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A PRINCIPAL BREAKTHROUGH IN GEORADAR TECHNOLOGY – ROTEG

The purpose of the research was to verify the extraordinary big theoretical penetration depth of new developed georadar in the real conditions of karsts areas. The new kind of the Ground Penetrating Radar (GPR) – Roteg – was developed in 2013 (RTG-Tengler 2013). Its technical parameters (pulse peak on the transmitting antenna 20 kV or more, and the sensitivity of the receiving antenna at least 2 uV, i.e. the real signal detection level around 20 uV) express that the real signal detection sensitivity is 9 orders, i.e. 180 dB. Such sensitivity means that the real penetration depth should be two orders bigger than in the case of common GPR's. We tested the real penetration depths in the suitable environmental conditions over the caves in the Moravian Karst and in Slovenia near Postojna cave. The measurements results showed that reflections from known caves are reliably detectable at depths of 40–210 m below the surface. Reflections from the geological structures up to a depth of 480 m, in which the bottom of Lift II is probably located, were observable on the profile above the Hranická abyss. The new kind of Roteg georadar with 20 kV pulses on the transmitting antennas was able to detect reflections from the Devon – Brno Granite contact at a depth of up to 850 m in the case of optimal conditions in the karst without soil cover (in the Malá Dohoda quarry in the Moravian Karst). The radarogram showed a change in the lithology between the Vilémovice – Lažánky limestone and layers of clasts in the bottom of limestone strata. Both of the tests mentioned above confirmed the extraordinary big penetration depth of the GPR signal which exceeded 500 m in karst conditions when using the maximum power on transmitting antennas. The quite new kind of GPR called Roteg with the extraordinary high voltage on transmitting antenna and pulse instead of harmonic signal generation of transmitted signal allows reach two orders bigger penetration depths than the common GPRs. The new kind of Roteg GPR makes it possible to obtain data (especially from karst areas) from depths that were previously only accessible by seismic methods or boreholes. GPR measurements are orders of magnitude cheaper and much faster in the field.

Key words: Ground Penetrating Radar; penetration depth; karst.

Introduction

The Ground Penetrating Radar (GPR) measurement is one of most effective geophysical measurements in the field. The GPR is based on the transmission of high frequency pulses (usually 25 to 1000 MHz) 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 (ε_1, ε_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 ε_1 of the material following the relationship of $v=c/\sqrt{\varepsilon_r}$, where c is speed of light and ε_r is relative permittivity. Limestone has relative permittivity of 2–2.5 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 permittivity ε_1 and ε_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 output of 300–1,500 V and the centre frequency of 10–1000 MHz (for example, IRIS GPRs or the ProEx GPR unit [IRIS GPRs, 2019]) up to several ten metres for several kV 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 m. 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.

Purpose

The purpose of the research was to verify the extraordinary big theoretical penetration depth of georadar in the real conditions of karsts areas, which follows from the quite new principle of pulse signal generation instead of harmonic signal generation on the transmitting antenna.

Methodology

Parameters of the georadar Roteg and the theoretical penetration depth

The table of basic parameters of Roteg georadar (Table 1) [RTG-Tengler, 2013] shows that the gain is much greater than 120 dB. In fact, the real gain is approximately 180 dB, because the output power on the transmitting antenna is 20 kV or more, and the sensitivity of the receiving antenna is at least 2 uV, i.e. the real signal detection level is around 20 uV. The ratio between 20 kV output and the real signal detection sensitivity is 9 orders, i.e. 180 dB.

Table 1

Basic parameters of Roteg georadar [RTG-Tengler, 2013]

FREQUENCY RANGE	0.1-1000 MHz
DATA	12 Bit
SAMPLING FREQUENCY	500 MHz – 4 GHz
RECORDING TIME	32 000 – 128 000 ns
MEASUREMENT RATE	> 3 000 scans/second (all pulses from transmitter)
VERTICAL RESOLUTION	0.25 – 2 ns (based on sampling frequency)
GAIN	> 120 dB **180 dB**
STACKING	1 – 1 000, adjustable
TRIGGERING MODE	Wheel, Time, Manual
STEP	5 mm to 10 m
WIFI	2.4 GHz
MEMORY	100 MB (WiFi send buffer)
BATTERY	9600 mAh
GPS ACCURACY	1 – 2 m (or external GPS)
BAROMETER ACCURACY	± 10 cm
IP CODE	IP53
DIMENSIONS	280 x 180 x 165 mm
WEIGHT	4.57 kg (with battery)
REAL TIME ON SCREEN DATA TRANSFER AND CONTROL BY WIFI WIFI DATA BUFFERING DETACHABLE DC 12 V ACCUMULATOR LOZA GPR COMPATIBLE	

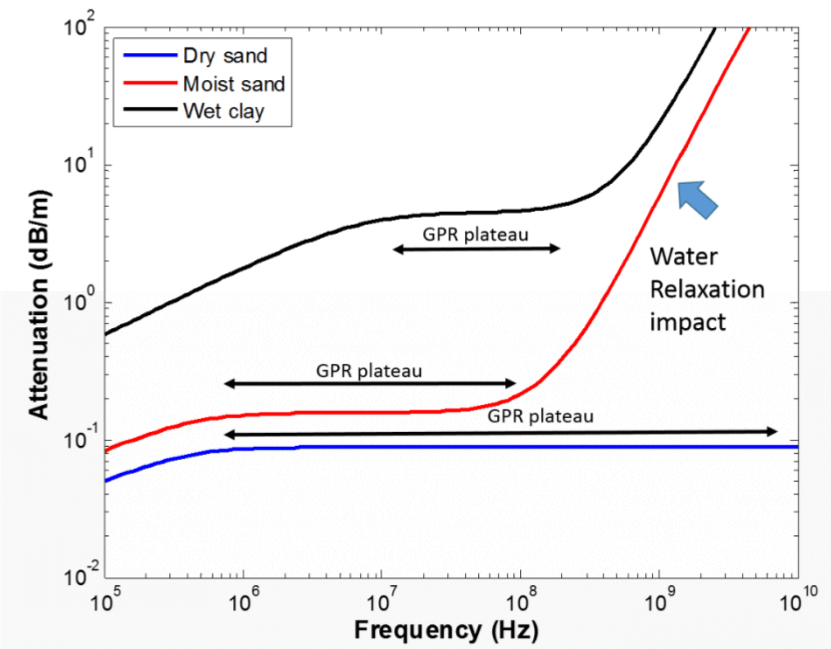

Fig. 1. The attenuation coefficients (for wet clay, wet sand and dry sand, dB/m (according to Sensors&Softwares Inc. – https://www.sensoft.ca/support/faq/)

For wet clays and the georadar frequency 25 MHz (Fig. 1), the attenuation coefficient is 5 dB/m, for wet sand is 0.2 dB/m and for dry sand is 0.08 dB/m. Than the theoretical penetration depths for Roteg georadar should be 180/5/2 m = 18 m for wet clays, 180/0.2/2 m = 450 m for wet sand and 180/0.08/2 m = 1125 m for dry sand. The limestone has similar attenuation coefficient as dry sand.

Results

Results of the penetration depth tests

In 2013, a new type of GPR (Roteg) was developed, one with an extremely high pulse output of several kV on transmitting antenna [RTG-Tengler, 2013]. In 2015–2017, tests were carried out, including the operation and interpretation, at the following sites (verified minimum penetration depth is shown in brackets): Pytlik Cave (20 m) [Kalenda et al., 2016], Malá Dohoda Quarry (20 m) [Kalenda et al., 2016], the area under the quarry of Na Bradinách (20 m) [Kalenda et al., 2016], Holštejn Cave (40 m) [Kalenda and Tengler, 2016], the cave of Spodní Suchdolská jeskyně (40 m) [Kalenda et al., 2016], Lopač Cave (20–60 m) [Tengler et al., 2016], cave No. 561A in the quarry of Velká dohoda (40 m with a 1-metre antenna and 150 MHz) [Kalenda et al., 2016], the cave of Amatérská jeskyně (90–110 m) [Tengler et al., 2016], and Pekárna Cave (140 m) [Kalenda et al., 2017a]. In the glaciofluvial gravel environment, the penetration depth was at least 60 m under the level of groundwater, and when measuring on profiles on the surface of Lake Tüttensee, we could even detect reflections of sediments at the depth of 10 m under the bottom of this lake.

In 2016, another version (2.0) was developed of a georadar with a big voltage pulse up to 20 kV on antennas. Encouraged by positive results, we tested the most efficient version of the radar above and behind the cave of Divaška Jama, Slovenia [Kalenda et al., 2018]. We could clearly detect the deepest parts of this cave (60–80 m), as well as unknown caves at the depths of 200 m below the surface.

Because we thought that in the case of a karst environment and a thin soil cover, the penetration depth of the GPR is at least 200 m, we decided to test the penetration depth of the GPR with maximum performance at the Hranická abyss. The Hranice Abyss (HA) is the world's deepest flooded cave with a depth of 404 m, according to figures recorded so far [Guba, 2016; Musil, 2017]. The next test of the penetration depth of the GPR was carried out in the quarry of Malá Dohoda, Holštejn near Blansko, and the results were compared with the geological cross-section [Baldík, 2016] that was traced in the distance of approx. 1 km from the quarry.

Here, in this paper, we will show the typical (and of high quality) results of the GPR measurements. We started with the Roteg GPR with 1-m (150 MHz) antennas in the quarry Velká Dohoda, where the optimal conditions for such measurements are. The thick limestone benches are separated by clay layers, which are at the roof of cavities, caves or corridors. Such cavities are placed in the top of the hyperbolas (Fig. 2).

Because the caves are known in the Velká Dohoda quarry, one of other profiles was lined up above one of caves (Cave in Velká Dohoda Quarry) (Fig. 3). Most of reflections come from the ceiling of this cave at a depth of 30 up to 40 m below the surface, but the valid reflections come from the depths up to 50 m (with 1-m antenna = = 150 MHz).

The other shallow caves are known in Moravian Karst near Suchdol at depths of approximately 40 metres. The test profiles Kal51 and Kal52 were perpendicular to a known Suchdolská cave and the profile Kal54 was situated almost above this cave at its known end (Fig. 4). The 3-m antennas (f = 50 MHz) were used. The top of hyperbolas practically at the middle of both profiles at the depth of 40 m confirmed both the position and the depth of the ceiling of this cave (Fig. 5). The same was seen on the profile Kal54.

Another known cave in the southern part of Moravian Karst is Pekárna cave. Although the depth of the ceiling is approximately 20 m below the surface, we used 6-m long antennas to detect all of cavities in the limestone strata and the contact between limestone and clastics in the basis of the sedimentary sequence at the depth approximately 100 m below Lažánecké limestone [Slezák, 1955-56; Slezák and Štelcl, 1963; Hašek and Štelcl, 1972; Rez, 2010; Slezák et al., 2016]. The Pekárna cave was detected practically on all of profiles by 6-m and by 3-m antennas as well [Kalenda et al., 2017a, 2018a]. Many of unknown caves, cavities and faults were detected at depths up to 100 m below the surface (Fig. 6).

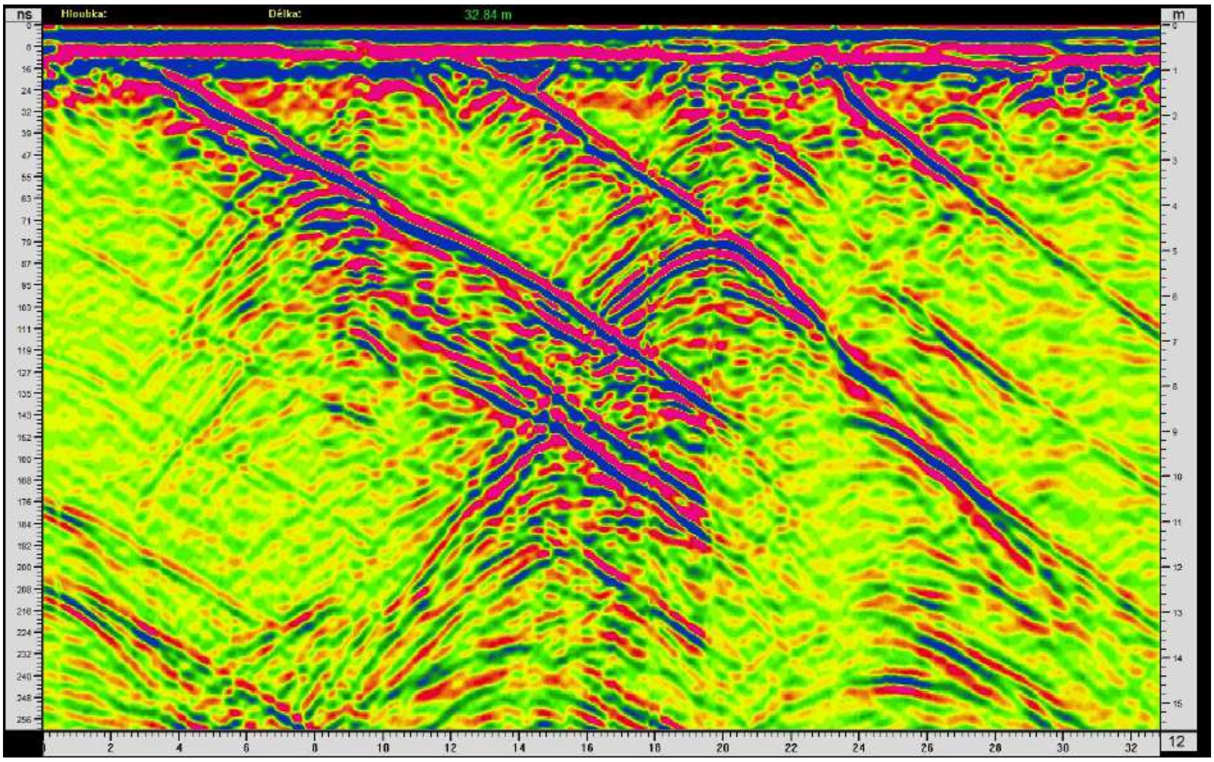

Fig. 2. Radarogram on profile P24
in Velká Dohoda quarry near Holštejn

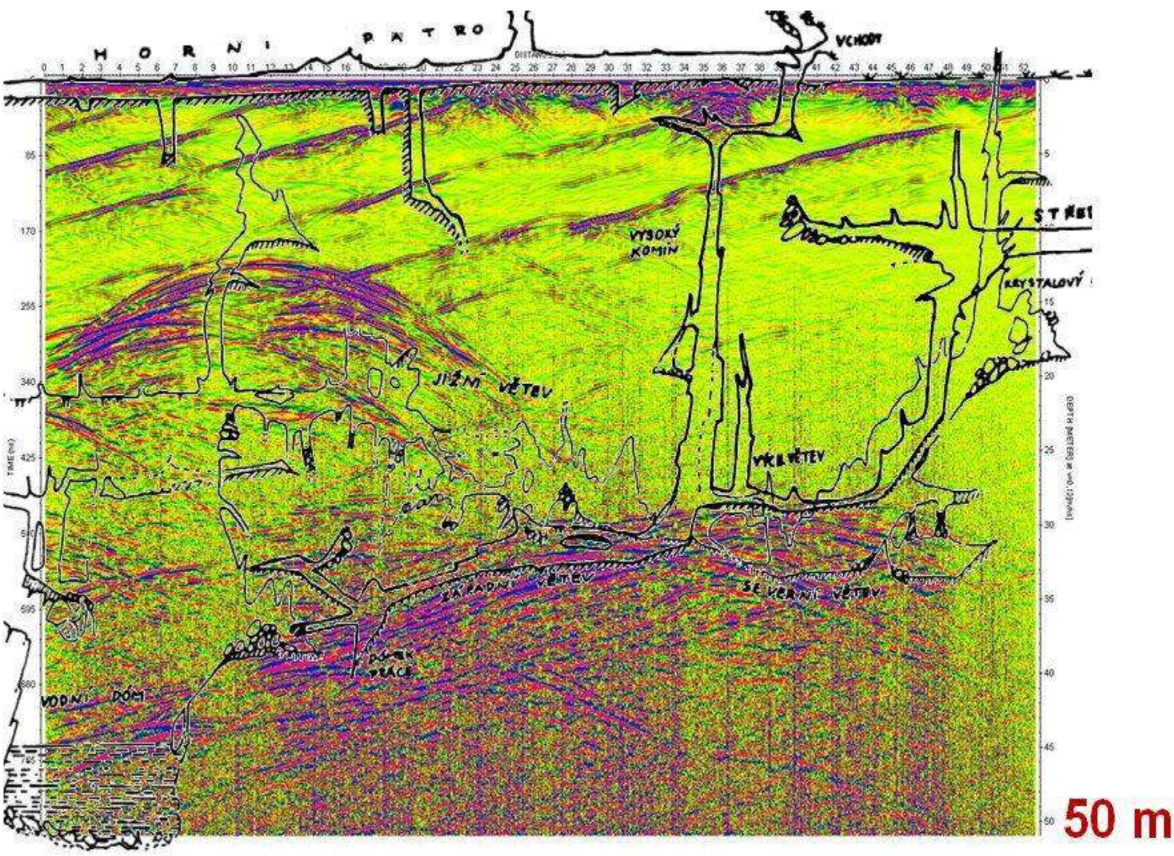

Fig. 3. Radarogram on profile P16 above cave in Velká Dohoda quarry.
Cave map by ZO 6-16 Tartaros, drawn by F. Musil 2001

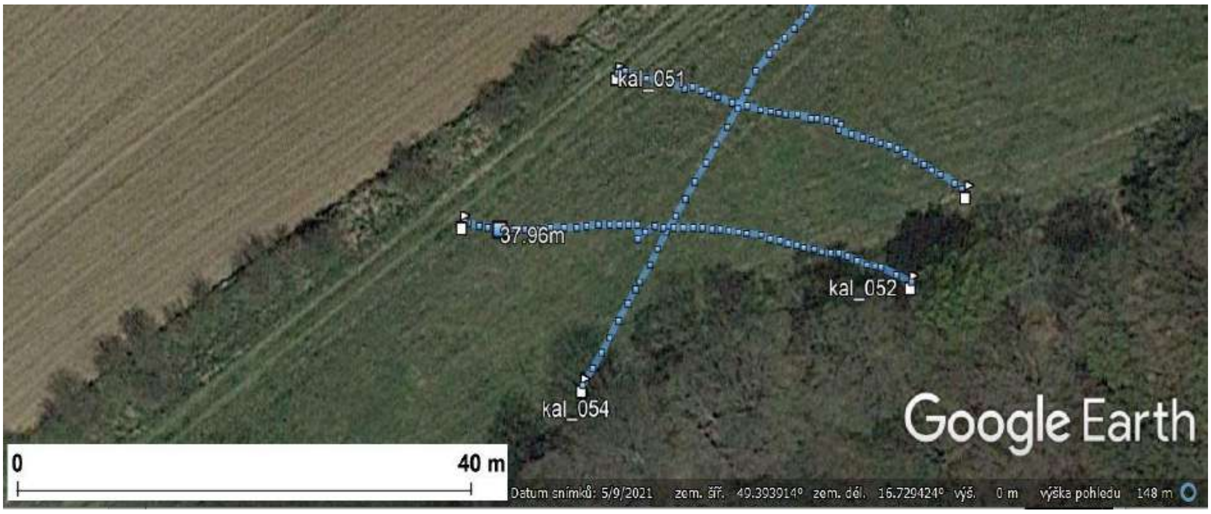

Fig. 4. Orthophotomap with profiles above Suchdolska cave

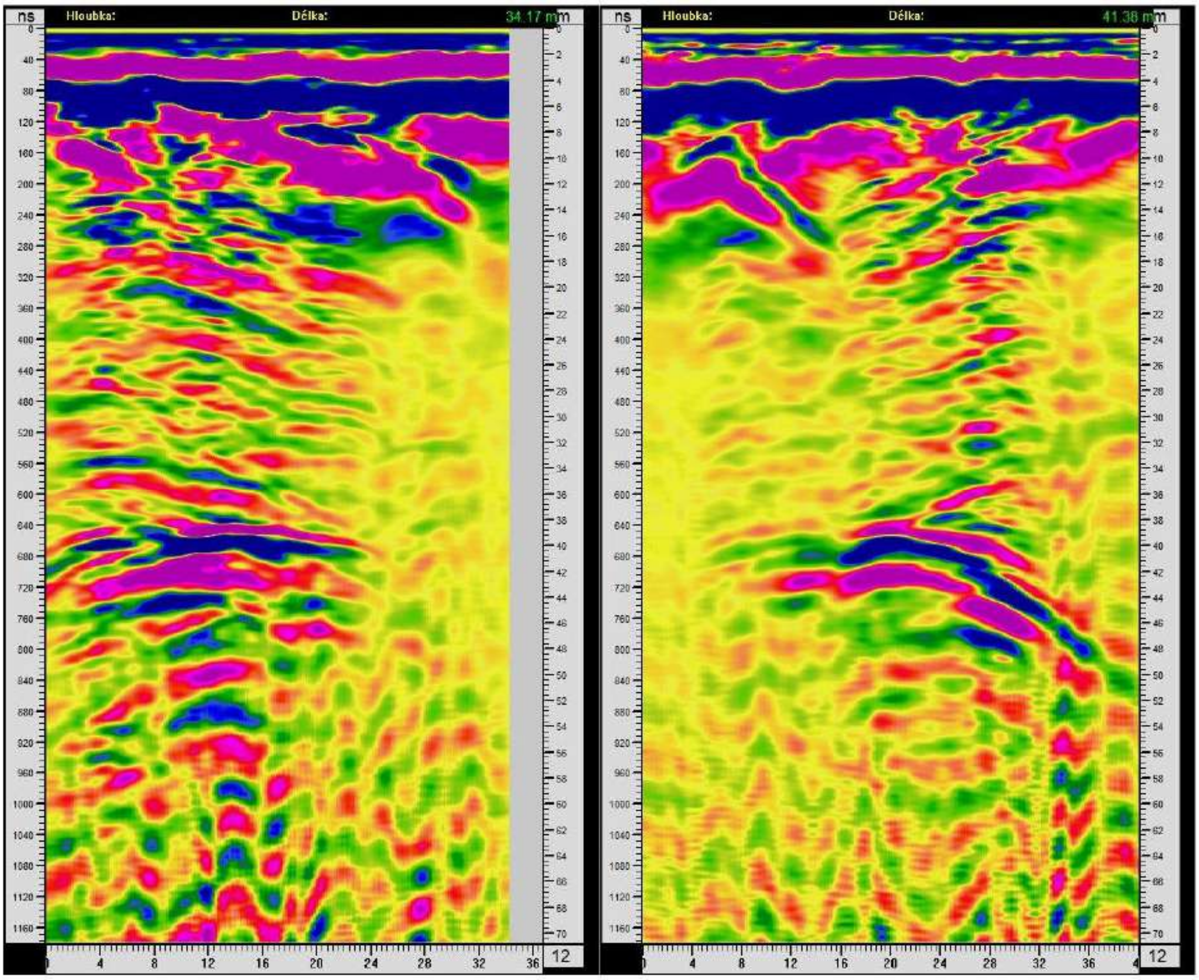

Fig. 5. Radarograms on profiles Kal51 and Kal52 above Suchdolská cave

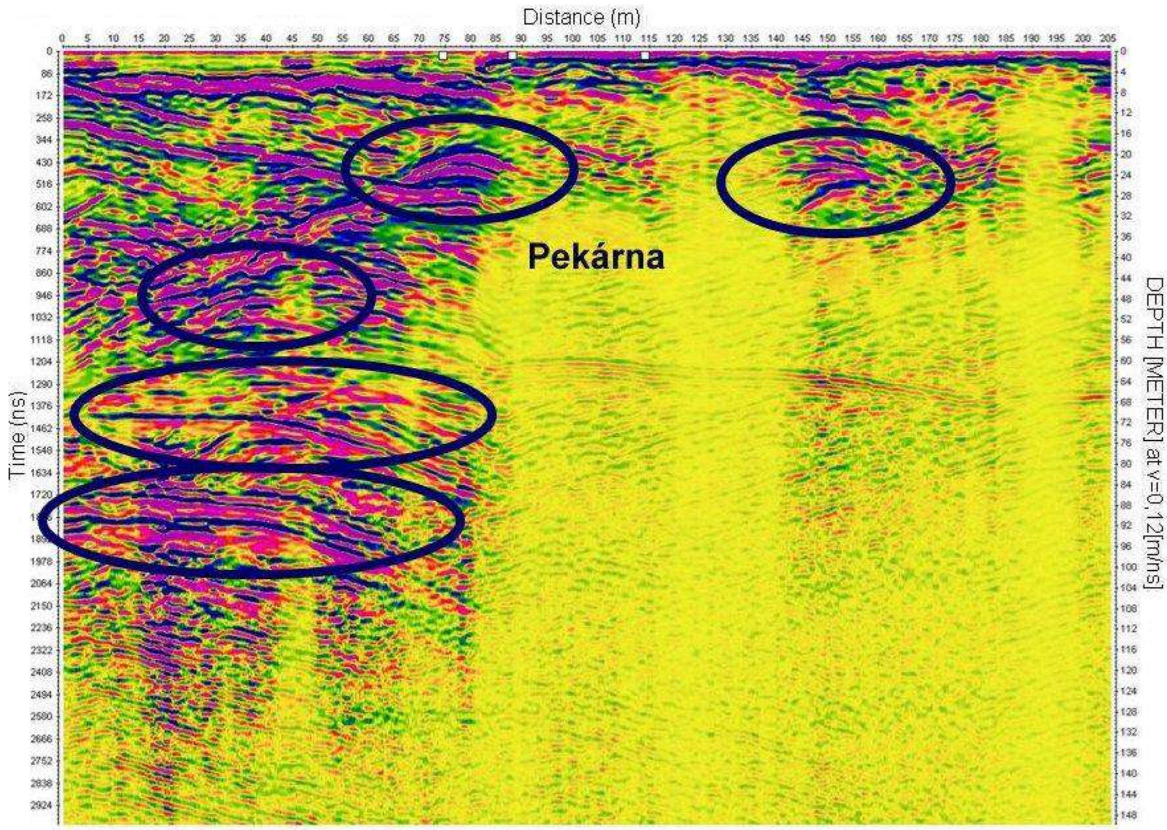

Fig. 6. Radarogram on profile P6.

Elipses mark the interpreted ceilings of the caves. The most distinct reflection is from the Pekárna Cave ceiling (position of 75–85 m, depth 19–24 m). The white dots mark beginning – centre – end of the depression, created by tectonics. (according to [Kalenda et al., 2017a])

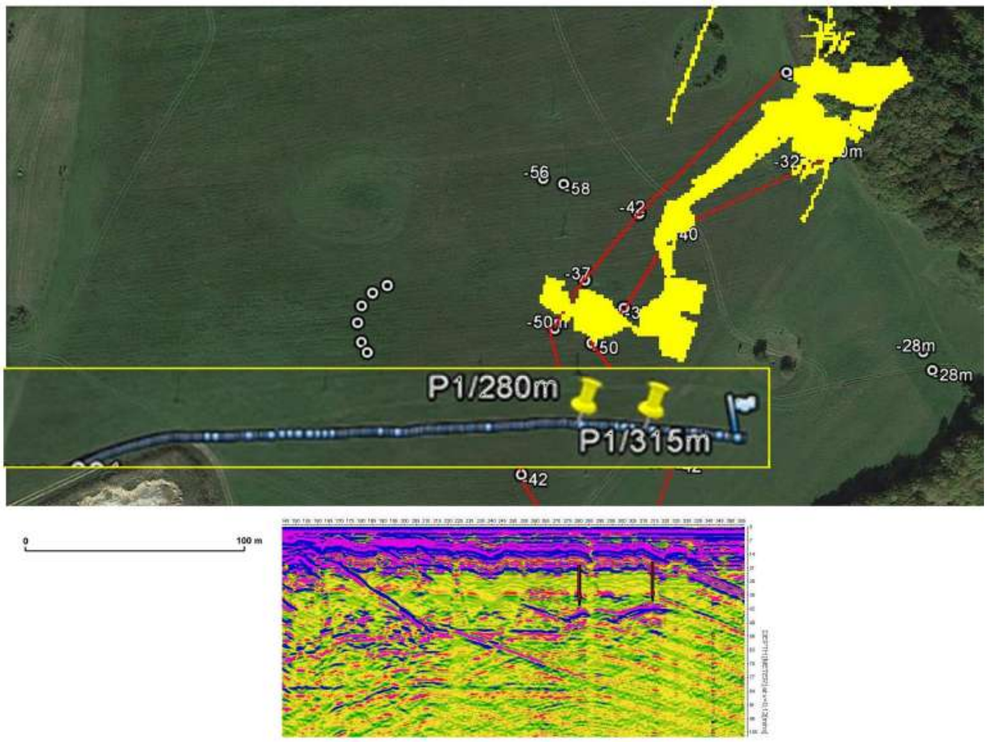

Fig. 7. Radarogram on profile P1 above Holštejnská cave (between distances 280 m and 315 m) (according to [Tengler et al. 2016])

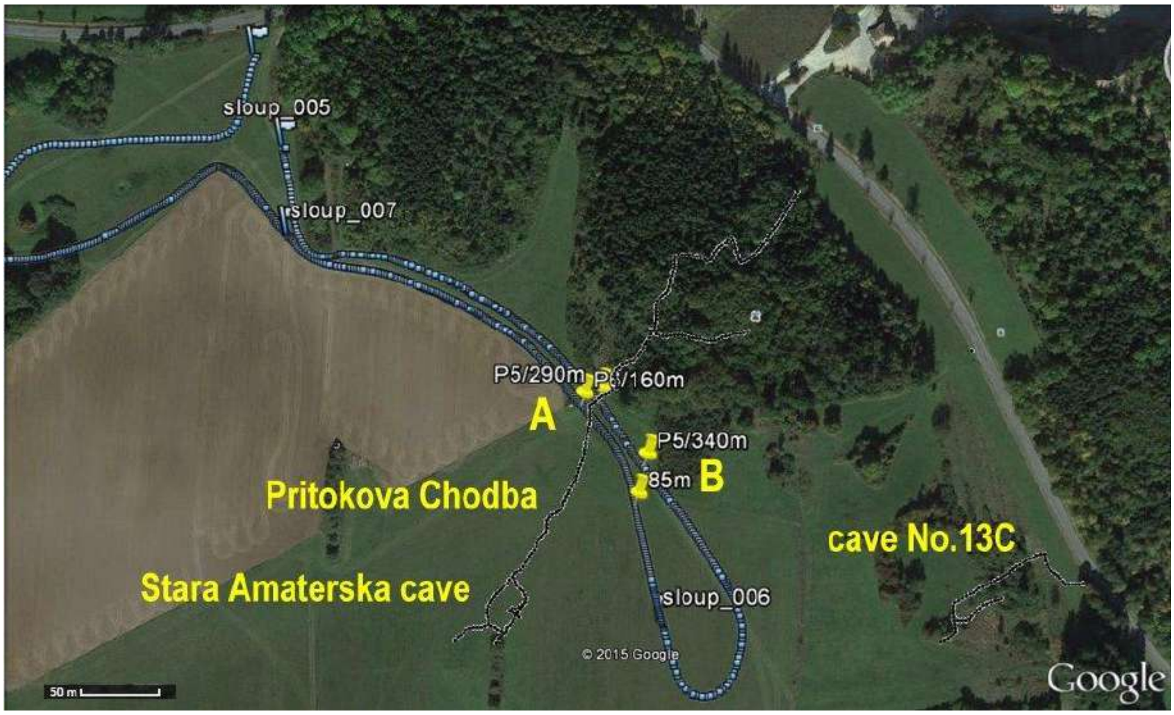

Fig. 8. Přítoková Chodba corridor in Stará Amatérská cave (according to [Tengler et al., 2016])

The Holštejnská cave is one of most famous caves in Moravian Karst, because the speleologists prolonged this fully filled cave to several hundred metres from the entrance during 30 years of works (Fig. 7) [Zámek and Zatloukal, 1993]. Although the practically sub horizontal ceiling of this cave is at the depth only 40 m below the surface, there was almost impossible to detect the next unknown parts of such cave with the help of other geophysical methods like VLF, gravimetric measurements, magnetometers, due to a small contrast of almost all geophysical parameters between limestone and sediments, filled the whole space inside the cave [Blecha and Kalenda, 2004; Blecha et al., 2005; Kalenda et al., 2006, 2008].

The 6-m antennas (25 MHz) were used pulled behind the cars and we were able to make the map of the unknown part of this cave during one day of measurements [Kalenda and Tengler, 2016].

The well mapped cave in Moravian karst is the main cave – Amatérská cave. The precision of the map of Amatérská cave is better than 0.5 m both in horizontal as well as vertical directions. The part of Stará Amatérská cave – Přítoková corridor – at depths of 60 m up to 80 m below the surface was used (Fig. 8). The 6-m antennas pulled behind cars were used. The Přítoková corridor was precisely detected on both opposing profiles Sloup05 and Sloup06 (point A). The unknown deeper corridor of Amatérská cave system, which is fully filled by water now, was detected too (point B) (Figs. 8 and 9).

The test measurements continued in Slovenia. The start was above known caves Jama na Poti and Crna jama (Figs. 10 and 11). The 6-m antennas were used. All of known caves were correctly detected [Kalenda et al., 2017b].

During the test of the maximum penetration depth, the experiment, that was made by Andrej Gosar in 2012, was repeated (Fig. 12). The Divaška jama is well known cave with the precise map and vertical cross-sections at many places to the end of known part of the cave [Gospodarič, 1985]. Andrej Gosar was able to detect the ceiling of Pretnerjeva Dvorana at the depth of 37 m with the help of GPR with special long antennas (100 MHz), but deeper parts of the cave were undetectable.

The 3-m antennas were used during our experiment and all known parts of the Divaška jama were easy detectable with high precision (Figs. 13 and 14). Therefore we continued with our measurement behind Divaška jama and we detected much deeper unknown parts of this cave system [Kalenda et al., 2018b]. Moreover, we prolonged our measurements towards the Lokev village and we found probably the other branch of cave system of Reka river at the depths between 150 and 200 m below the surface (Fig. 15).

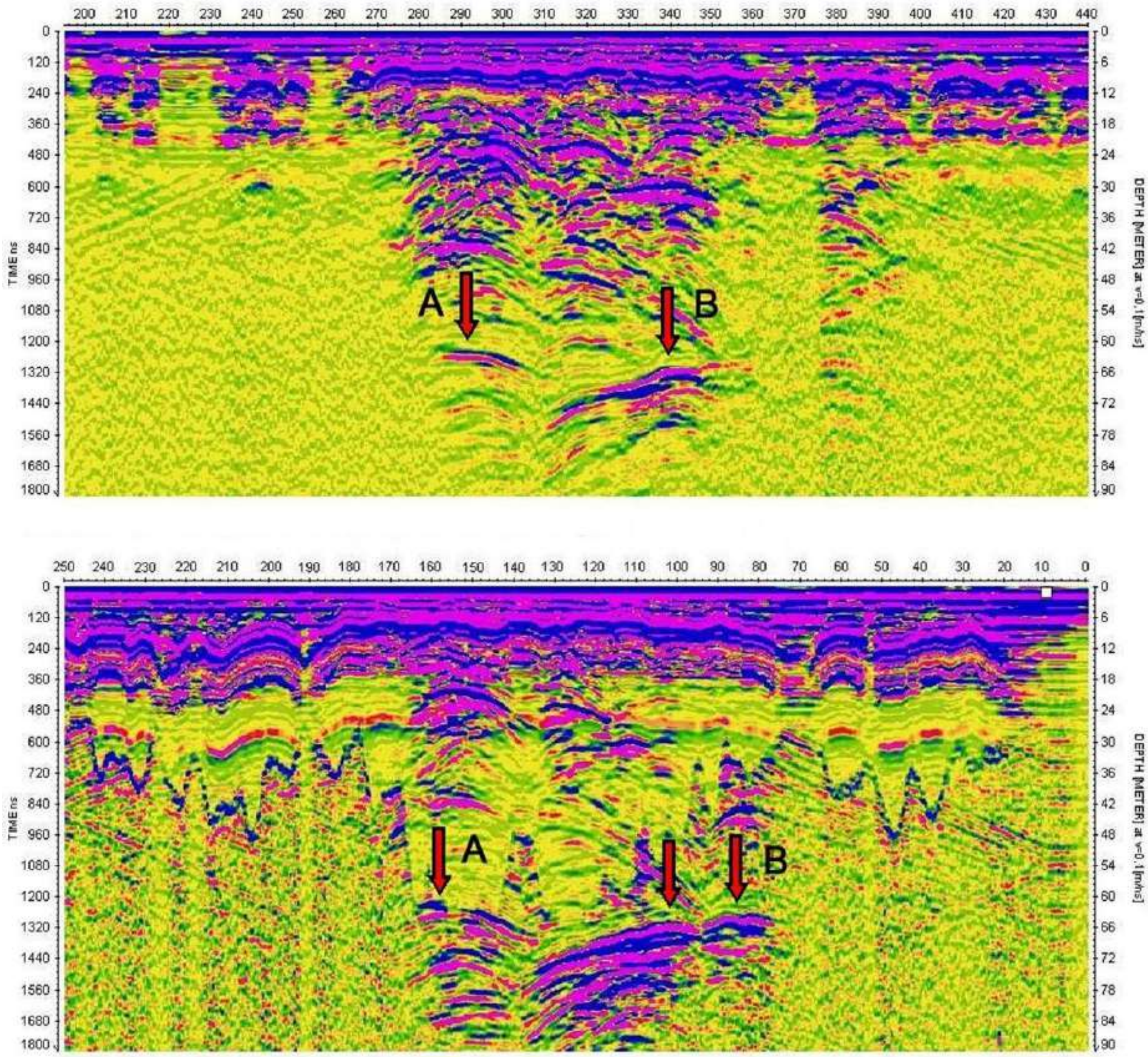

Fig. 9. Radarograms on profiles Sloup005 and Sloup006 above Amatérská cave (according to [Tengler et al., 2016])

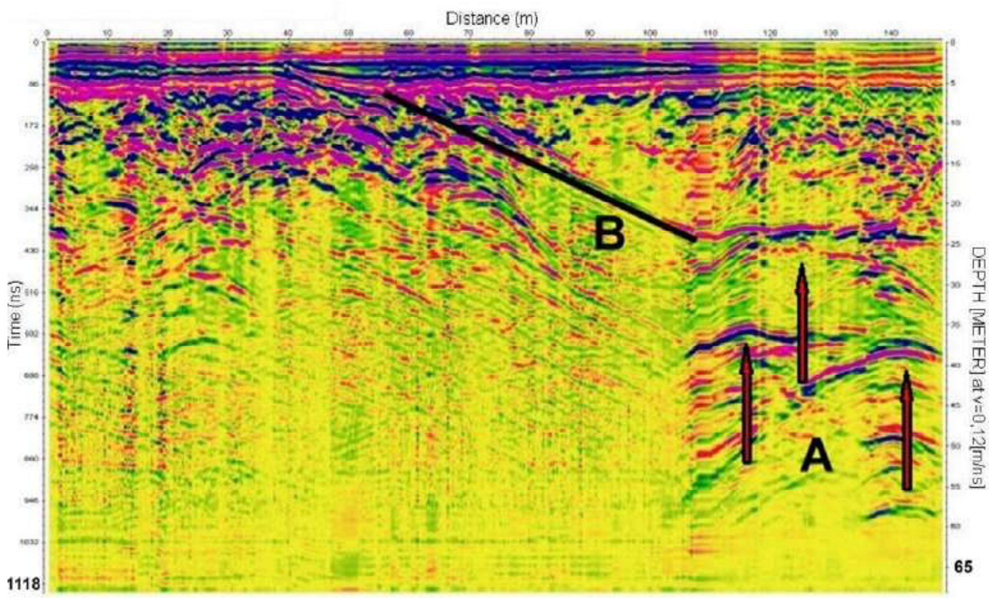

Fig. 10. Radarogram on profile P2 above Jama na poti (Slovenia) [Kalenda et al., 2017b]

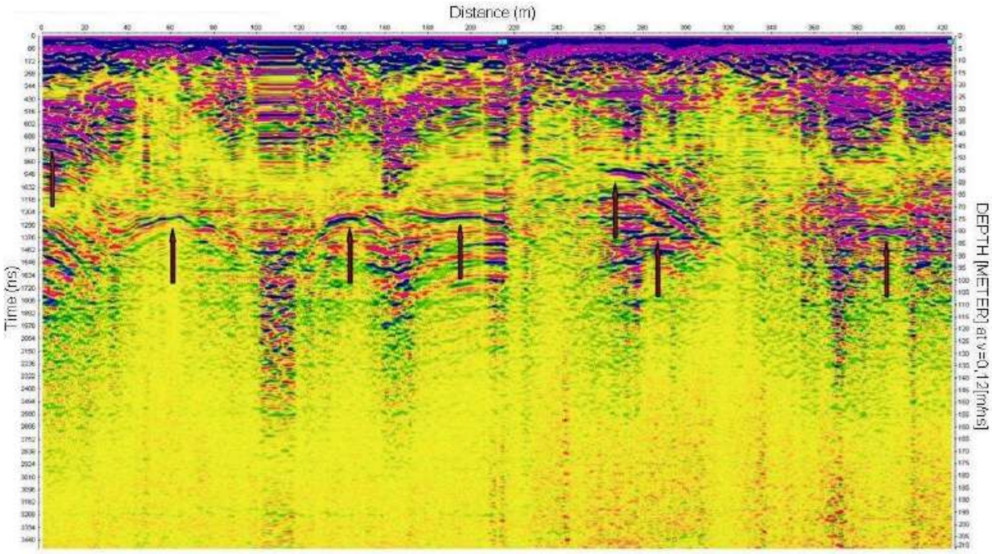

Fig. 11. Radarogram on profile P3 above Crna jama (Slovenia) [Kalenda et al., 2017b]

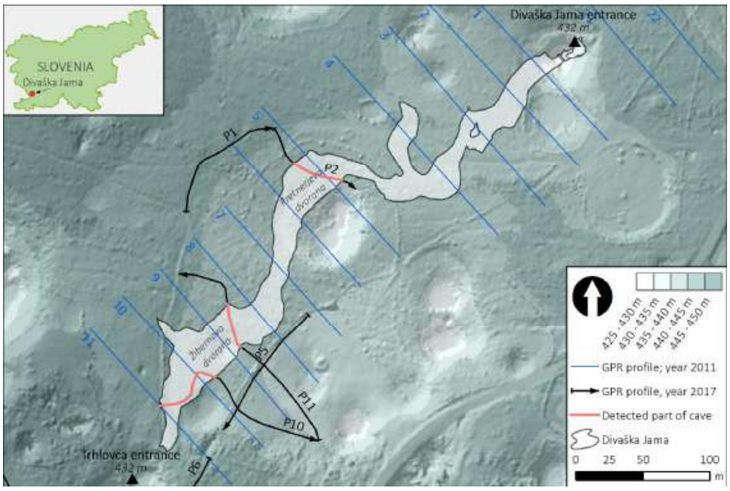

Fig. 12. Map of Divaška jama with profiles by [Gosar, 2012] (blue lines) and by [Kalenda et al. 2018b] (black and red curves) (according to [Kalenda et al., 2018b]). Red parts of curves denoted the detected parts of cave

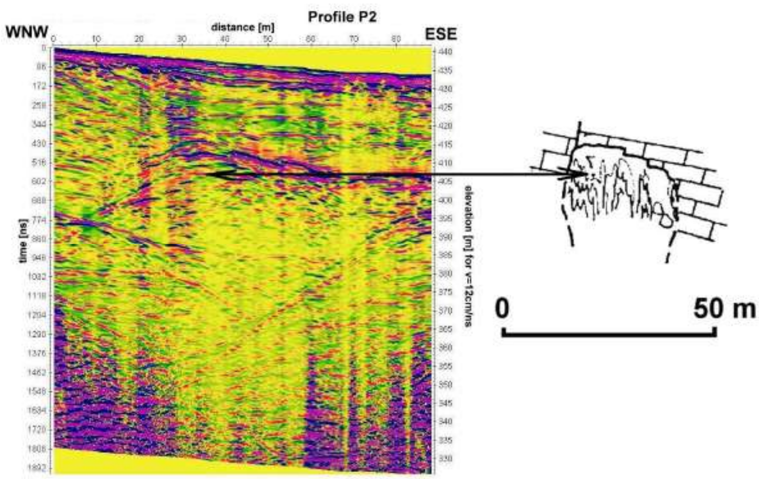

Fig. 13. Radarogram on profile P2 above Pretnerjeva Dvorana. Cross-section by [Gospodarič, 1985] (according to [Kalenda et al., 2018b])

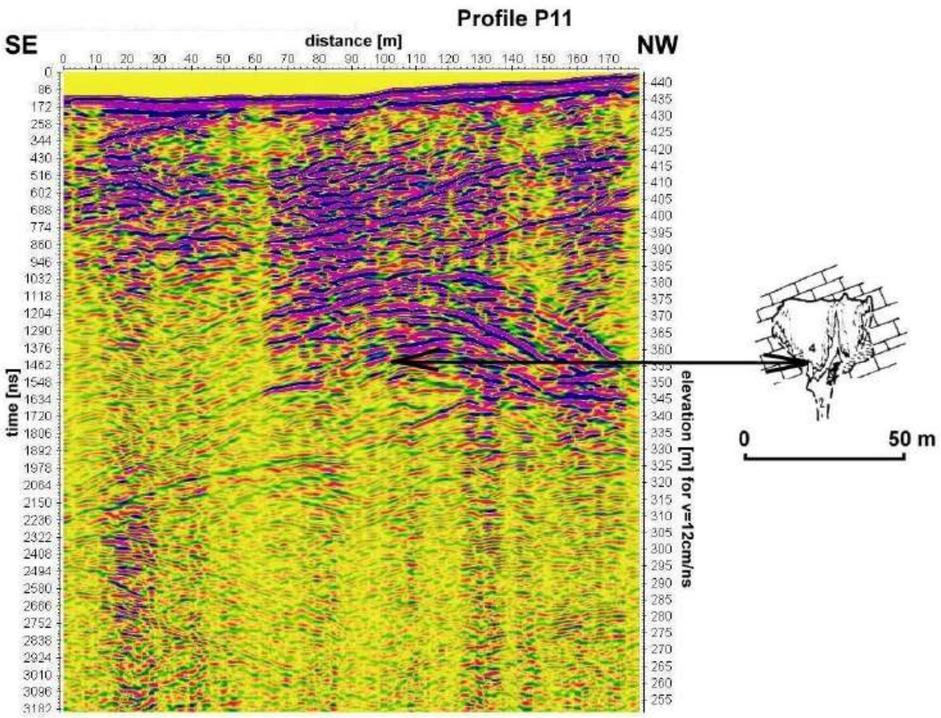

Fig. 14. Radarogram on profile P11 above Žibernova Dvorana. Cross-section by [Gospodarič, 1985] (according to [Kalenda et al., 2018b])

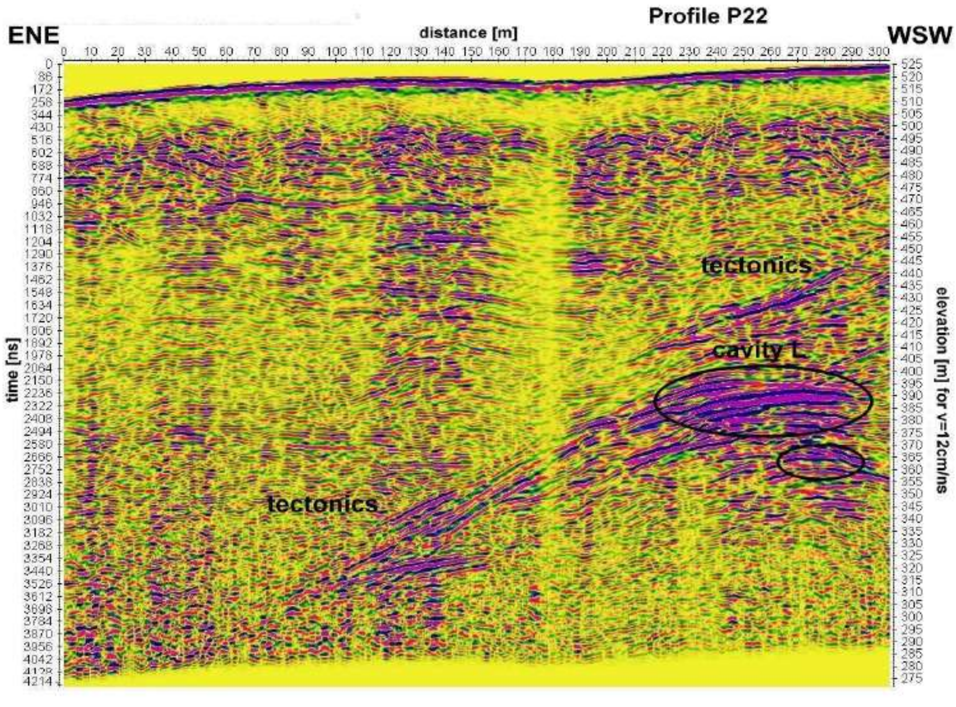

Fig. 15. Radarogram on profile P22 behind Divaška jama (according to [Kalenda et al., 2018b])

Because of nice results obtained behind Divaška jama, we decided to test the radar near Škocjan caves, to find the possible fossil corridors at the depths of 100–150 m below surface. The 3-m antennas (50 MHz) were used in the same manner as in the case of the measurements behind Divaška cave [Kalenda et al., 2018c]. The huge corridors were detected 100–150 m below the surface westerly from Martelova dvorana in Škocjan cave (Figs. 16 and 17). The findings were communicated to local speleologists even in 2017 and published in prestigious cave journal Speleofórum in 2018 [Kalenda et al., 2018c]. According to our suggestions, the Slovenian speleologists turned their attention to the western wall of Martelova Dvorana and to the Fedrigotov Dihalnik hole and at the beginning of 2019 they discovered the biggest discoveries for last 100 years in Škocjan caves (Primorske novice 28.1.2019). The discoverers confirmed explicitly on the press-conference [STA.novice 29.1.2019] that the found old corridors (Skrita jama) were perfectly at the depth and position, as were published in Speleoforum 2018 journal (Fig. 16).

In 2019 we repeated several test measurements in Slovenia and we were invited to Črnotiče limestone quarry to confirm the position and depth of detected border between limestone and claystone along overthrust´s plane, which was interpreted based on geological drilling holes [Celarc et al., 2012]. Both measurements with 3-m long and 1-m long antennas easily detected such huge discontinuity at the depths of 50–100 m (Fig. 18).

Fig. 16. Georadar profiles above and westerly of Škocjan Caves

The names mark the beginnings of profiles. Thumbnails mark the positions, where the cavities and caves were detected. Numbers are depths of cavities. Orange arrows points to the most probable continuation of the upper cave level, which is 60–100 m above recent flow. The cave Kačna Jama with Reka river flow is drawn. (Adopted from [Kalenda et al., 2018c])

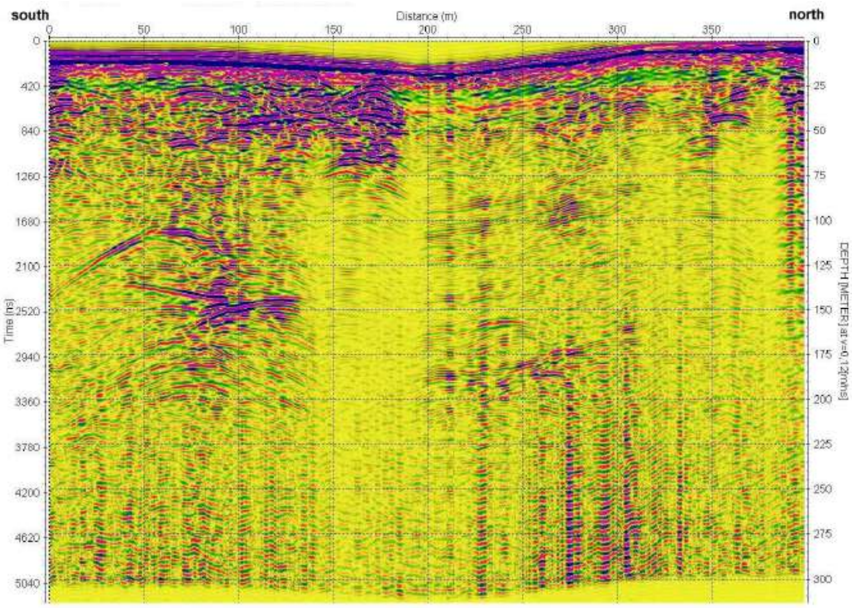

Fig. 17. Radarogram on profile Sko01 with the unknown corridor at the depth of 145 m at the distance 100 m (according to [Kalenda et al., 2018c])

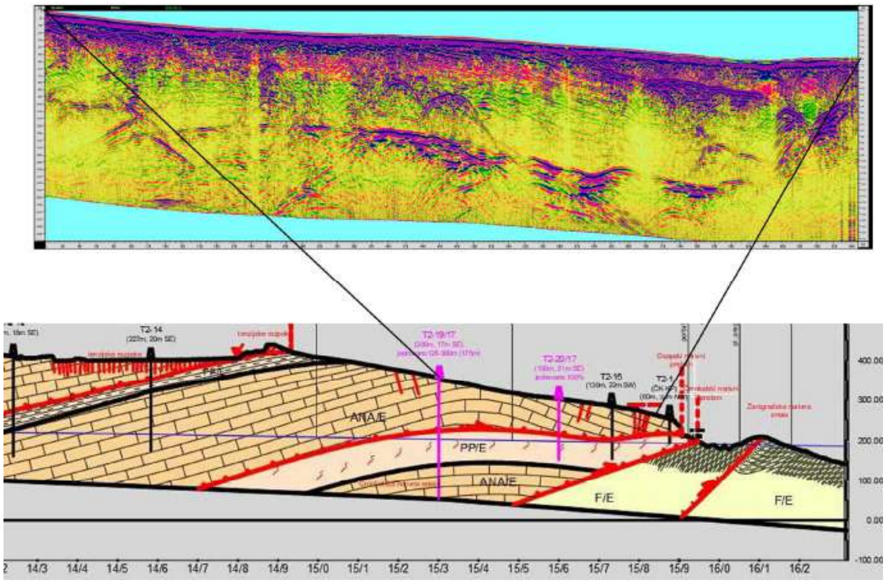

Fig. 18. Radarogram and geological cross-section via Črnotiče quarry (according to [Celarc et al., 2012]) (adopted from [Tengler and Kalenda, 2019])

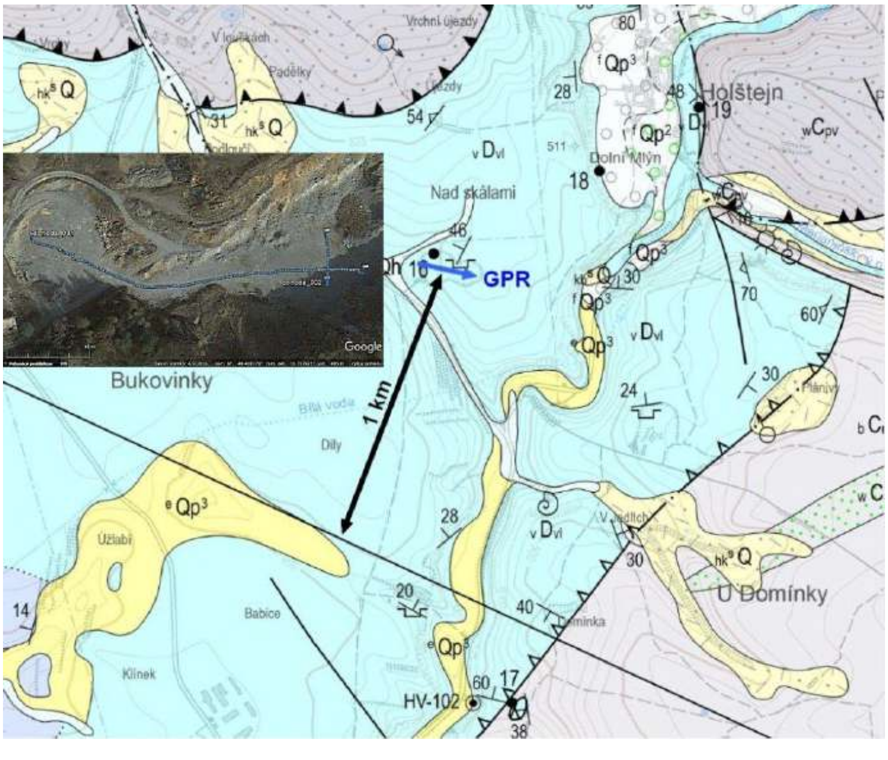

Fig. 19. Geological map of Malá Dohoda quarry surrounding (according [Baldík, 2016] and profile P1 in the quarry (blue arrow) (according to [Kalenda et al., 2020])

The deepest measurements were made already in 2016 in the Malá Dohoda quarry [Kalenda et al., 2020] in the optimal conditions at the bottom of the quarry (Fig. 19). The 6-m long antennas (25 MHz) were used and the length of the record was set to 16000 ns to reach depths of at least 750 m in limestone. The GPR profiles were measured approx. 1 km outside the geological cross-section [Baldík, 2016]. On the radarogram there are well visible the cavities (karstification) to the depths of 4500 ns (cca 500 m for 9.1 cm/ns) (Fig. 20). This is in agreement with the minimal water level before Baden transgression. The principal level between two kinds of limestone is detected at the depths of 7900 ns (approx. 870 m for 9.1 cm/ns). The limestone above this level are much compact than limestone below this level. The stratification is well visible below this level. The other huge borders are visible at the depths of 13000 ns and 14300 ns (approx. 710 m and 785 m for 9.1 cm/ns), which is in agreement with the geological cross-section, that placed to these depths the borders between limestones, basal conglomerates and Brno granite [Baldík, 2016] (Fig. 21) [Kalenda et al., 2020].

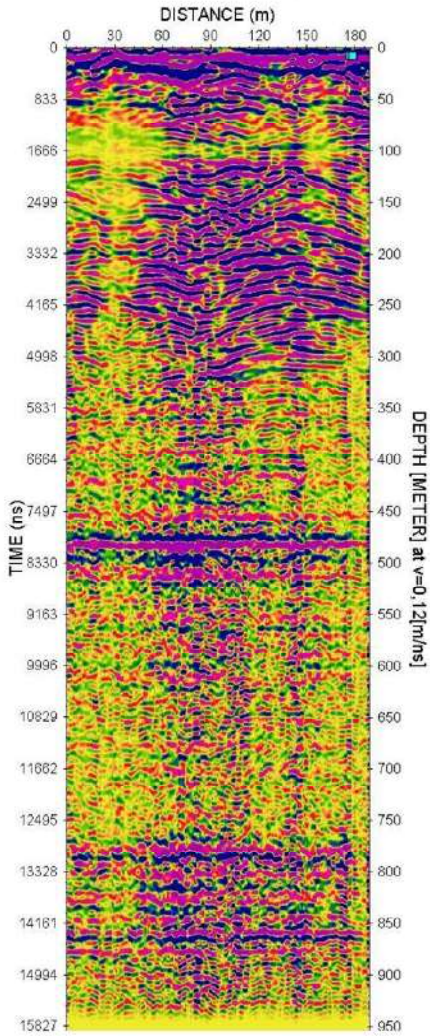

Fig. 20. Radarogram on profile P1 in the Malá dohoda quarry (adopted from [Kalenda et al., 2020])

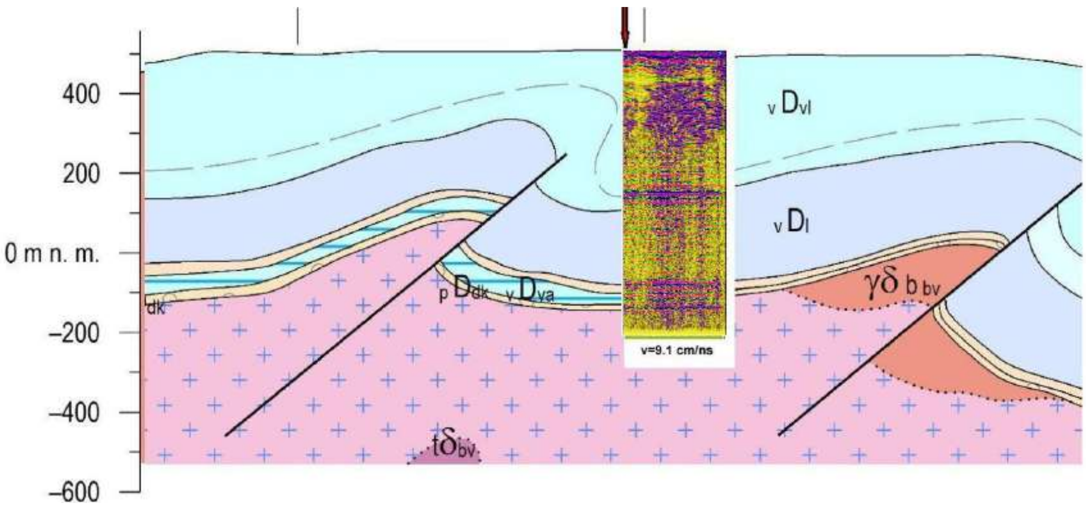

Fig. 21. Comparison between radarogram on profile P1 in Malá dohoda quarry and parallel geological cross-section [Baldík, 2016] (adopted from [Kalenda et al., 2020])

Originality

The quite new kind of GPR called Roteg with the extraordinary high voltage on transmitting antenna and pulse instead of harmonic signal generation of transmitted signal allows reach two orders bigger penetration depths than the common GPRs. Such results are unique and until now they have not been described in the literature.

Practical significance

The practical significance is obvious. The new kind of Roteg GPR makes it possible to obtain data (especially from karst areas) from depths that were previously only accessible by seismic methods or boreholes. GPR measurements are orders of magnitude cheaper and much faster in the field.

Conclusions

New type of Roteg GPR, which bypasses the semiconductor switching elements on the generator side, discharging the current from the capacitor directly into the spark gap, reducing its length to a minimum even at high output voltages (5–20 kV) and increasing dynamic range between the transmitting and receiving antennas of more than 180 dB, is able to increase the penetration depth many times. The theoretical penetration depth for wet clays should be 18 m, for wet sand 450 m and for dry sand (and limestone more than) 1125 m.

In the field experiments we subsequently verified the actual penetration depth for known caves. In the Moravian Karst, caves were clearly detected to depths of about 140 m below the surface, and in Slovenia we detected large caves to depths of about 250 m in the Classic Karst. Our results were confirmed by the discovery of the largest passage in the Škocjan cave system (the main discovery during last 100 years – Hidden Cave in the depth of 140 m below the surface).

The deepest reflections were detected at the Hranicka Abyss (580 m below the surface) and in the optimal conditions of the Mala Dohoda quarry near Holštejn (870 m below the surface).

References

Annan, A. P. (2005). Ground-penetrating radar. In: Near surface geophysics. Butler DK (ed). Society of exploration geophysicists: Tulsa, Investigations in Geophysics, 13; 357–438. https://doi.org/10.1190/1.9781560801719.ch11

Baldík, J. (2016). The basic geological map of Czech Republic 1:25000. List 24–233: Ostrov and Macochy (in Czech).

Blecha, V., & Kalenda, P. (2004). Gravimetric survey of the Holštejnská cave in the Moravian Karst. Zprávy o geol. výzkumech v roce 2003, 128–130 (in Czech).

Blecha, V., Kalenda, P., Mravec, P., & Kučera, J. (2005). Gravimetric survey of the continuation of the Holstein Cave. *Speleofórum,* 2005, 6–8 (in Czech).

Celarc, B., Jurkovšek, B., Placer, L., & Milanič. B. (2012). The structural building of the area between the Dinarides and the Istrian peninsula: the influence of plate tectonics on the construction of large infrastructural facilities (example 2. Tira Divača – Koper). Razprave 6. posvetovanja slovenskih geotehnikov, Lipica, 14–15. junij 2012. SloGeD (in Slovenian).

Chamberlain, A. T., Sellers, W., Proctor, C. and Coard, R. (2000). Cave detection in limestone using ground penetrating radar. *Journal of Archaeological Science,* 27, 957–964. https://doi.org/10.1006/jasc.1999.0525.

Gosar, A. (2012). Analysis of the capabilities of low frequency ground penetrating radar for cavities detection in rough terrain conditions: The case of Divača cave, Slovenia. *Acta Carsologica*, 41, 1, 77–88. https://doi.org/10.3986/ac.v41i1.49.

Gosar, A., and Čeru, T. (2016). Search for an artificially buried karst cave entrance using ground penetrating radar: a successful case of locating the S-19 Cave in the Mt. Kanin massif (NW Slovenia). *International Journal of Speleology*, 45, 2, 135–147. https://doi.org/10.5038/1827-806X.45.2.1979

Gospodarič R. (1985). On the spelogenesis of Divaška jama and Trhlovca Cave. *Acta carsologica,* xIII: 5–32, Ljubljana.

Guba, M. (2016). Press release on the in-depth exploration of the Hranická abyss and the achievement of a new maximum depth of –404 m. http://www.hranickapropast.cz/.

Hašek, V. and Štelcl, O. (1973). Some results of geophysical research of the Moravian Karst. Československý kras, 24: 37–49 (in Czech).

IRIS GPRs (2019): Ground penetrating radars by Mastrad Limited, Douglas, United Kingdom. http://www.mastrad.com/gpr.htm.

Kalenda, P., Blecha, V., Hrutka, M., & Mravec, P. (2006). Bukovinky – gravimetric measurement in the Moravian Karst. *Speleofórum,* 2006, 77–78 (in Czech).

Kalenda, P., Duras, R., & Kučera, J. (2008). Geophysical mapping using the very long wave method in the vicinity of the Hranická abyss – first results. *Speleofórum,* 2008, Vol. 27, 128–132 (in Czech).

Kalenda, P., Tengler, R.; Doležal, F. K., Reichel, V. and Chlup, L. (2016). *Geophysics Week 2015. Speleo.* 68, 15–23. ISSN 1213-4724 (in Czech).
Kalenda, P. and Tengler, R. (2016). Comparison of the results of geophysical methods above the Holstein Cave. *Speleofórum,* Vol. 35, 31–34 (in Czech).
Kalenda, P., Tengler, R., Cendelín, R., Slezák, L. and Pokorný, J. (2017a). Georadar measurements above Pekárna cave 2016. *Speleofórum, 2017,* Vol. 36, 30–35 (in Czech).
Kalenda, P., Tengler, R., Blatnik, M. and Drole, F. (2017b). Georadar measurements Postojna 2016. *Speleofórum, 2017.* Vol. 36, 87–89 (in Czech).
Kalenda Pavel, Tengler Rudolf, Cendelín Richard, Slezák Ladislav, & Pokorný Josef (2018a). Georadar measurements above Pekárna cave 2017. *Speleofórum, 2018,* Vol. 37, 25–29 (in Czech).
Kalenda, P., Tengler, R., Šebela, S., Blatnik, M., & Gosar, A. (2018b). Detection of Divaška jama behind Trhlovca jama. *Acta Carsologica,* Vol. 47, No. 2–3, 153–167. https://doi.org/10.3986/ac.v47i2-3.5187.
Kalenda, P., Tengler, R. & Šebela, S. (2018c). Where do the upper floors of the Škocjan Caves go from Martel's Chamber? *Speleofórum 2018.* Vol. 37, 72–75 (in Czech).
Kalenda, P., Tengler, R., & Geršl, M. (2020): Test of the maximum penetration depth of the Roteg GPR above the Hranice Abyss and in the Moravian Karst. GVMS, Vol. 27, No. 1–2, 98–105. https://doi.org/10.5817/GVMS2020-13587, https://journals.muni.cz/gvms/article/view/13587.
Łyskowski, M., Mazurek, E. and Zientek, J. (2014). Ground Penerating Radar investigation of limestone karst at the Odstrzelona Cave in Kowala, Swietokrzyskie Mountains, Poland. *Journal of Cave and Karst Studies,* Vol. 76, No. 3, 184–190. https://doi.org/10.4311/2014EX0001.
Musil, J. (2017). The Hranice Abyss became the deepest underwater abyss in the world! In: Bosák P, Geršl M, Novotná J (ed) Speleofórum, Vol. 36. Proceedings from Meeting of cavers in the Moravian Karst. Czech Speleological Society, Sloup, Czech Republic, 10–15.
Primorske novice 28.1.2019: https://www.primorske.si/primorska/srednja-primorska/jamarji-so-se-prebili-do-novih-delov-skocjanskih-j?fbclid=IwAR0aMx9_AaEzLB3Q_8KxUWRzIB51pzvy558HTgXj0x0o8JC-zbuBN9SabdI (in Czech).
Rez, J. (2010). Structural-geological development of the southern part of the Moravian Karst. Masarykova Univerzita, Brno (in Czech).
RTG-Tengler (2013). Available from: http://georadar.rtg-tengler.cz/geologicky-zlom-u-sobotky .
Slezák, L. (1955–1956). Geological research of Devonian limestones in the vicinity of Mokré. Diplomová práce: 1–76. Universita Jana Evangelisty Purkyně. Brno (in Czech).
Slezák, L. and Štelcl, O. (1963). Geological conditions of the southern part of the Moravian Karst and adjacent areas. *Časopis Moravského muzea,* 48, 89–104 (in Czech).
Slezák, L., Cendelín, R., & Pokorný, J. (2016). Back to the Pekárna cave. *Speleofórum, 2016,* 35, 29–31 (in Czech).
Smith, D. G. and Jol, H. M. (1995). Ground penetrating radar: antenna frequencies and maximum probable depths of penetration in Quaternary sediments. *Journal of Applied Geophysics, 33,* 1–3, 93–100. https://doi.org/10.1016/0926-9851(95)90032-2.
STA.novice 29.1.2019: https://www.facebook.com/STA.Novice/videos/1184180211759505/ (in Czech).
Tengler, R., Kalenda, P., Doležal, F. K. and Chlup, L. (2016). Testing a new type of georadar with a big penetration depth. *Speleofórum, 2016,* Vol. 35, 35–42 (in Czech).
Tengler, R., & Kalenda, P. (2019). Report of georadar (GPR) measurements in Slovenia 2019. Internal report of Črnotiče quarry.
Van der Kruk, J., Slob, E. C. and Fokkema, J. T. (1999). Background of ground-penetrating radar measurements. *Geologie en Mijnbouw, 77,* 177–188. https://doi.org/10.1023/A:1003546619639.
Zámek, E., 7 Zatloukal, R. (1993). 26 years of work in the Holštejn Cave. *Speleo, 11,* 22–25 (in Czech).

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ПРИНЦИПОВИЙ ПРОРИВ У ТЕХНОЛОГІЇ ГЕОРАДАРІВ – ROTEG

Мета досліджень – перевірити надзвичайно велику теоретичну глибину проникнення нового розробленого георадара в реальних умовах зон вапняків. У 2013 р. розроблено новий вид георадара (GPR) – Roteg (RTG-Tengler 2013). Його технічні параметри (амплітуда імпульсу на передавальній антені 20 кВ і більше, чутливість приймальної антени не менше ніж 2 мкВ, тобто реальний рівень виявлення сигналу близько 20 мкВ) свідчать про те, що реальний динамічний діапазон реєстрації сигналу становить 9 порядків, тобто 180 дБ. Така чутливість означає, що реальна глибина проникнення повинна бути на два порядки більшою, ніж у випадку звичайних георадарів. Ми перевірили реальну глибину проникнення за відповідних умов навколишнього середовища над печерами в Моравському Карсті та в Словенії біля печери Постойна. Результати вимірювань показали, що відбиття від відомих печер надійно виявляються за їх глибин 40–210 м під поверхнею. На профілі над Границьким проваллям простежуються відбиття від геологічних структур до глибини 480 м, де, ймовірно, розміщене дно Колодязя ІІ. Новий вид георадара Roteg з імпульсами 20 кВ на випромінювальній антені зміг виявити відбиття від контакту Девон – Граніти Брно на глибині до 850 м в оптимальних умовах у вапняках без ґрунтового покриву (в копальні Мала Дохода у Моравському Карсті). Радарограма показала зміну літології між вапняком Вілемовіце – Лажанки та шарами уламкових порід у низах вапнякової товщі. Обидва згадані вище випробування підтвердили надзвичайно велику глибину проникнення сигналу георадара, яка перевищувала 500 м в умовах вапняків із використанням максимальної потужності передавальних антен. Зовсім новий вид георадара під назвою Roteg із надзвичайно високою напругою на передавальній антені та генерацією зондувального імпульсу замість гармонічного сигналу дає змогу досягти на два порядки більшої глибини проникнення, ніж звичайні георадари. Новий тип георадара Roteg дає можливість отримати дані (особливо із зон вапняків) з глибин, які раніше були доступні лише за допомогою сейсмічних методів або свердловин. Георадарні вимірювання на порядки дешевші та набагато швидші в польових умовах

Ключові слова: георадар; глибина проникнення; карст.

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