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OBSERVATIONS AND RESULTS OF GPR MODELLING OF SINKHOLES IN UPPER SILESIA (POLAND)

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[Manuscript received July 30, 2001]

Using a RAMAC-GPR with a 200 MHz antenna, we obtained radargrams in an old coal-mining district of Upper Silesia (Poland), where exploitation holes represent a danger of collapse for existing structures. Despite some drawbacks, GPR methods seem to be the best technique for mapping and monitoring these holes, which may reach the surface after some time. In the first part of this paper, we show actual field measurements for a typical case, and in the second part we present preliminary theoretical investigations. We construct 2D synthetic radargrams based on the information we obtained from available geological data and the interpretation of the real radargrams. Thus, we formulate suggestions on how to optimize the methodology of locating sinkholes by the GPR technique, and give some clues concerning the theoretical interpretation of GPR data in this particular case.

Keywords: applied geophysics; coal mining, Upper Silesia; field measurements; ground-penetrating radar, GPR; sinkholes; theoretical modelling

1. Introduction

Upper Silesia is the region of oldest coal mining in Poland, and nowadays it is paying the price for this privilege in the form of local disasters. Already in the 18th century, and even more so in the 19th century, the coal was extracted from very superficial beds. In unsettled times, miners having lost their employment often used to exploit the outcropping seams or those just beneath the ground level. The structures supporting these excavations were not built with any thought for the sequels of such an exploitation in the long-term. Therefore, we are now facing uneven settling of the rock overlying the excavated coal beds, and the formation of sinkholes which migrate very slowly towards the surface. The holes which have reached the surface are visible as craters or shallow depressions. In particular, the buildings and railway tracks above holes which are reaching the outer surface are at a constant risk of destruction by subsidence of the terrain on which they are built. Upper Silesia is a most urbanized part of Poland, where mining is still continued under built-up areas. Thus, the risk of destruction caused by sinkholes is all but negligibly small, and appropriate investigations for localizing holes approaching the surface constitute important and challenging tasks for environmental geophysicists.

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1. Introduction

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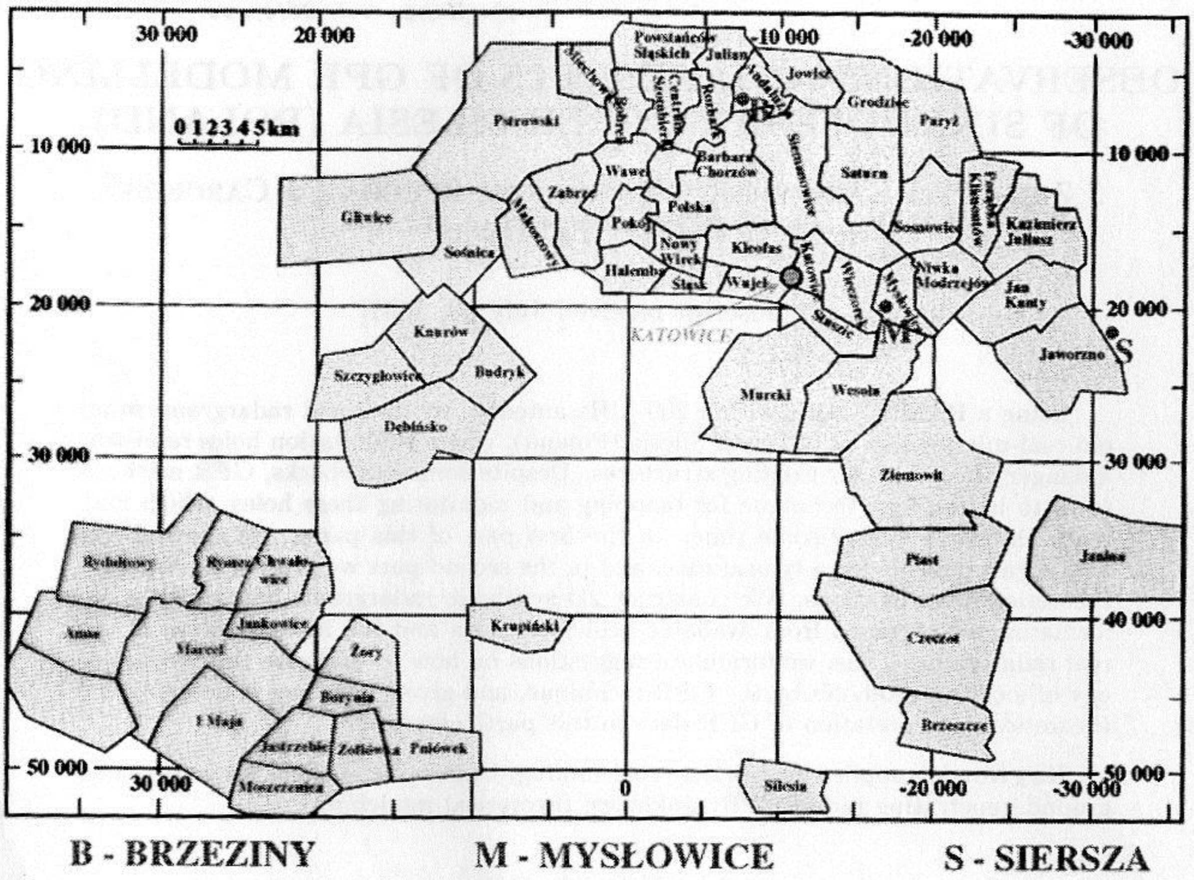


Fig. 1. Map of the mining area around Katowice (Upper Silesia, Poland)

In the Mysłowice district, not far from Katowice, the coal seams occur relatively close to the surface. This is, in particular, the case of beds 501 and 510 (see Fig. 2), which were excavated at the end of the 19th century. The geographical map of the area is shown in Fig. 1, and the different geological strata are sketched in Fig. 2. Above the coal seams are layers of loose sand, whereas the coal beds themselves are interleaved with shale. The basement rocks are overlain by a layer of clay, which had been assumed to be impervious and, thus, prevent water from penetrating below. Nevertheless, after many years, the water penetrated the bedrock, and this caused the holes to move upwards.

Above the mining site runs the railway line Berlin-Kiev, which is heavily used in this sector (Fig. 3). In 1968, there appeared a swallow hole, 20 m in diameter and 12 m deep, which made the railway line momentarily impracticable (Fig. 4a). A signal house close to the railway track was severely damaged too (Fig. 4b).

Protection of surface structures against such collapse phenomena can only be granted if it is possible to determine precisely the location of sinkholes before collapse occurs. Under these circumstances, openings can be drilled and the holes can be filled up with special material mixtures, which under favourable geological and hydrological conditions may contain dangerous waste. The filling of the holes thus prevents collapse and local instabilities of the soil. In 1968, when the swallow hole shown on Fig. 4a opened, attempts to fill it were made, but the cavity reappeared

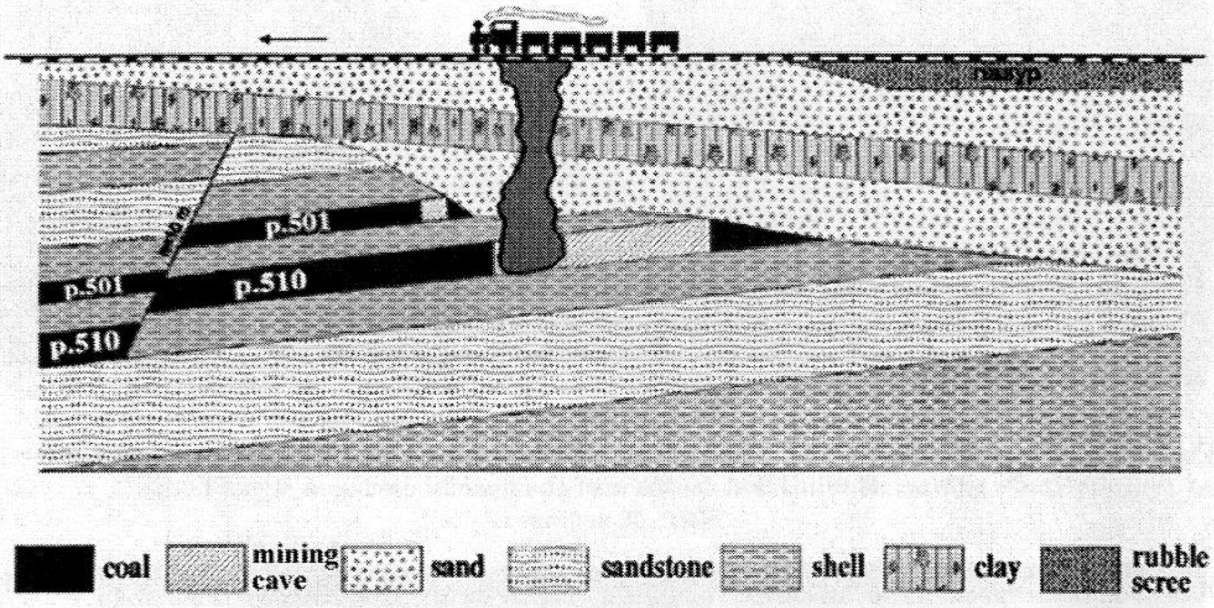


Fig. 2. Geological cross-section of the area of the coal mine Mysłowice, showing a mining sinkhole under the railway track Berlin-Kiev (after Fajklewicz et al. 1997)

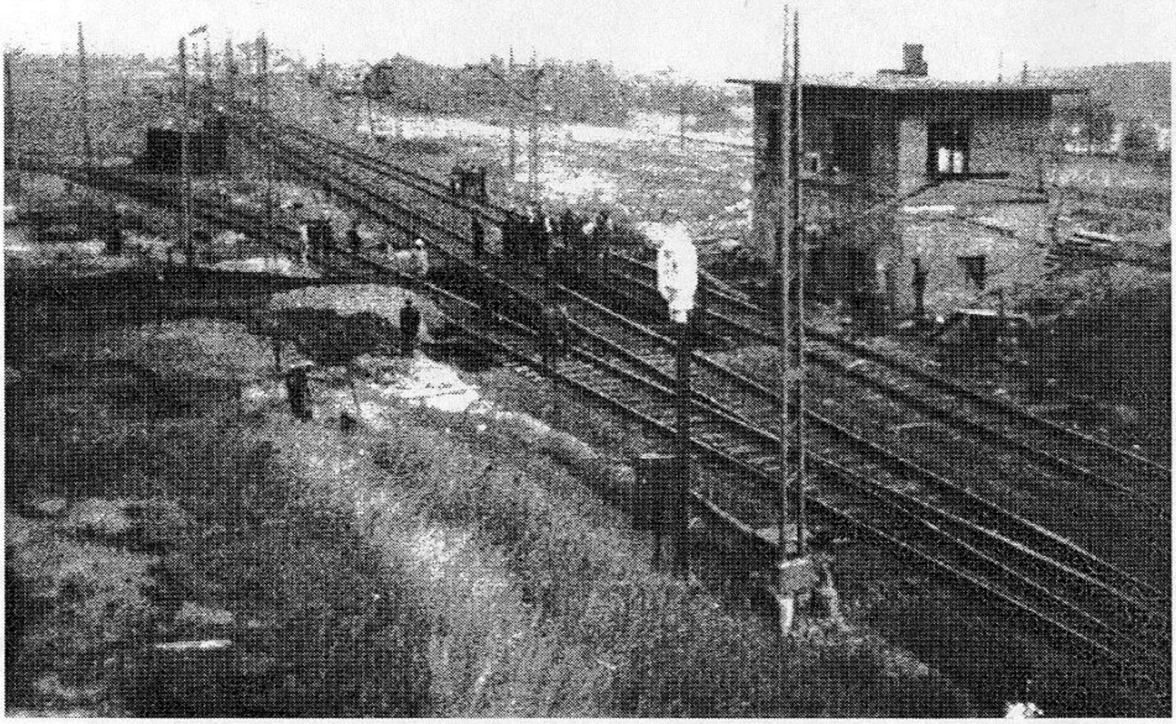
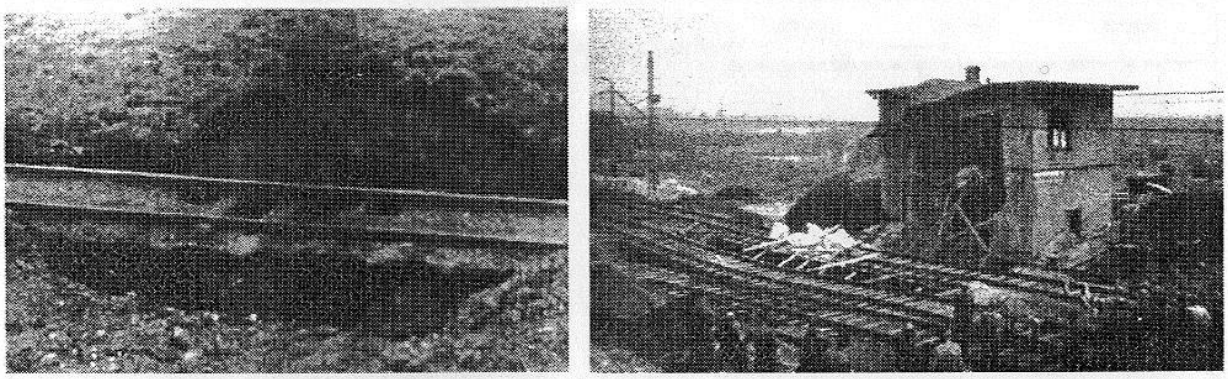


Fig. 3. Mining sinkhole over a coal seam exploited in 1861

several times. At this time, various geophysical investigations — electric, seismic and gravimetric — were performed, but no georadar studies were yet undertaken, because this technology was not available then in Poland.

Our experiments with ground-penetrating radar equipment, using 200 MHz antennae, demonstrated that under favourable geological conditions, an emergent sinkhole can be detected down to a depth of at least 12 metres.



a) b)

Fig. 4. a) Close-up view of the collapse hole which occurred in 1968 in Mysłowice below the railway track Berlin-Kiev. b) View of the heavily damaged signal house

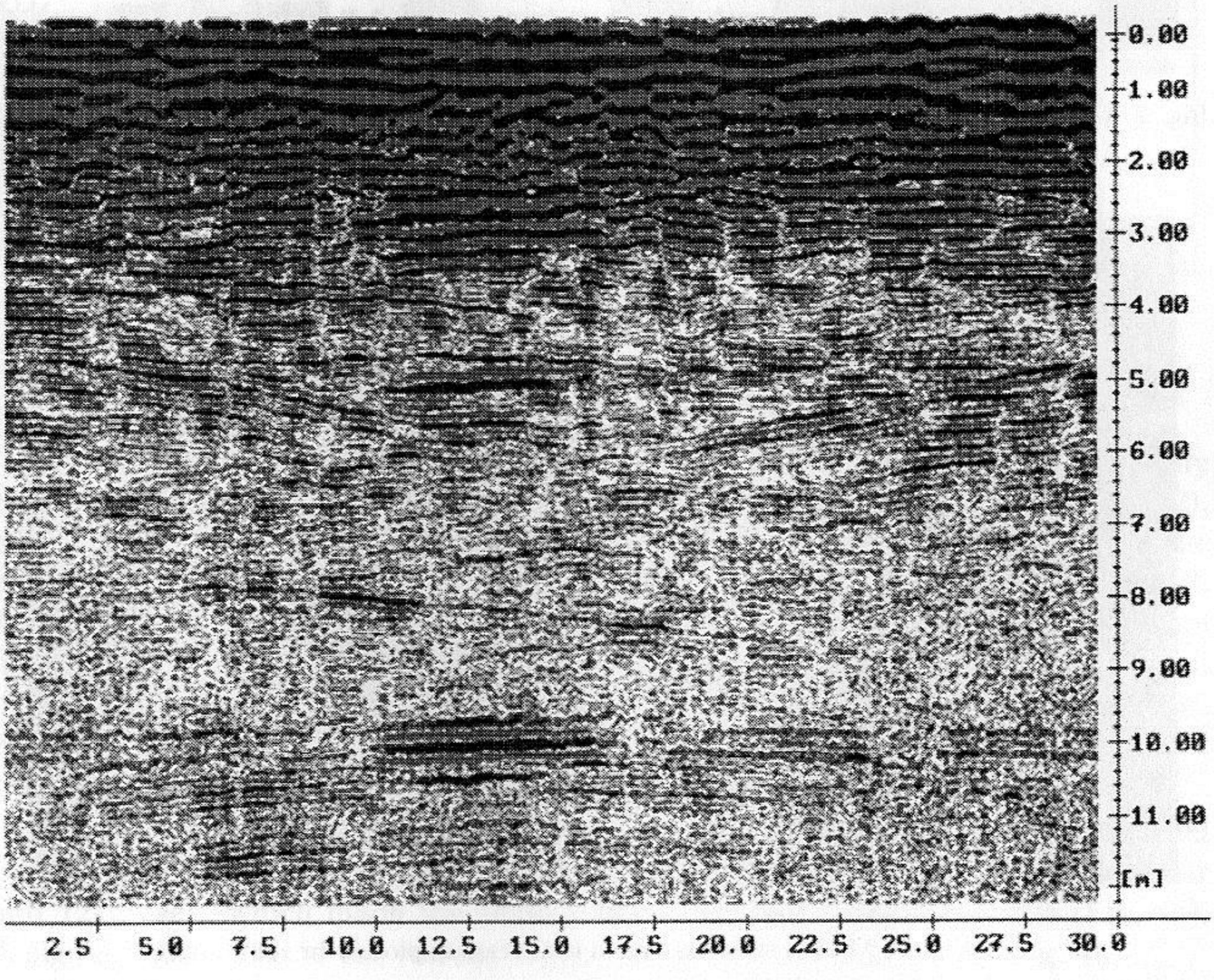


Fig. 5. Georadar profile recorded in Brzeziny (200 MHz antennae, v=8.5 cm/ns)

An example is shown on the radargram of Fig. 5, which we obtained during our investigations in Brzeziny. Although the signal is not all too sharp and our interpretation may be questioned to some extent, we notice the existence of a rather perturbed underground structure, which we identify with a sinkhole whose vertical axis is centred roughly on abscissa 13.0. The top of this sinkhole is located some

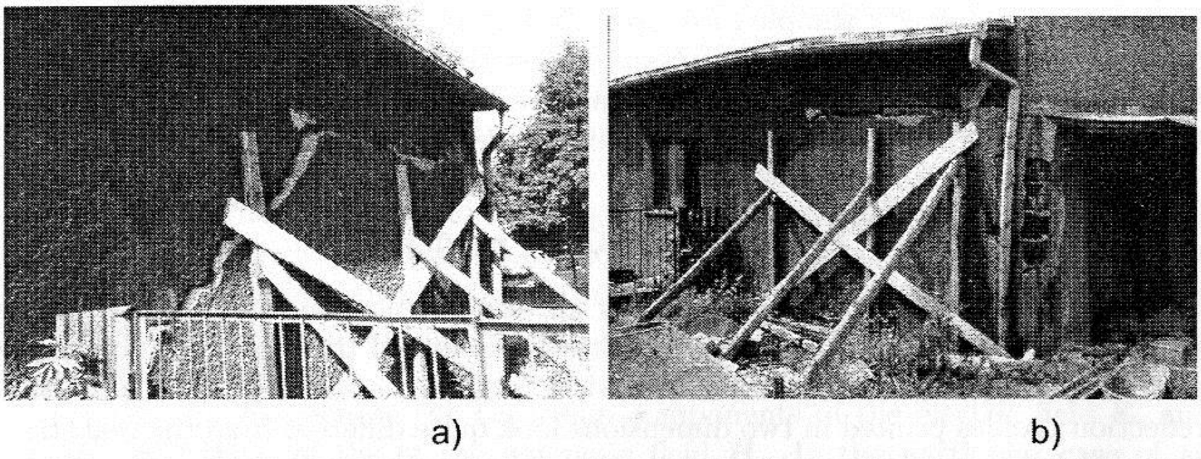


Fig. 6. Two views of a house damaged by an active hole in Piekary Śląskie (Brzeziny) on November 25, 1998

4 or 5 metres below the surface. The whole structure appears to be quite large and dangerous, for the house shown on Fig. 6 is situated at a distance of 40 metres from the vertical axis of the underground hole detected by means of the radargram shown in Fig. 5. The state of near-collapse of the building illustrated on Fig. 6 results from the significant ground deformation caused by the underground cavity.

2. Concept of the project and methodological steps

The shape of a mining sinkhole is often irregular and complicated. Keeping the fact in mind that sinkhole localization by means of geophysical methods leads sometimes to unreliable results, we tried to find out to what extent synthetic radargrams based on computer models can improve the interpretation of actual radargrams recorded *in situ*. Basically, in this project we try to check whether rather simple computer models can be brought into a reasonable agreement with observations.

To achieve this goal, we proceed as follows: 1. find a place where a mining sinkhole is expected; 2. carry out georadar measurements; 3. drill bore-holes; 4. elaborate a geological model; 5. construct a computer model based on the geological data at hand; 6. compare the results of computer models with the results of georadar measurements, and 7. draw conclusions.

The radargrams presented in this study were obtained by means of a georadar RAMAC/GPR produced by the Swedish firm Mala-Geoscience. This instrument can work with nine different sets of shielded or unshielded antennas in the frequency range between 10 MHz up to 1 GHz. The antennas are connected to a central processing unit by optical fibers. The latter design eliminates a great part of the noise which would occur in cables, and prevents possible interference between different cables. The device is capable of recording up to 200 traces per second. Because the measurement efficiency is very high, the maximum number of stacks is 32 768. Thus, low amplitude noise is virtually eliminated, and the signal-to-noise ratio is greatly increased. The RAMAC/GPR equipment is exceptionally light and quite handy to use. Its essential components, besides the central unit, consist of a transmitter, a receiver, a hip chain, a trigger box, and a laptop computer (notebook). The specifications are as follows: sample rate, up to 200 scans/s; performance factor, 150 dB; time window, max. 12 μs; number of samples per trace, 128–2048; number of stacks, 1–32768; weight (incl. batteries), 4.9 kg; antennas, unshielded: 10, 25, 50, 100, 200, 400 MHz, shielded: 200, 500, 1000 MHz, bore-hole: 100, 250 MHz.

3. Synthetic GPR modelling

Two-dimensional profiles produced by moving antennas along transects are not always easy to interpret in terms of the stratigraphy and the cavities which can be seen in trench profiles or outcrops. Indeed, it is often the case that GPR processed reflection profiles printed in two dimensions look quite different from the real structure and features of the underground. There are several reasons for this. One is that GPR antennas transmit energy into the ground in a wide beam, and therefore the receiving antenna is not looking straight down, but also in front, in back, and to the sides. Thus, when the antenna is in front of a cavity or a buried object, the travel time for an electromagnetic wave to leave the antenna, reflect off the hole or object, and return directly to the antenna is somewhat longer than when the antenna is directly above the hole. The net effect is a hyperbolic reflection pattern over the hole as the antenna moves over it. Another reason that GPR reflection profiles can look very different from the actual features that need to be resolved is the phenomenon of multiple reflections, which can occur within the ground as radar waves are reflected more than once off subsurface discontinuities before being recorded at the surface. Such instances of a double 'echo' of the subsurface reflector can lead to problems of interpretation of the radargrams.

The synthetic radargram technique can be helpful in identifying buried structures, provided some prior information about the site is available. In particular, the stratigraphic and electrical characteristics of sediment and soil, as well as the geometry of overburden units and of the investigated structure, need to be inferred. These data are then processed by means of a ray-tracing computer program to create a two-dimensional model which simulates, in a simplified manner, a slice through the earth. This model can then be used by another numeric code to predict the reflectivity constants encountered at the various interfaces, the signal attenuation with depth, the velocity at which radar energy propagates in the different media, and the amplitude of the received reflections (Goodman 1994). After the model is run, the simulated reflections are shown as a 2D-plot in the same way as standard GPR profiles. Relative amplitudes of reflections are customarily highlighted by using different gray scales or colours. A good reference concerning various aspects of georadar measurements is chapter 12 of the book written by Reynolds (1997), and supplementary general information on how to create a synthetic radargram can be found in the book by Conyers and Goodman (1997).

The synthetic radargrams presented in this paper were obtained by means of the software package 'GEMS' (Georadar Electromagnetic Modelling and Simulation) based on the theory and algorithms described and discussed by Carcione (1996). This package designs the geological model, provides the kinematic and dynamic properties of each medium, and generates synthetic radargrams for various antennae configurations. An essential task of the code is to integrate Maxwell's equations for the boundary conditions and interfaces prescribed by the geological model. A physically most appealing approach to the study of the traditional Maxwell equations for nonhomogeneous, nonlinear, and nonisotropic media is provided by the standard text of Lorrain and Corson (1970). Carcione (1996) implements a formalism, based on Chew (1990), which still generalizes Maxwell's equations to include the possibility of dielectric relaxation. Moreover, to reach an even greater degree of generality, he considers a source term corresponding to magnetic current densities, already introduced by Chew (1990, p. 9) to make Maxwell's equations symmetrical with respect to sources.

Let (E_x, E_y, E_z) denote the Cartesian components of the electric field $\mathbf{E}$, and (H_x, H_y, H_z) those of the of the magnetic field $\mathbf{H}$. In the particular case of an isotropic continuum where electromagnetic wave propagation occurs in the (x,z)-plane and the material properties are constant with respect to the y-coordinate, the field components E_x, E_z, H_y are decoupled from the components E_y, H_x, H_z. Assuming, moreover, a single dielectric relaxation mechanism, Carcione (1996) puts the differential equations containing the transverse magnetic (TM) field component H_y into the compact matrix form

$$\frac{\partial \mathbf{V}}{\partial t} = \mathsf{M}\mathbf{V} + \mathbf{S} \tag{1}$$

where $\mathbf{V}$ is the unknown vector field $[H_y, E_x, E_z, e_x, e_z]^T$, e_x and e_z being hidden field variables describing dissipation due to relaxation processes (Carcione 1990, 1993), $\mathbf{S}$ is a source vector, and M is a matrix containing material parameters and spatial derivatives. Its explicit expression is given in Carcione (1996, Eq. 46).

Equation (1) is solved with a direct grid method, which evaluates the spatial derivatives of the field variables by using the Fourier pseudo-spectral technique (Canuto et al. 1988), and propagates the solution in time by means of a fourth-order Runge-Kutta algorithm (Forsythe et al. 1977). Under certain circumstances, the differential system (1) becomes stiff. In this case, the software uses a splitting time integrator for the stiff part, and the Runge-Kutta integrator for the non-stiff part.

4. Sinkhole in Siersza

In Siersza (Upper Silesia) we encountered a situation rather similar to that of Brzeziny, and we decided to test the usefulness of mathematical modelling in this particular case. Our investigations were prompted by the appearance and fast development of a depression in a garden. We decided to proceed to a systematic surveying of the site with ground-penetrating radar, according to the grid of parallel measurement profiles indicated in Fig. 7. For some profiles, the corresponding recorded radargrams showed traces which we tentatively ascribed to sinkholes. Of particular interest to us, the geophysicists, and even more so to the occupants of the house, was the radargram corresponding to the profile close to the building, shown in Fig. 8.

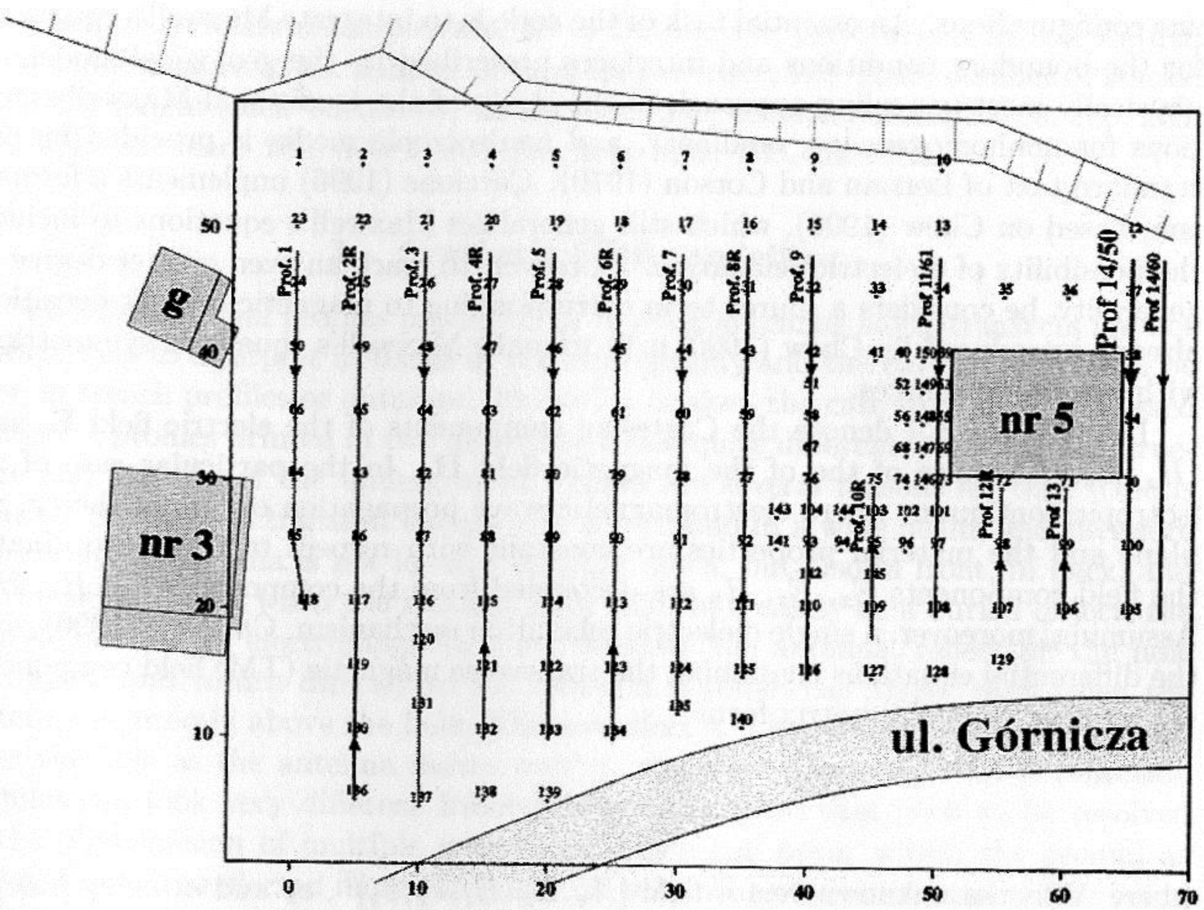


Fig. 7. Grid of parallel measurement profiles in Siersza

The latter exhibits a pattern which we interpreted as being produced by a sinkhole, and this diagnosis was, indeed, confirmed by drilling at two points to a depth of about 9 metres. The locations of the two bore-holes are indicated by thick vertical line segments in the *geological model* sketched in Fig. 9, where they correspond roughly to the abscissae 2 and 20, respectively. The upper layer consists of loose aggregates (thickness $\vartheta \approx 2\,\text{m}$; typical electric conductivity $\sigma \approx 2\times10^{-4}\,\text{S m}^{-1}$; typical relative electric permittivity $\varepsilon_r \approx 10$). Below is a layer of sandy soil ($\vartheta \approx$ 6–7 m; $\sigma \approx 3\times10^{-4}\,\text{S m}^{-1}$; $\varepsilon_r \approx 6$), which overlies a layer of sandstone or sandy silt ($\vartheta \approx$ 5–6 m; $\sigma \approx 10^{-4}\,\text{S m}^{-1}$; $\varepsilon_r \approx 7$ in the silt, 5 in the sandstone). The borehole at abscissa 20 showed the existence, at a depth of about 8 metres and essentially localized within this sandstone and sandy silt layer, of a hole filled with a mixture of loose sand, clay and water. It should be emphasized that the only direct information on which the geological model presented in Fig. 9 is based, consists of these drilling results as well as of the known depth of the coal seam 207 (roughly 14 m). The clay layer below, with physical characteristics $\vartheta \approx$ 4–6 m; $\sigma \approx 2\times10^{-2}\,\text{S m}^{-1}$; $\varepsilon_r \approx 5$, has been established with a lesser degree of certainty, and the substratum of sandstone ($\sigma \approx 10^{-3}\,\text{S m}^{-1}$; $\varepsilon_r \approx 14$) containing cracks and cavities ($\sigma \approx 10^{-3}\,\text{S m}^{-1}$; $\varepsilon_r \approx 4.5$) is even slightly more hypothetical.

Anyway, we used this geological model as an input to a preliminary mathematical model which we processed with the 'GEMS' software package. In the direct grid

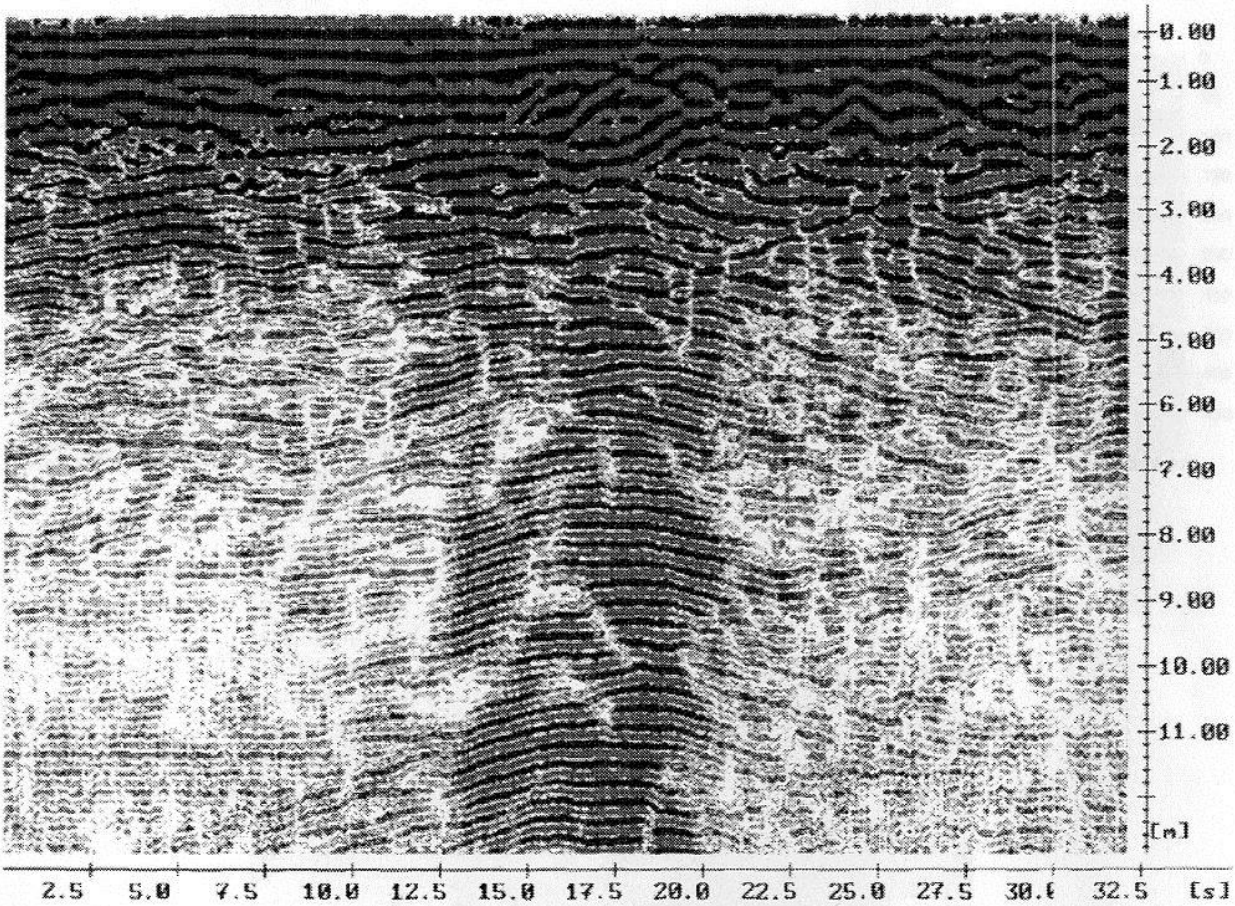


Fig. 8. Georadar profile recorded in Siersza (200 MHz antennae, v=8.5 cm/ns)

method, we considered a numerical mesh with 405×405 grid points, with a grid spacing of 7.5 cm. The source is a Ricker-type wavelet with a central frequency of 200 MHz, applied as a horizontal electric current plane wave, in order to approximate a stacked radargram. The algorithm uses a time step of 0.05 ns and absorbing strips of length 18 at the boundaries of the numerical mesh.

Figure 10a shows the synthetic radargram based on the geological model in Fig. 9 for a transient magnetic field H_y at a frequency of 200 MHz, in a lossy medium. Figure 10b shows the same, but for a frequency of 50 MHz. Finally, Fig. 10c shows the H_y-radargram for a lossless medium at a frequency of 200 MHz. Figure 11a shows the associated synthetic radargram corresponding to a transient electric field E_x at a frequency of 200 MHz, for a lossy medium. Figure 11b shows the same, but for a frequency of 50 MHz, and Fig. 11c shows the E_x-radargram for a lossless medium at a frequency of 200 MHz.

In the geological model sketched in Fig. 9, the average value of the relative electrical permittivity ε_r is close to 8. This corresponds to an average propagation speed of electromagnetic waves of about 0.106 m/ns. On the synthetic radargrams in Figs 10 and 11 we notice a sharp signal corresponding to a double propagation time from the outer surface of about 150 ns, i.e. a depth of 8 m. Hence, our geological model predicts a sharp georadar signal at a depth of 8 m. The recorded actual radargram (Fig. 8) appears rather blurred, because the actual structure is hardly as

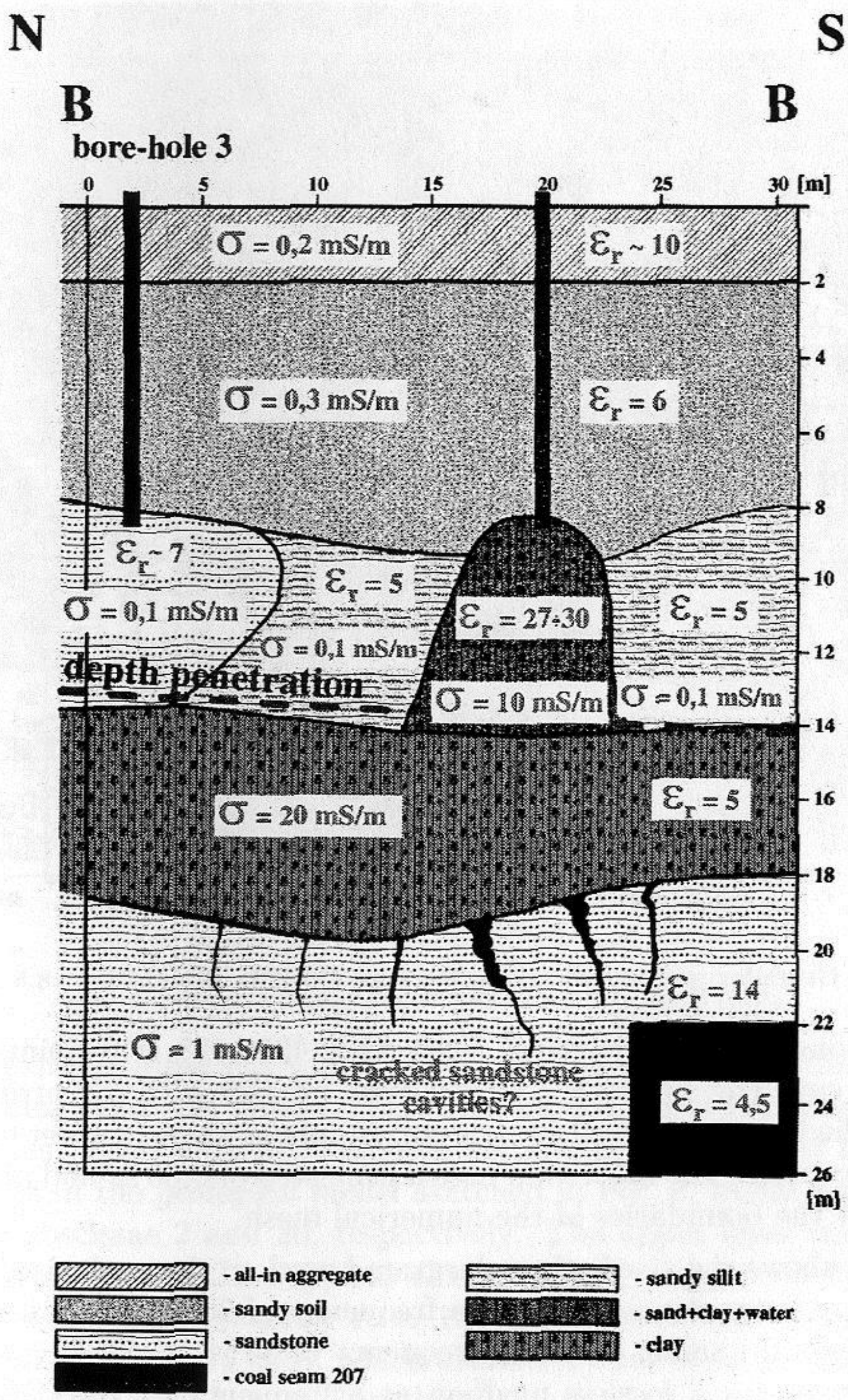


Fig. 9. Geological model around a sinkhole in Siersza derived from core sampling

simple as the one used for modelling. Nevertheless, after some careful inspection, we may recognize a number of common features on both the recorded and the synthetic radargrams which obviously reflect the existence of the sinkhole found by drilling at a depth of 8 m.

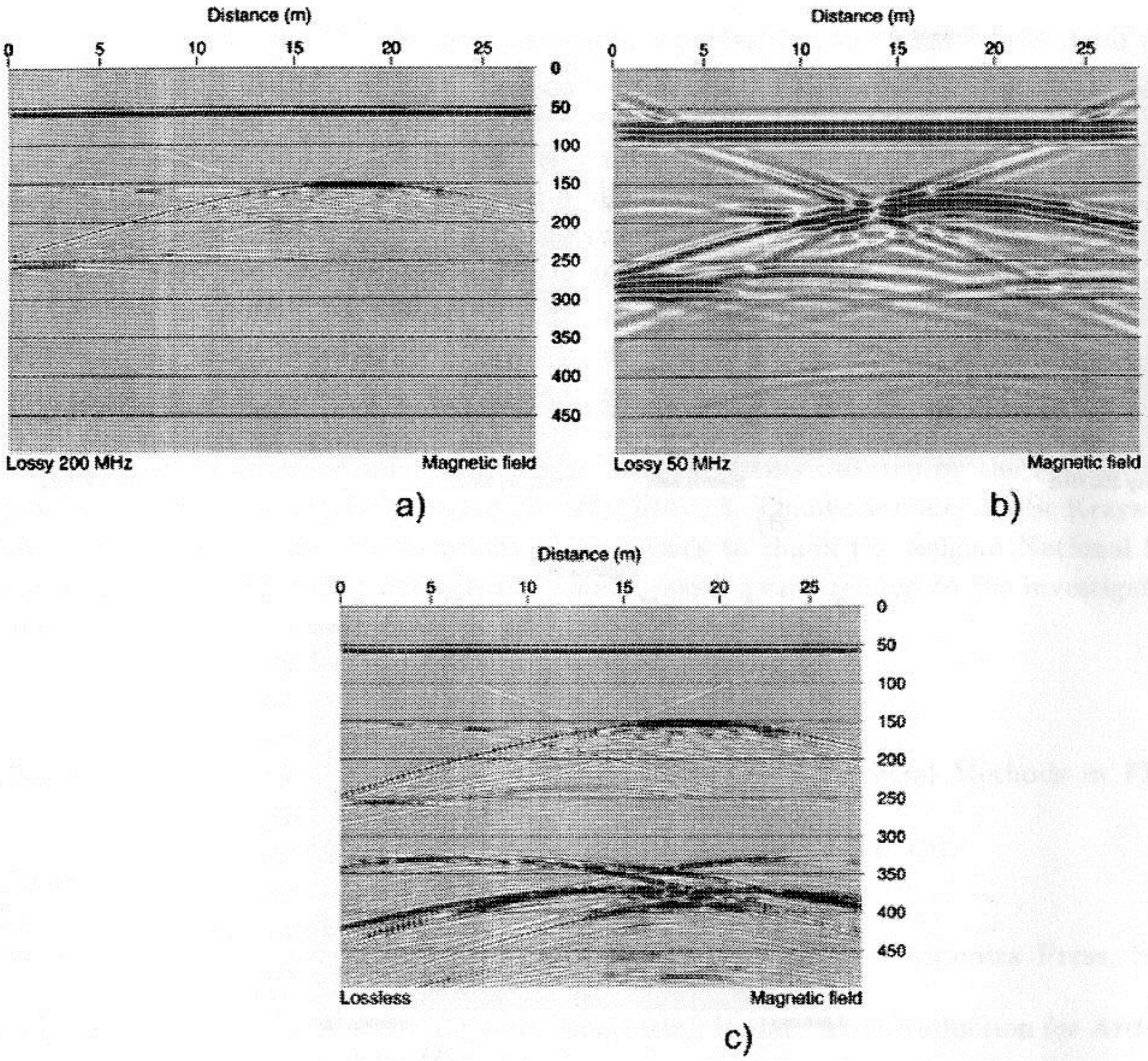


Fig. 10. Synthetic magnetic radargram for a) a lossy medium and a 200 MHz antenna; b) a lossy medium and a 50 MHz antenna; c) a lossless medium and a 200 MHz antenna. The horizontal axis represents the distance along the profile, whereas the vertical axis is depth, expressed in terms of twice the propagation time (in nanoseconds) to the reflector

5. Discussion and conclusions

In the particular case of the Siersza sinkhole investigated in this paper, geological modelling reveals a sharp contrast of physical properties between the mining sinkhole and its geological environment. As a matter of fact, the real borders are diffuse and the contrast is less striking. This is one reason that a difference between the synthetic radargram and the real one exists. The model predicts a sharp georadar signal at a depth of 8 m. The latter can be observed on the field profile only after careful inspection. Thus, in this case, the depth of the hole corresponded more or less both in computer modelling and in georadar scanning. In practice, however, the unstable zone extends closer to the surface and a more complicated formulation of the model has to be considered in order to achieve a better detailed agreement between theory and observations. In particular, the improved model should describe changes within the hole, such as the development of fractures and

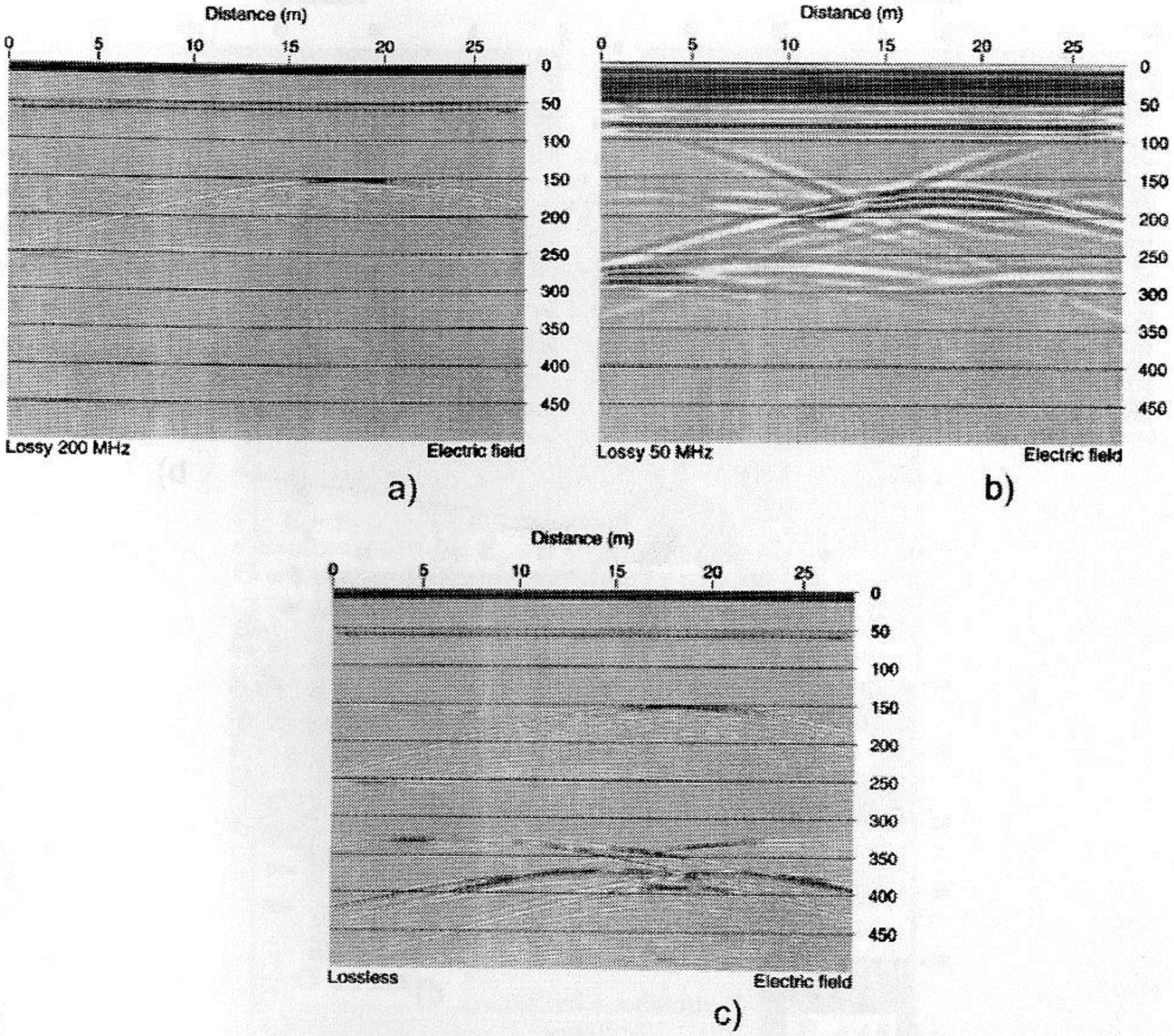


Fig. 11. Synthetic electric radargram for a) a lossy medium and a 200 MHz antenna; b) a lossy medium and a 50 MHz antenna; c) a lossless medium and a 200 MHz antenna. The horizontal axis represents the distance along the profile, whereas the vertical axis is depth, expressed in terms of twice the propagation time (in nanoseconds) to the reflector

discontinuity layers. The discrepancy along the profile (horizontal axis), which can be seen when comparing the observed radargram (Fig. 8) with the synthetic ones (Figs 10 and 11), indicates that the assumption that the borders are continuous and sharp is an oversimplification. Future models should at least provide for continuous changes in the physical properties of the different media.

We have described here a particular case study suggesting that in many cases the georadar method should allow to precisely locate sinkholes in old mining districts. The georadar technique definitely offers an advantage over other geophysical methods because it is cheap and yields results rapidly. Quite often, raw observational material lends itself to geophysical interpretation. Moreover, a comparison of theoretical results, based on mathematical modelling, and field results leads to a better understanding of the processes occurring around a mining sinkhole, and permits to study the development of the hole. However, there is clearly a need for a better knowledge of the physical parameters pertaining to the sinkhole itself and its surroundings in order to ensure, in future investigations, a more comprehensive interpretation of a broad set of measurements, including electric, seismic and gravimetric sounding profiles. As far as theoretical modelling is concerned, we have to keep in mind that the geometry of a sinkhole and its immediate environment is, as a rule, not simple enough that we can expect a realistic modelling with 2D computer programs. Realistic modelling obviously will become feasable only with flexible 3D codes.

Acknowledgements

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