameter of about 30 m – Lift I (Vysoká 2017) – see Fig. 3.

A relatively small sub vertical corridor opens into the ceiling of Lift I, leading to the water surface where it opens into an area called Rotunda. The bottom of Lift I at the depth of 180 m (250 m below the surface) forms a significant tilting area with a shaft, partly blocked by tree trunks. From here, K. Starnawski reached another vertical shaft in 2012 – Lift II (Starnawski 2012). In 2014, K. Starnawski dropped a probe from the ceiling of Lift II to the depth of 384 m; in 2016, a groundwater robot manufactured by GRALmarine penetrated to the depth of 404 m without reaching the bottom (Kamenský 2016). At this depth, Lift II transforms into a wide corridor tilting towards N (NW–NE) – see Fig. 3.

Similarly to the Hranice Karst, the Moravian Karst is developed in the Devonian and Lower Carboniferous carbonates, part of the Macocha and Líšeň formations

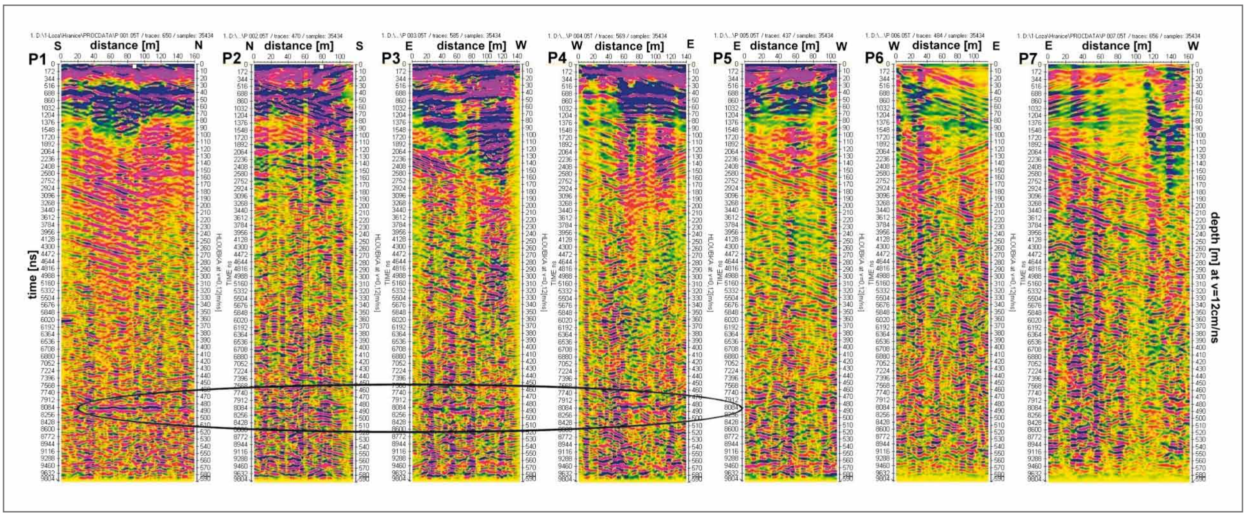

Fig. 3: Radarograms on profiles P1–P7. Ellipse: interpreted reflection boundary at a depth of 485 m (v = 12 cm/ns).

(upper Eifelian up to lower Visean). The basement of the Macocha formation is formed by Lower Devonian basal clastics represented by sandstones, conglomerates, arcoses and greywackes – the latter lay discordantly onto the Brno granite massif (Slezák 1955–1956; Slezák and Štelcl 1963; Hašek and Štelcl 1973).

Limestone in the roof gradually transforms into the Ostrov and Březina shales, Lower Carboniferous greywacke, and the shales of the Rozstání formation (Dvořák et al. 1993).

## Results of measurements above the Hranice Abyss

The aim of the work was to detect reflections, both above (approx. 245 m a. s. l.) and under the level of groundwater. Altogether, we measured 13 profiles in the surroundings of the Hranice Abyss (Fig.1). Profiles P1 to P8 and P14 (Figs. 3 and 4) allowed measuring the area north and east of the Hranice Abyss where the VLF measurement revealed a few tectonic lines of E–W to NW–SE directions (Geršl et al. 2007; Kalenda et al. 2007).

Georadar measurements at the Hranice Abyss were carried out on 4 November 2016, when the temperature on the surface dropped below zero. The typical speed of 12 cm/ns for limestones was determined from the diffraction hyperbolas which were detected on Profile P9 (Fig. 2).

We can clearly see in profiles P1–P4 a reflection boundary at the depths of around 480–485 m (Fig. 3). In profile P5, this reflection is detectable only and, in the very north profiles of P6 and P7, it is completely missing. This reflection could represent a sub-horizontal corrosive plane formed near the groundwater surface in the past, or it could be a reflection from a structure in the abyss, i.e., the bottom, the ceiling, or a sub-horizontal / little-tilted interlayer plane. We must exclude a possible reflective structure on the surface at the same (time) distance of 175 m from profiles P1–P4 (for the speed of 33 cm/ns) because any such structure existing on the surface would create a diffraction hyperbola, which is not the case here.

The most illustrative was the radarogram of profile P9 that ran in the north-south direction above Rotunda, Lift I, and Lift II (Fig. 2), and then around the southern wall of the abyss to SE. We wanted to confirm or disprove the possibility of detection of reflections from the ceilings of Lift I or Lift II below the level of mineralised groundwater. In the radarogram of profile P9 (Fig. 2), we can clearly see a number of reflections from inhomogeneities from a limited space that form typical hyperbolas defined by the wave reflection into other directions than

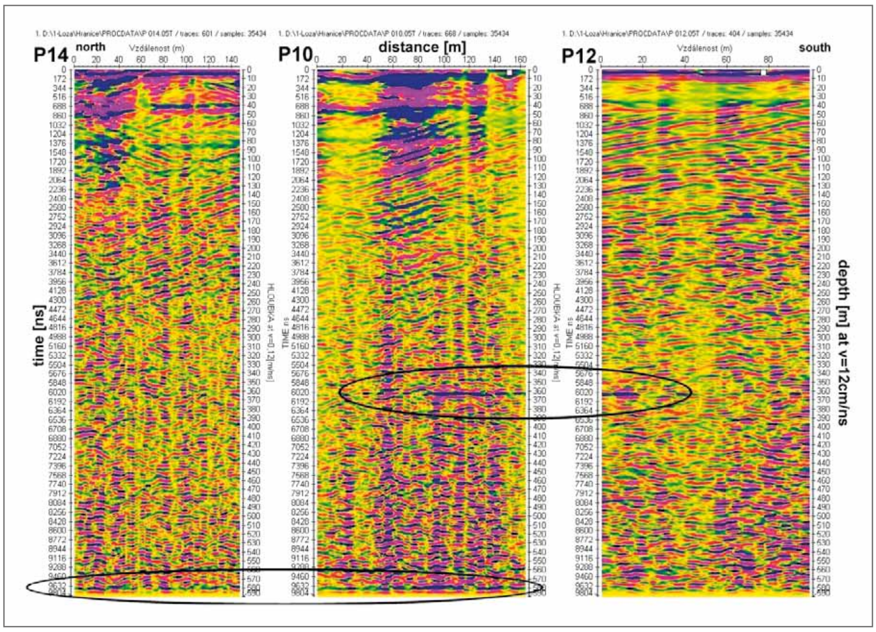

Fig. 4: Radarograms on profiles P14 (north) – P12 (south). Ellipses: interpreted reflection boundaries at depths of 360 m and 580 m (v = 12 cm/ns).

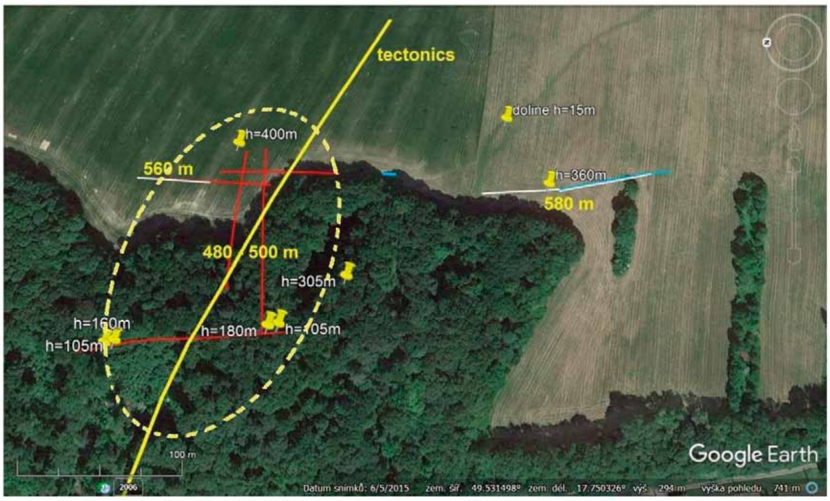

Fig. 5: The map with radarogram interpretations. Thumb-tacks mark the positions of significant 2D or 3D structures (probably caves) with the depth below the surface. Light blue lines along profiles: a sub-horizontal boundary detected at the depth of 360 m below the surface. Red lines along profiles: a sub-horizontal boundary detected at the depth of 485 m below the surface. White lines along profiles: a sub-horizontal boundary detected at the depth of 580 m below the surface. Yellow ellipse: an area of deep horizons at the depths of 100–560 m below the surface. Yellow lines: tectonics according to VLF measurements (Kalenda et al. 2007; Geršl et al. 2007).

those perpendicular to the boundary. The most prominent hyperbola has its peak at the depth of 105 m in the position on profile P9 of 115 m. It can correspond to the tectonic line on which Zubatice or the ceiling of Lift I were developed. The area of another boundary is much larger, which is evident in the long linear reflection at the depths of 140–145 m and positions of 30–70 m. Another prominent hyperbola has its peak in the position of 20 m and at the depth of 160 m; it continues with a long linear reflection as far as another hyperbola with its peak in the position of 150 m and at the depth of 182 m. We suppose that the hyperbola corresponds to a tilting tectonic area intersecting Lift I approximately in the middle that has been formed on a prominent intra-layer slip or a nappe structure of the Líšeň formation. A horizontal reflection between the positions of 30 m and 120 m at the depth of 180 m is also present. At the depth of 240–260 m, a number of small reflections are apparent on the radarogram in a continuous strip and are interpreted as reflections from inhomogeneities and material lying on the bottom of Lift I and the ceiling of Lift II.

Other prominent hyperbolas appear on the radarogram at the depths of 305 m and 320 m with the peaks in the positions of 180 m a 150 m, which can be interpreted as local inhomogeneities formed on an intra-layer slip or a nappe inside the Macocha formation, as can be seen from the linear continuation between the positions of 30 a 70 m at the depth of 325–340 m.

On profiles P10 and P12, we can clearly see a sub-horizontal boundary at the depth of 360 m with the total length of nearly 100 m (from the 90 m position on P10 to the 20 m position on P12 – see Fig. 5). At the beginning of this structure, there is an indication of a hyperbola, suggesting a presence of a linear (2-D) or isometric (3-D) structure that reflects electromagnetic pulses to all directions. Another sub-horizontal boundary is detectable on profile P10 at the depths of 560–580 m (Fig. 5).

We did not detect any distinctive sub-horizontal boundary in the radarogram of profile P13, which suggests diminishing corrosion in the area more distant from the Hranice Abyss, including occurrence of the most significant tectonic lines. On the other hand it doesn´t mean that there are not any boundaries or tectonics below the profile P13. Their thickness could be too small for the visibility on reflected rays.

The interpretation of the detected inhomogeneities (Fig. 5) shows that the whole area north of the Hranice Abyss is intersected by a number of tectonic structures, with both open spaces (e.g. at the beginning of profile P9 on 20–70 m positions at the depths of 105 m and 160 m), and sub-horizontal boundaries, especially at the depth of 485–500 m. This underground depth corresponds, approximately, to the depth of 420–440 m below water level, where we expect to find the bottom of Lift II which is approx. 15–35 m lower than the bottom depth as recently detected by means of the robot on the guiding cable (404 m, 27-09-2016) (Guba 2016). Such sub-horizontal space has developed throughout the area north of the Hranice Abyss.

The fact that the open spaces do not end at the depth of 485–500 m is supported by the reflections on the sub-horizontal boundary that come from the depths of approx. 580 m below the ground, i.e. approx. 515 m below the water level. These reflections were detected both north of the abyss at the beginning of profile P2, and, more distinctively, on profile P10 south-east of the abyss (Figs. 2 and 4).

The interpretation of individual geophysical boundaries in this area is quite a difficult task. Complicated tectonic development is behind the stratigraphic inversion in the drilling hole of Opatovice-1 (Dvořák et al. 1981). The karstification is developed in Devonian-Carboniferous (Givetian to Tournaisian) carbonates of the Macocha and Líšeň Formation (Dvořák, Friáková 1978).

A part of the carbonate sequence was overprinted by late Variscan penetrative, which largely controls karst morphology. The thickness of the carbonate succession is not known in the Hranice Karst. The Palaeozoic rocks are deformed into a thin-skinned stack of thrust sheets separated by N/NW-dipping thrust faults (Čížek, Tomek 1991).

Theoretically, the issue of the depth of the Hranice Abyss could be resolved by the knowledge of the total thickness of carbonates. Basement igneous rocks, however, were not detected in the Hranice Karst by any drilling. The nearest drilling at Choryně-9 (Vysoká) provided evidence of igneous rocks at the depth of 1 462 m, while no such rocks were encountered by the drilling at Valašské Meziříčí (maximal depth of 3 036 m) and at Potštát-1 (maximal depth of 4 200 m). Part of the hydrothermal fluids found in the Hranice Abyss belongs to the outer mantle of the Earth (Meyberg, Rinne 1995). This indicates the necessary presence of an exit route that goes through the basement igneous rocks. Therefore, the existence of the Hranice Abyss cannot be connected with Palaeozoic carbonates only; its continuation is probably to be found in the basement rocks.

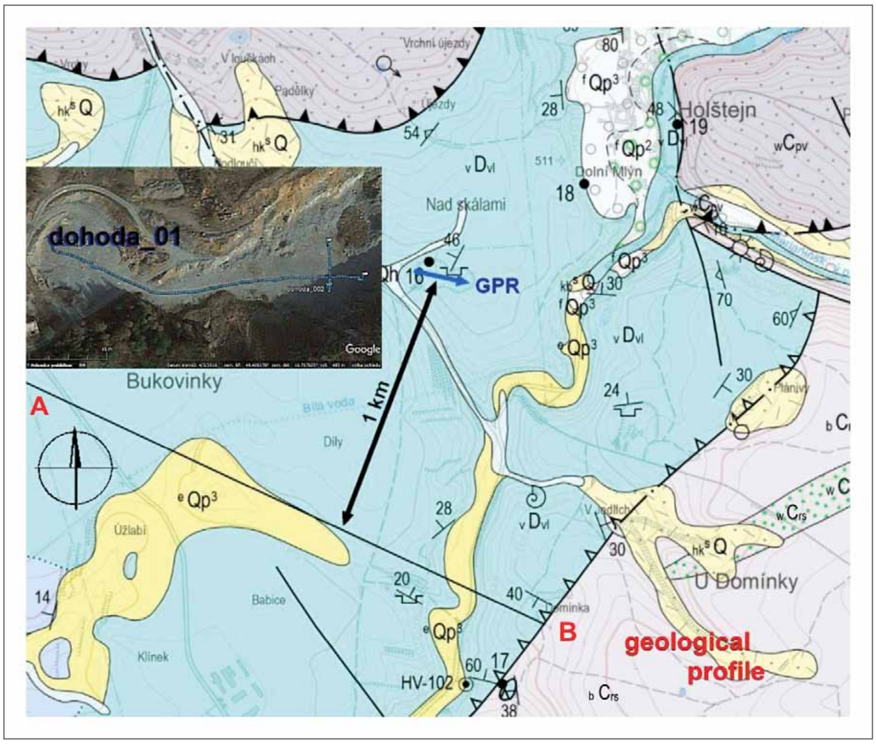

Fig. 6: Profiles Dohoda_001 and Dohoda_002 in the quarry of Malá Dohoda, Holštejn, approximately 1 km from the geological cross-section (Baldík et al. 2017). Profile names are indicated at the beginning of each profile. Explanations: ${}^{e}Qp^{3}$ – loess clay, ${}_{w}C_{pv}$ – massive greywackes (Ponikev Fm.), ${}_{w}C_{rs}$ – massive greywackes (Rozstání Fm.), ${}_{b}C_{rs}$ – shales (Rozstání Fm.) ${}_{v}D_{vl}$ – Vilémovice limestone, ${}_{v}D_{l}$ – Lažánky limestone, ${}_{v}D_{va}$ – Vavřinec limestone.

### Results of measurement in the quarry of Malá Dohoda

In order to carry out an independent test of the penetration depth of the Roteg GPR at a different location as well as to connect the radarogram to the nearby geological drills which were absent in Hranice, we measured the bottom of the Malá Dohoda limestone quarry, the municipality of Holštejn (16.767978°, 49.400041°, 487.8 m) (Fig. 6), on 14 May 2017. Around the quarry, there is a new geological cross-section constructed

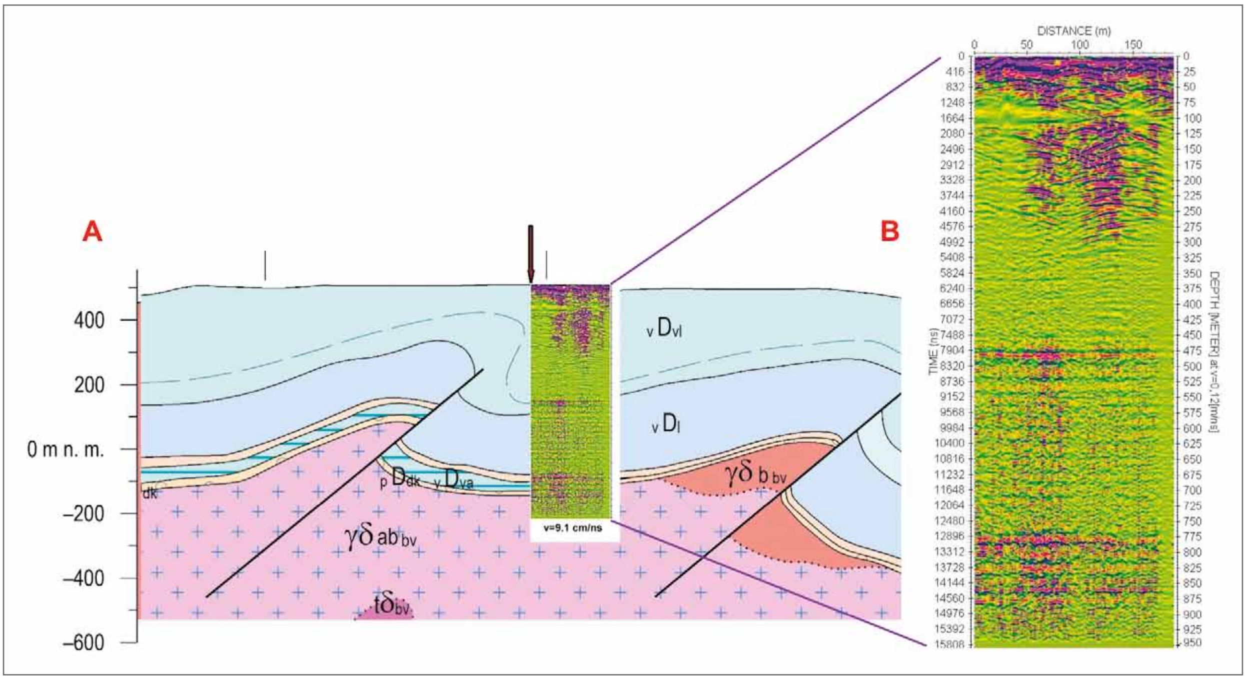

Fig. 7: The geological cross-section at the quarry of Malá Dohoda (Baldík et al. 2017) and the radarogram on the profile of *Dohoda_001*. The red arrow marks the location of the quarry of Malá Dohoda (1 km off the profile). Explanations: ${}_{v}D_{vl}$ – Vilémovice limestone, ${}_{v}D_{l}$ – Lažánky limestone, ${}_{v}D_{va}$ – Vavřinec limestone, ${}_{p}D_{dk}$ – Devonian clastics, $\gamma\delta b_{bv}$ – biotite granodiorite to granite, $\gamma\delta ab_{bv}$ – amphibole-biotite to biotite-amhpibole granodiorite.

on the basis of the HV-101 and HV-102 deep boreholes and the surface geological mapping (Baldík et al. 2017).

We plotted the radarogram of the longest profile (Dohoda_001) of the length of 188 m onto the cross-section of the geological profile to compare the depths of reflexive boundaries and changes in lithology (Fig. 7).

The optimum correlation of the boundary depths between the Vilémovice and Lažánky limestones at the depth of 400 m and significant reflections would be 10 cm/ns for the wave speed. The optimum correlation of the whole limestone sequence and significant reflections is for the wave speed of 9.1 cm/ns (Fig. 7), but the real thickness of the limestone sequence is probably bigger under the quarry than indicated by the cross-section due to the inclination of the strata towards the N–E, i.e., toward the quarry. For the table wave speeds of 12 cm/ns in limestone, all the boundary depths between the Lažánky limestone and basement clastics – as well as basement of Devon sitting on the granodiorites of the Brno massif – move to about 20% bigger depths. The character of reflections, however, definitely corresponds to the lithology of all the rocks. In the Vilémovice limestone that is very clean and compact, a number of "point" reflections are observed, probably coming from cavities or caves up to the depth of approx. 250 m. The layered structure is visible in the Lažánky limestone. In the case of the basal Devonian clastics, it is even more evident. The relative thickness of all the formations corresponds to the geological cross-section as well. The discrepancy of approx. 20% between the depths in the geological cross-section and the depths detected from the GPR for the wave speed in limestone (12 cm/ns) can be caused by both the lower wave speeds in limestone in the given location and inaccuracies in determining all the boundaries in the geological cross-section. In fact, the cross-section was only based on the data from the nearby boreholes, the tilting layers in the boreholes, and on the surface, which does not have to be identical at bigger depths. Moreover, the distance between the geological cross-section and the quarry of Malá Dohoda is approx. 1 km, and against the general gradient of the layers.

The verified maximal penetration depth of almost 800 m in optimal conditions in the Malá Dohoda quarry using 25 MHz antennas and 20 kV pulses corresponds to the depth of 98 m using common GPR with 25 MHz antennas and short pulses of length less or equal to 3 ns, because conventional GPRs have power output of approximately 300 W. Because these GPRs use CMOS off-switches, the output signal on antenna is rather sinusoidal and not pulse; the real maximal penetration depth is approximately twice less than for pulses, which corresponds to the experimentally estimated (Smith and Jol 1995) or theoretically derived maximal penetration depth (Chamberlain et al. 2000). If we would use the pulses of the power of TW like during a lightning, the maximal penetration depth would be at least 100 km, i.e. the whole Earth's crust.

## Conclusion

Conventional GPRs are able to detect reflections of inhomogeneity from the depths of about 20–30 m below the surface under optimal conditions (karst area without a thick soil cover).The new kind of GPR Roteg ver. 2.0 with extremely high power output (up to 20 MW in the pulse regime) was used for testing the "maximal penetration depth" parameter under optimal conditions in the Hranice Karst near the Hranice Abyss and in the quarry of Malá Dohoda located in the Moravian Karst. Typical hyperbolas from 2-D or 3-D structures (mainly caves) are clearly detectable on filtered radarograms even from the depths of 320 m, i.e., 250 m below the water level in the Hranice Abyss – something which was not expected. Sub-horizontal reflections are detectable on radarograms from the depths of up to 580 m; this was limited by the length of the record in this case.

The measurement in the quarry of Malá Dohoda located in the Moravian Karst confirmed the results from the Hranice Abyss. Typical hyperbolas were seen on radarograms to the depths of 250 m, which showed the karstification of limestone to these depths. Moreover, all significant changes of lithology were detectable on the filtered radarogram to the maximal depths of approx. 850 m for the wave speed of 12 cm/ns (or 650 m for 9.1 cm/ns). We can also validate that, under the optimum conditions of karst without the soil cover, the penetration depth of the new type of the Roteg GPR – particularly its new version 2.0 with the longest antennas (6 m), the low frequency (25 MHz), and the maximum voltage on the antennas (20 kV) – is at least 700 m.

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