GEOLOGICA CARPATHICA, JUNE 2005, 56, 3, 285–294

Seismic reflection investigations for gas storage in aquifers (Mura Depression, NE Slovenia)

ANDREJ GOSAR[1, 2]

[1]Environmental Agency of the Republic of Slovenia, Dunajska 47, SI-1000 Ljubljana, Slovenia; andrej.gosar@gov.si
[2]University of Ljubljana, Faculty of Natural Sciences and Engineering, Askerčeva 12, SI-1000 Ljubljana, Slovenia

(Manuscript received January 7, 2004; accepted in revised form June 16, 2004)

Abstract: Two antiform structures in the Mura Depression were investigated as the most promising in Slovenia for the construction of an underground gas storage facility in aquifers. Seventeen reflection profiles with a total length of 157 km were recorded, and three boreholes were drilled at their locations. Structural models based on interpretation of the reflection seismic data, were constructed for the two main horizons (the pre-Tertiary basement and the Badenian/Sarmatian boundary). Evaluation of different seismic velocity data was carried out to establish lateral velocity variations in order to perform correct time-to-depth conversion. The porous rock in the Pecarovci structure is a 70 m thick layer of dolomite, occurring at a depth of 1900 m, whereas layers of marl, several hundred meters thick, represent the impermeable cap rock. Due to faults, the Dankovci structure, at a depth of 1200 m where the reservoir rocks consist of thin layers of conglomerate and sandstone, was found to be less reliable. 1D synthetic seismograms were used to correlate the geological and seismic data at the borehole locations. Raytracing modelling was applied to confirm lateral continuity of some horizons and to improve the structural interpretation at the locations of faults, which are critical factors for the storage of gas.

Key words: Pannonian Basin, Mura Depression, raytracing modelling, synthetic seismograms, gas storage, seismic reflection.

Introduction

Slovenia imports almost all the gas it needs. The supply through the pipelines is fairly constant throughout the year, but consumption is subject to seasonal changes. For this reason, gas must be stored in the summer months in order to permit higher consumption during the winter. For economic and safety reasons, the storage of natural gas is reasonable only when underground (Dussaud 1989). There are four main types of underground storage: salt caverns, abandoned mines, aquifers or depleted oil or gas fields, and hard rock caverns (Gaussens 1986).

The geological structure of Slovenia only permits storage in aquifers (Fig. 1). Geological investigations for such facilities have been ongoing for more than 15 years. The goal has been to find an appropriate antiform structure, at a depth of between 500 and 2000 m, composed of porous (reservoir) rock with an impermeable covering layer (Tek 1989; Flanigan 1995). In the first stage, 13 different locations (Sadnikar 1993) were investigated and two of them (Pecarovci and Dankovci) in the Mura Depression were selected for further exploration. Geophysical methods, especially reflection seismics, had an important role in the evaluation of possible suitable locations.

The Pecarovci and Dankovci structures are located in the Mura Depression (Gosar 2005), on the slope of the Murska Sobota massif, which dips towards the Radgona depression. In this area, the depth to the pre-Tertiary basement (Pt horizon) is between 1800 and 2000 m. The possible collector rocks for gas storage are the Mesozoic carbonates in the pre-Tertiary basement and the thin layers of porous conglomerates and sandstones above the discordant boundary between the Badenian and Sarmatian layers (KB horizon) inside the Tertiary sediments (Turk 1993).

Seismic reflection investigations

A dense net of reflection seismic profiles was recorded at the Pecarovci-Dankovci location. For the construction of a structural model in an area measuring 8×8 km (Fig. 2), we used 17 profiles. The total length of these profiles is 157 km and their length inside the modelled area is 94 km. Geofizika Zagreb performed the field data acquisition. Most of the profiles were recorded with line explosive sources (Geoflex and

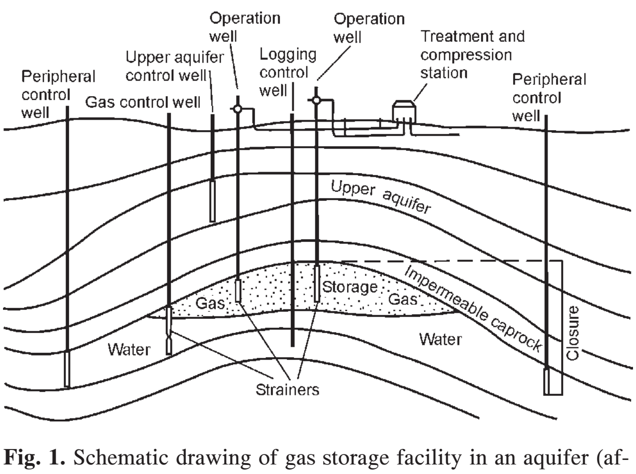


Fig. 1. Schematic drawing of gas storage facility in an aquifer (after Gaussens 1986).

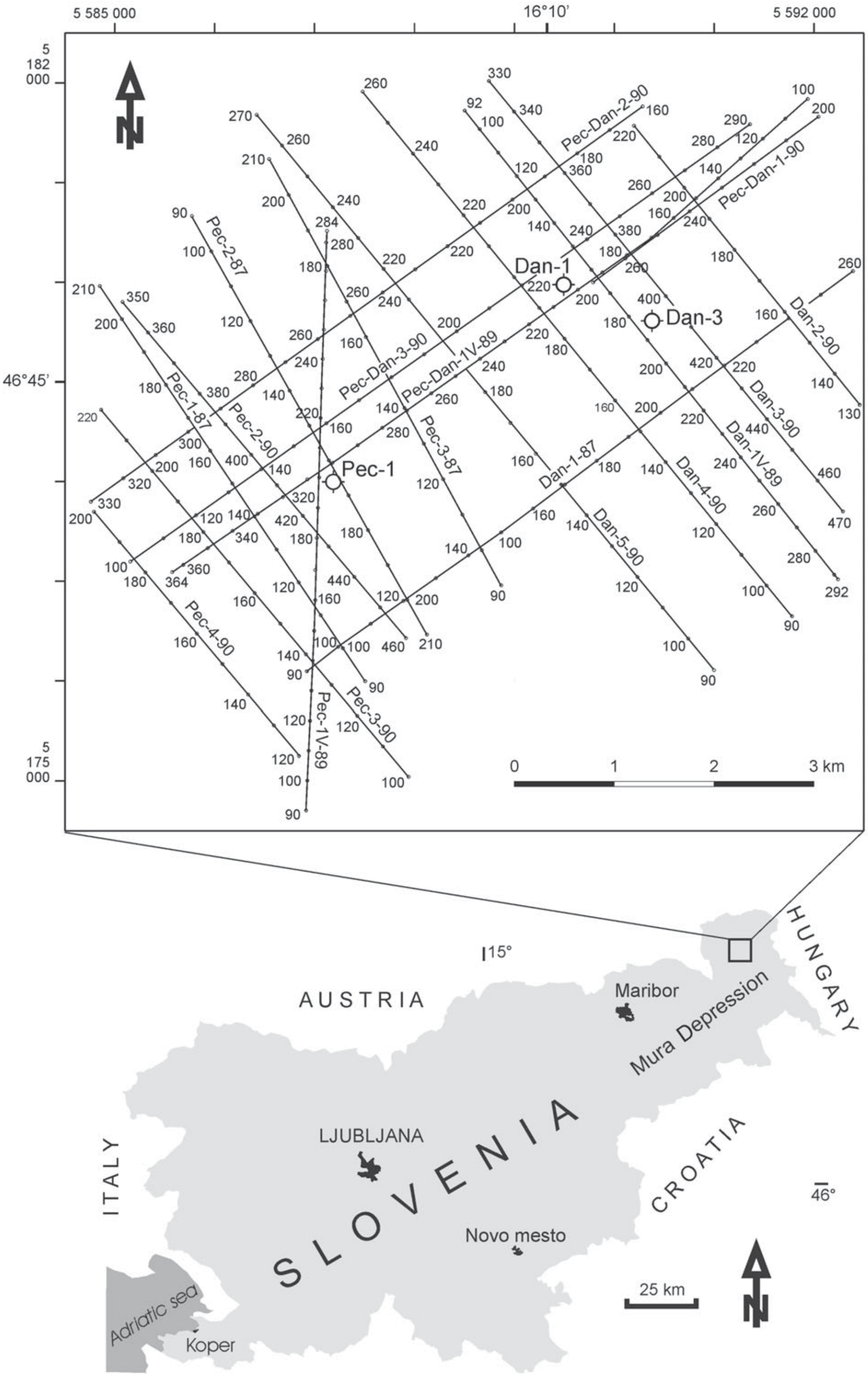


Fig. 2. Location map of the seismic profiles and boreholes at the Pecarovci–Dankovci location.

Primacord), end-offset layout and a Texas Instruments DSF IV seismograph. The distance between geophone groups was 40 m, and CMP coverage was 24- or 30-fold. Three profiles (Pec-1v-89, Dan-1v-89 and Pec-Dan-1v-89) were recorded with Vibrosise source, split offset layout, a Texas Instruments DSF V seismograph, 30 m geophones group spacing and 24-fold coverage. Linear geophone arrays composed of 24 SM-4/UB 10 Hz geophones were used. Standard data processing was performed by INA-Naftaplin in Zagreb and by Western Geophysical in London.

In the region of the Pecarovci and Dankovci structures, three deep boreholes have been drilled to date (Fig. 2). Two of them (Dan-1 and Pec-1) have reached the pre-Tertiary bedrock at a depth of between 1800 and 1950 m, while Dan-3 has terminated below the KB horizon at a depth of 1400 m (Sadnikar 1993). In the older Dan-1 borehole drilled for oil exploration,

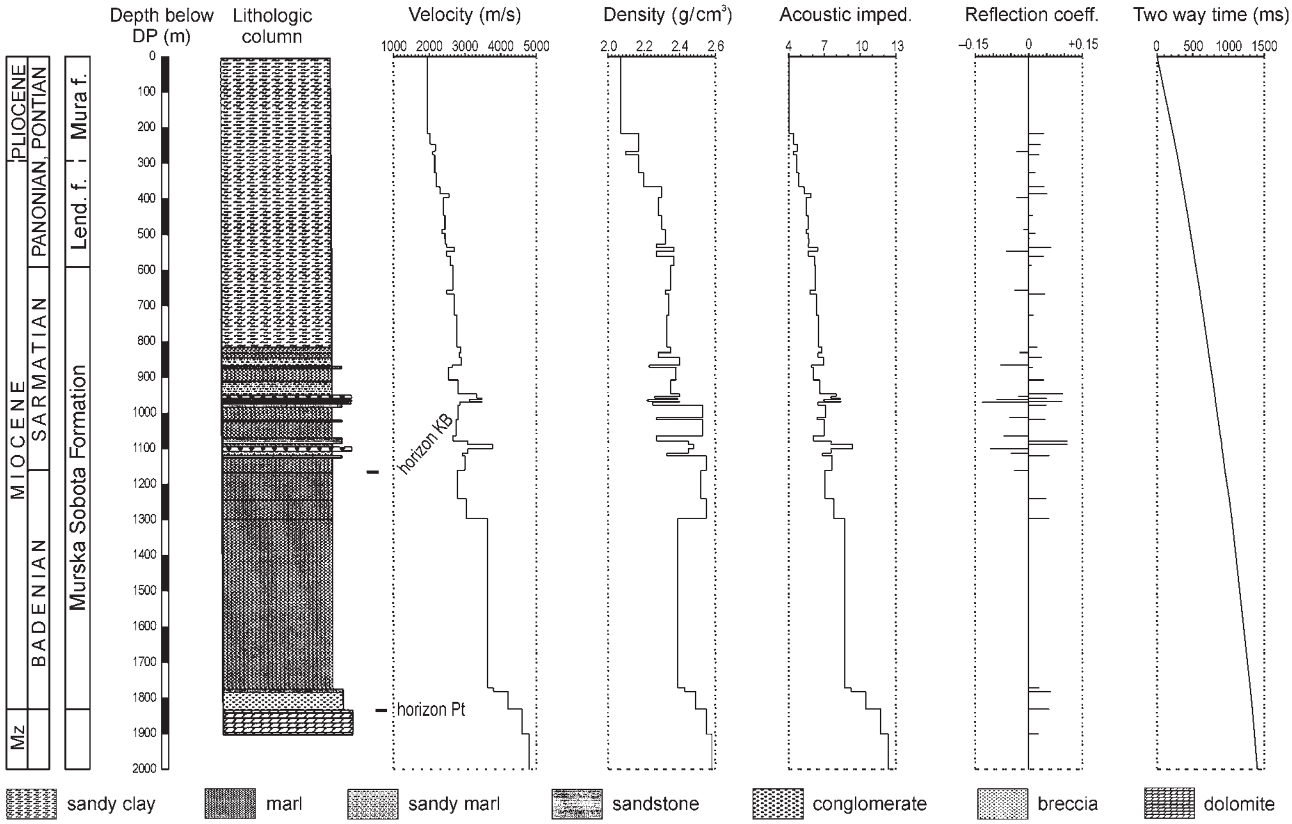


Fig. 3. Lithologic column, interval velocity, density, acoustic impedance, reflection coefficient and two way time diagrams for the Pec-1 borehole.

only basic electrical well-logging was performed. In the Dan-3 and Pec-1 boreholes, a complete set of well-logging measurements was performed, including sonic velocity measurements. In the Dan-3 and Pec-1 boreholes, down-hole seismic velocity measurements were also performed. In the Mesozoic dolomites, overlying metamorphic complex thermal water with the temperature of 102 °C was drilled in the Pec-1 borehole at a depth of 1850 m (Sadnikar 1993). This borehole (Fig. 3) has drilled the Mura, Lendava and Murska Sobota Formations (Gosar 2005). The main horizons interpreted in all seismic reflection profiles in the region are the KB horizon, which corresponds to the discordant boundary between the Badenian and Sarmatian sediments, and the Pt horizon, which corresponds to the pre-Tertiary carbonate or metamorphic bedrock.

1D synthetic seismograms

Seismic modelling in one dimension (1D) is a commonly applied tool for the correlation of seismic (time) data with geological or well-logging (depth) data (Sheriff & Geldart 1995). This is important because, for the seismic data, lower vertical resolution limited by the wavelength of the signal is characteristic, but good lateral coverage along the profile is also apparent. On the other hand, data from boreholes has good vertical resolution, but is limited in lateral extent (Neidell 1981). In the case of 1D modelling, the geological structure near the borehole is approximated by horizontal layers. If the wavelength of the signal is small compared to the distance between adjacent interfaces, then good separated reflections are obtained. But, in cases where the layers are thin with respect to the wavelength, the seismic trace is a result of the interference of signals reflected from several interfaces. The theoretical vertical resolution of seismic data is 1/4 of the signal wavelength, whereas in practice it is not greater than 3/8 of the wavelength (Widess 1973).

At the Pecarovci–Dankovci location, very thin layers and the problem of interference close to the KB horizon were encountered. 1D modelling was therefore applied in order to improve the interpretation of the KB horizon, and to correlate the seismic and borehole data. For this modelling, synthetic seismograms were constructed for boreholes Pec-1 and Dan-3 using the Vista software package (Sis 1990). The reflectivity series was computed from the sonic and density log data. The sonic log was corrected on the basis of the down-hole measurements. In the lowest part, close to the Pt horizon, the results of laboratory measurements of velocity on cores were also used. In the Pec-1 borehole, 49 layers of different acoustic impedance were distinguished (Fig. 3). The highest reflection coefficients corresponded to the top and bottom of the thin conglomerate layers above the KB horizon. We compared the synthetic seismograms with two seismic profiles measured close to the borehole location. Comparing the synthetic traces with the Pec-Dan-1v-89 profile (Fig. 4b), which is trending SW–NE, good correlation can be observed at 0.5 s, near the KB horizon (0.9 s), and at the Pt horizon (1.35 s), but poor

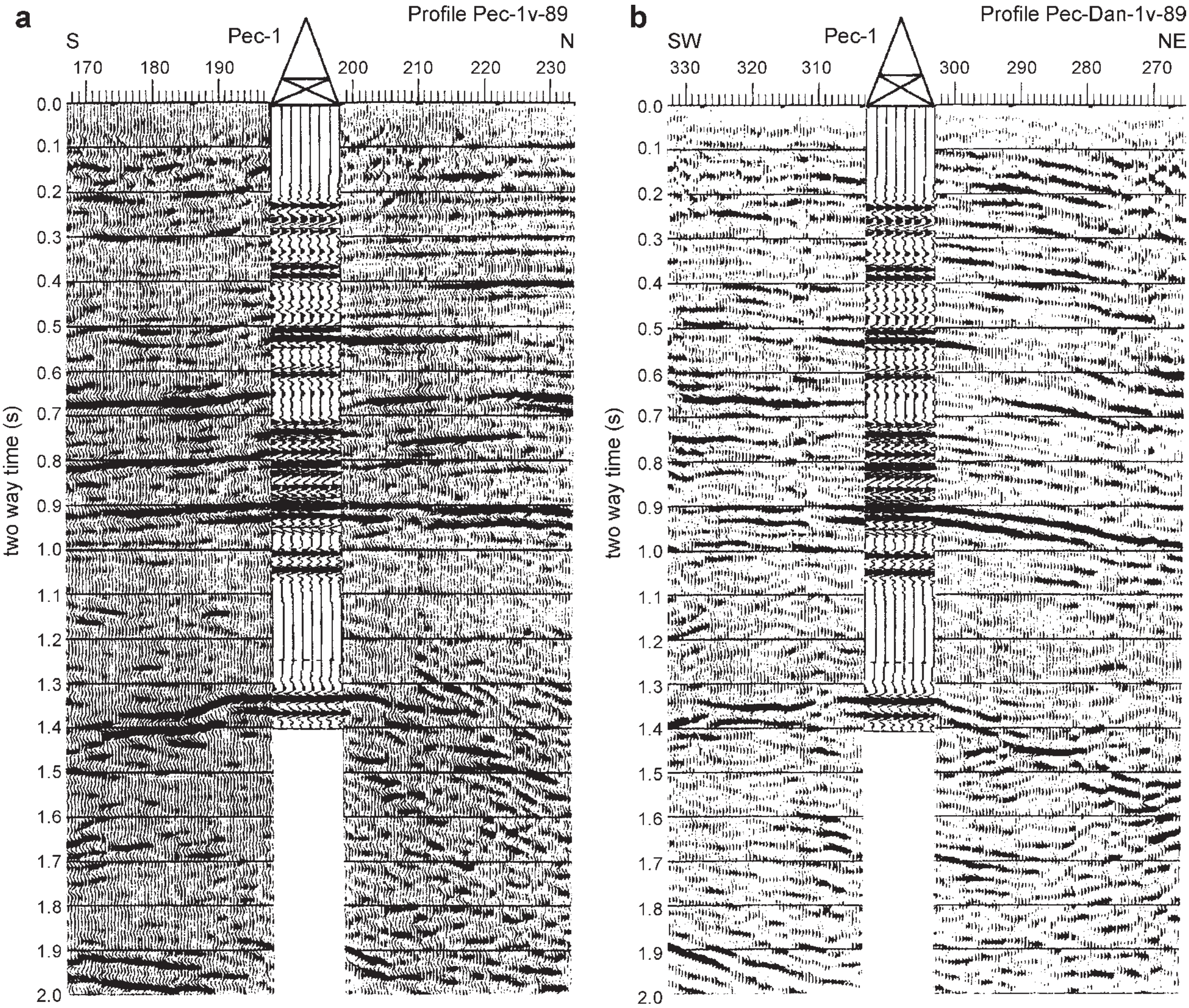


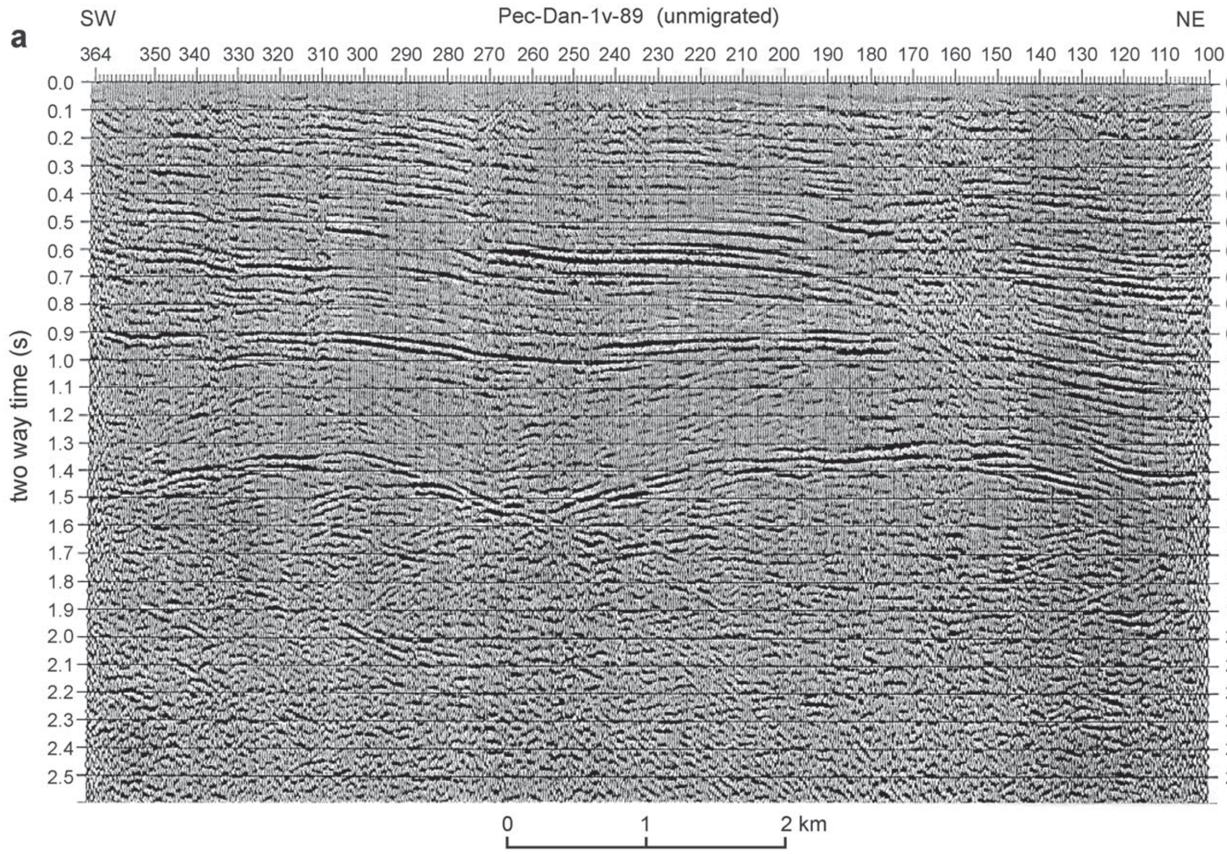
Fig. 4. Comparison of the synthetic seismogram for the Pec-1 borehole with the profiles Pec-1v-89 (**a**) and Pec-Dan-1v-89 (**b**).

correlation between 0.7 and 0.9 s. If the same synthetic traces are compared with the Pec-1v-89 profile, which is trending S–N (Fig. 4a), there is also a good correlation at both main horizons and at 0.5 s, but two or three good reflections between 0.7 and 0.85 s not visible on the previous profile can also be observed. It can be concluded that, in this area, a high degree of velocity anisotropy is encountered. 1D modelling was also used to test what influence the frequency content of the input signal has on the vertical resolution of the seismic data to support advanced processing of the data (Yilmaz 1987).

Raytracing modelling

With 2D raytracing modelling stacked seismic sections, field shot records and CMP (common midpoint) gathers were simulated (Fagin 1991). 2D modelling was performed using the Sierra Quik package (Sierra 1990) on the models constructed with the Sierra Mimic program. Quik programs use the asymptotic raytracing theory methods to find the path of seismic energy between the source and receivers (May & Covey 1981). At each intersection of the ray with a horizon, the program computes the time and the reflection coefficient. In each layer, the program uses straight rays even if the velocity varies. This approximation is good enough for most models. At interfaces, the rays are refracted according to Snell's law. In layers with variable velocity, the direction of the ray is calculated in following manner. When the ray enters the layer, the local velocity is used to determine direction. The ray then continues straight to the next interface, where a new local velocity is used to compute the direction in the lower layer. The result of a simulation is a spike section of reflection coefficients. The convolution of a spike section with the input wavelet results in a synthetic seismogram. Using this method, fully complex seismic amplitudes can be obtained in geological structures of almost arbitrary configuration.

By 2D modelling of stacked seismic sections, an attempt was made to confirm the continuity of some reflections related to the KB horizon and the interpretation of faults at the Pt horizon (Gosar 1995). The results of the simulation are presented for the characteristic profile, Pec-Dan-1v-89 (Fig. 5). The basis for interpretation and construction of the time model was



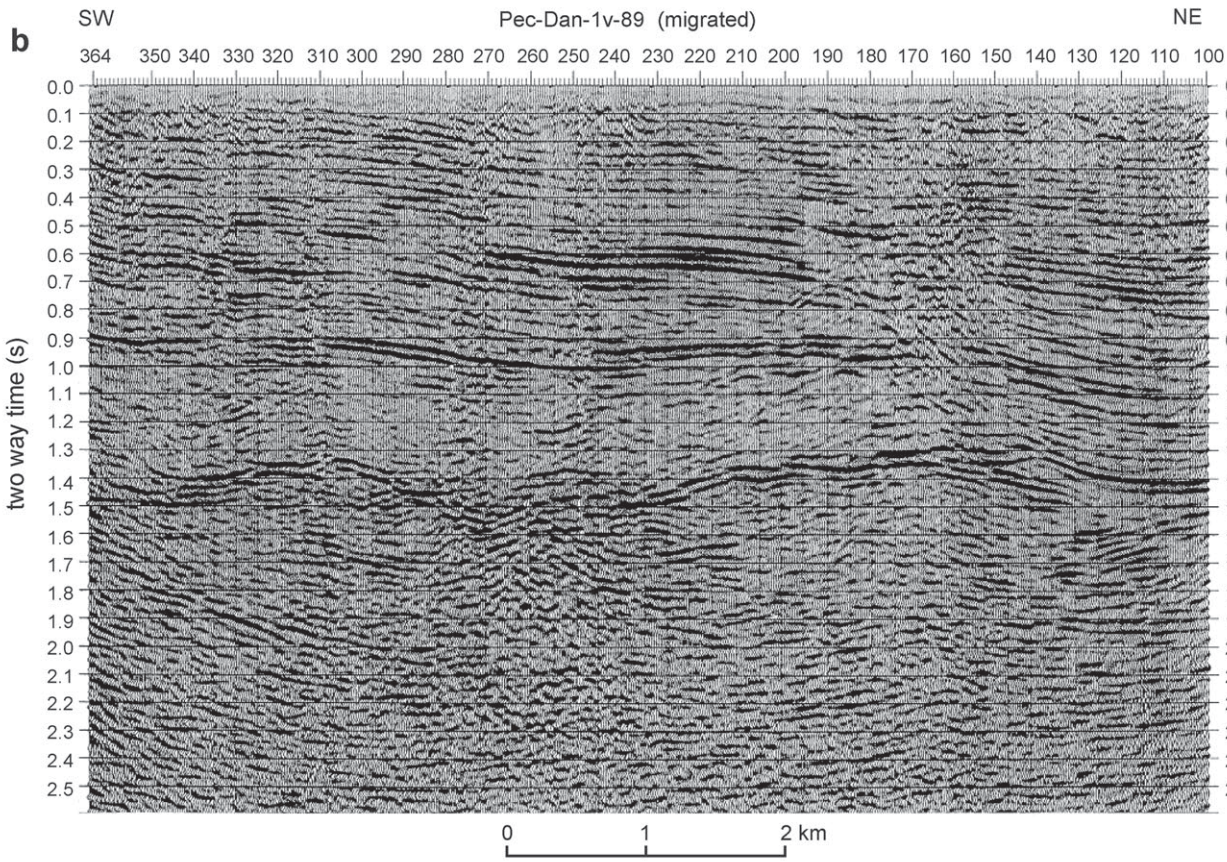


Fig. 5. The unmigrated **(a),** and migrated **(b)** seismic profile Pec-Dan-1v-89.

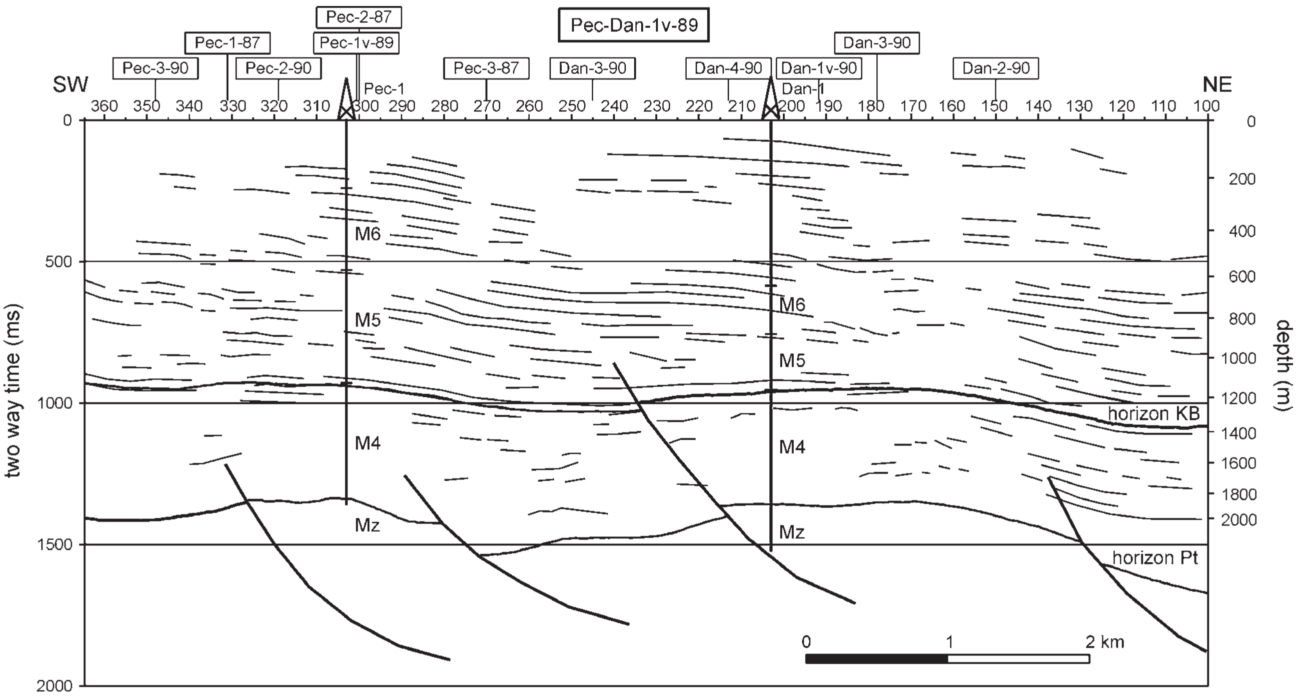


Fig. 6. Line drawing interpretation of the seismic profile Pec-Dan-1v-89.

the migrated seismic section (Figs. 5b and 6). When evaluating the structural interpretation of the Pt horizon, it was proved that better results are obtained with modelling of the unmigrated seismic section (Fig. 5a), where faults are more evident because of diffractions. The input model consists of nine layers of different velocity (Figs. 6 and 7). The two thin layers of higher velocity represent the conglomerate sequences above the KB horizon. Between the Pecarovci and Dankov-

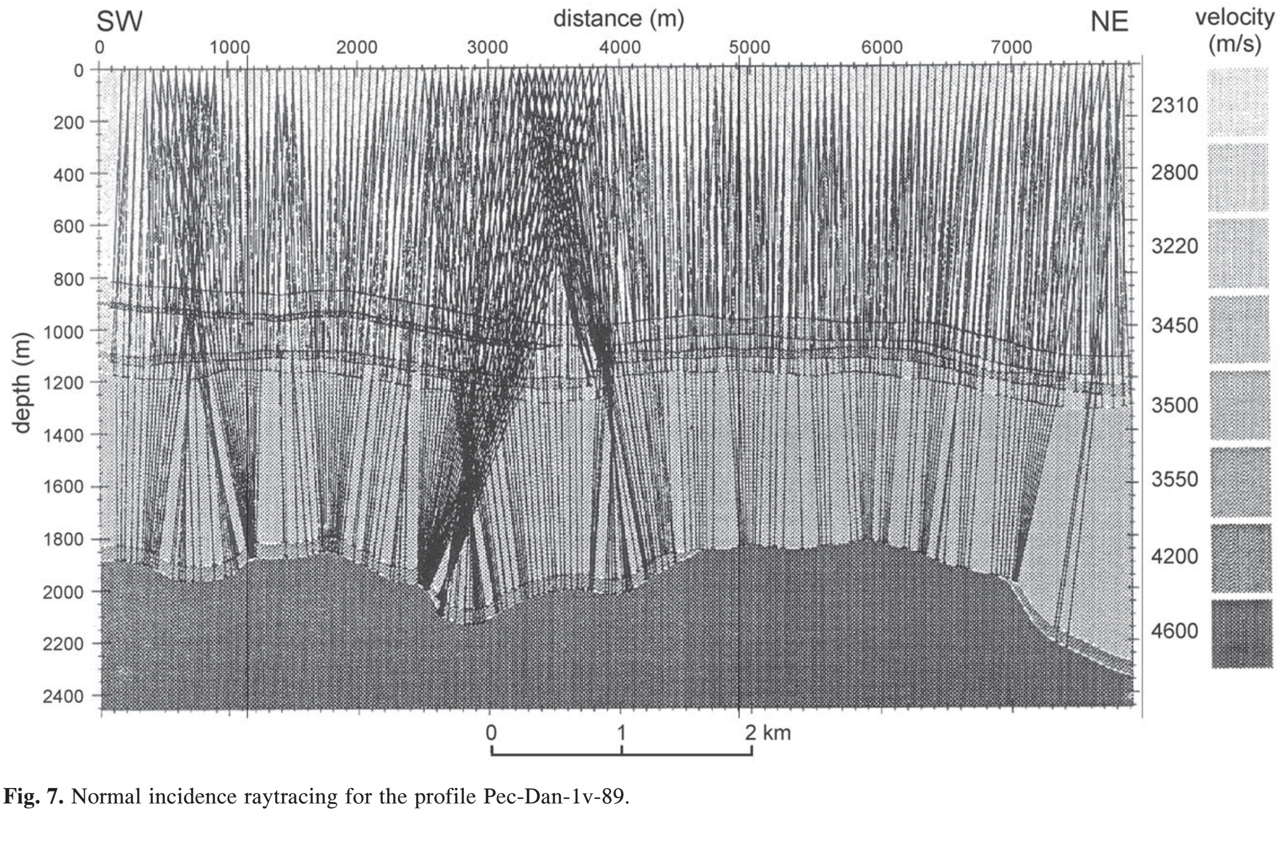


Fig. 7. Normal incidence raytracing for the profile Pec-Dan-1v-89.

ci structures there is a fault at which one sequence terminates and the second is displaced. Above the Pt horizon, there is a 50 m thick layer of breccia. Normal incidence raytracing, which simulates the unmigrated seismic section, is shown on the depth model of this profile in Fig. 7 and the corresponding synthetic seismogram in Fig. 8a. By comparing the synthetic and the original seismic section (Fig. 5a), it was concluded that the structure on the NE side of the Pecarovci antiform is more complex. To prove this, a new model of the Pt horizon was constructed at this location with two normal faults on the NE side of the Pecarovci antiform instead of only one. This model was simplified to only one interface because it was recognized that the upper layers do not affect the rays significantly. The synthetic seismogram for this simulation (Fig. 8b) showed better correspondence with the seismic section (Fig. 5a). Therefore, we concluded that the Pecarovci structure has, on its NE side, at least two normal faults. It is possible also that the structure is even more complex.

Structural models

For structural modelling based on seismic reflection data, a square area, 8×8 km in size, was selected. Seventeen profiles with a total length of 94 km, and data from three boreholes, were used (Fig. 2). The aim of the structural modelling was to construct time and depth maps of the two most important horizons, that is the KB — the top boundary of the Badenian

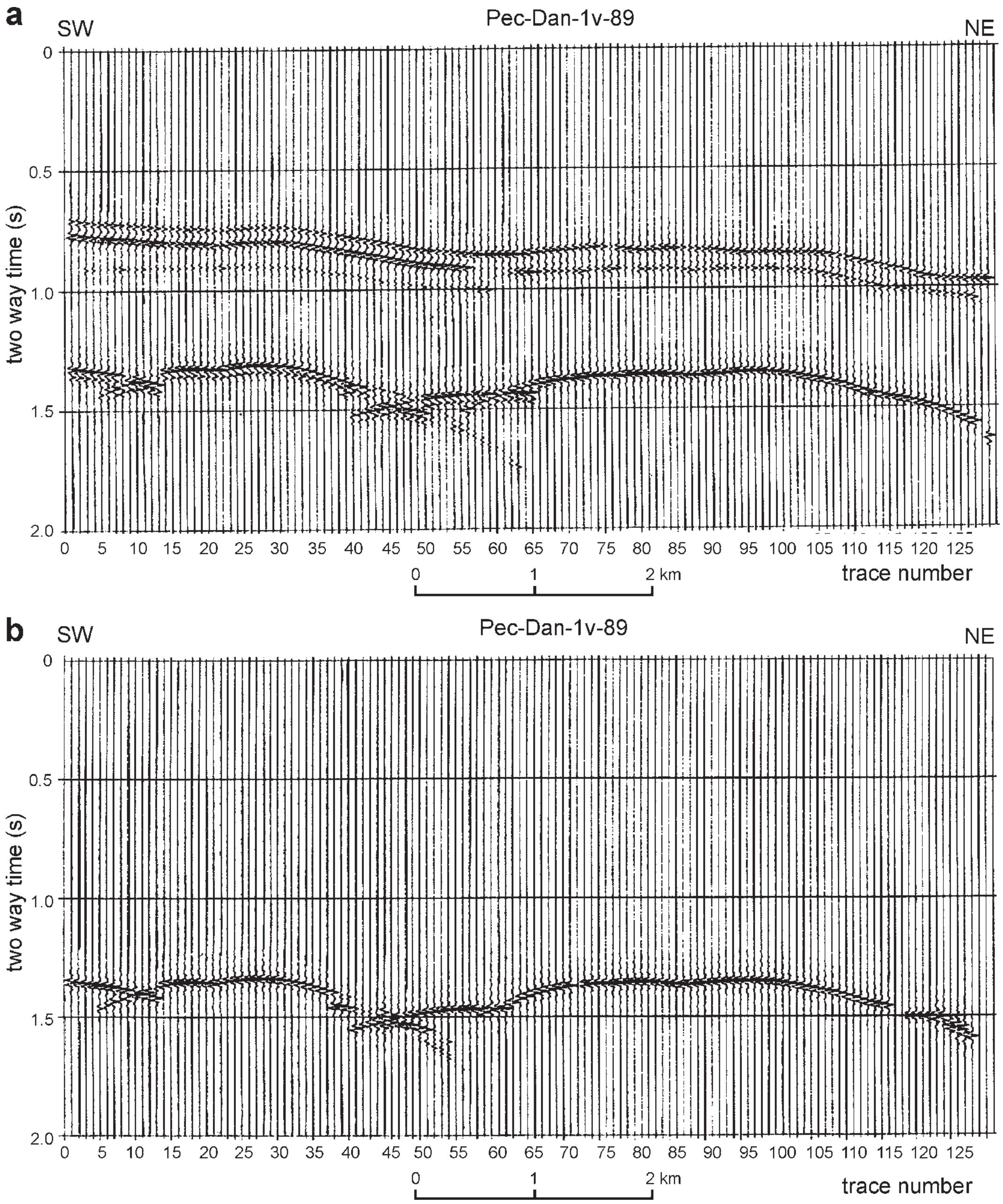


Fig. 8. Synthetic seismograms for normal-incident raytracing shown in Fig. 7 (**a**) and for the corrected model (**b**).

rocks, and the Pt — pre-Tertiary basement. Computer assisted contouring of interpreted surfaces, taking into account fault traces, was applied.

First, a detailed analysis of the available velocity data was carried out to enable correct time-to-depth conversion. Four types of velocity data were used: **a** — velocity analysis from seismic data; **b** — down-hole measurements in boreholes; **c** — sonic logs; and, **d** — laboratory measurements on cores. The velocity function was based on the sonic log data, which were corrected using the down-hole measurements, and fitted to the datum plane of the seismic profiles (150 m above sea level). Laboratory measurements on cores were used in the deeper part of the Pec-1 borehole, where no other data was available. Reflection velocity analysis data was used mainly to determine lateral velocity changes. The velocity isolines for the characteristic profile Pec-Dan-1v-89 measured in the SW–NE direction showed no significant lateral velocity variations in the upper part of the section, until a two-way time 1.0 s was reached. However, there was a slight increase in velocity in the NE direction, between 1.0 and 1.5 s. Established velocity variation was applied for time-to-depth conversion.

The structural model of two main horizons (KB and Pt), showing two-way traveltime isochrons of reflected waves, was first constructed (Figs. 9 and 10). A structural time map of the KB horizon (Fig. 9) shows a closed antiform structure at Dankovci confined by the 980 ms (milliseconds) isochron, which has a peak at 950 ms. Five faults cut the structure, but they do not indicate significant slips. The reservoir rocks in this horizon are thin layers of conglomerate and sandstone. Small quantities of oil and gas were found in these layers, proving the tightness of the cap rocks. On the other hand, because of the thin layers (a couple of meters thick), a fault could easily separate two parts of the layer and reduce the volume of the reservoir. At the Pecarovci location, there is no closed antiform structure in the KB horizon.

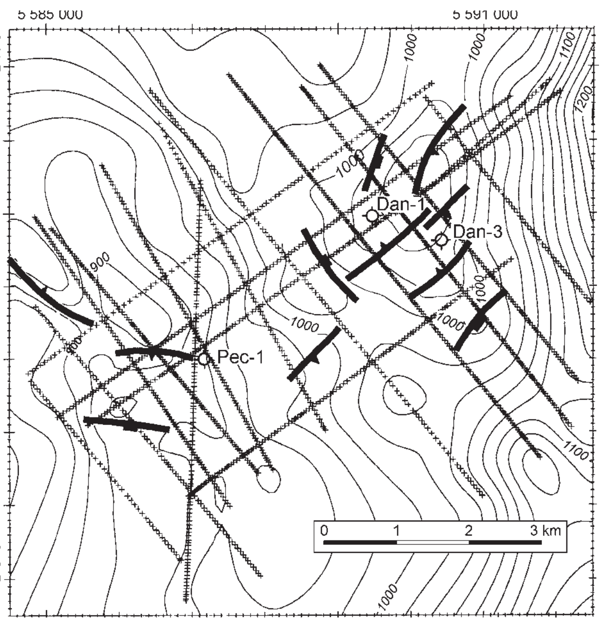


Fig. 9. Time structural map of the KB horizon, equidistance = 20 ms, x — digitized points.

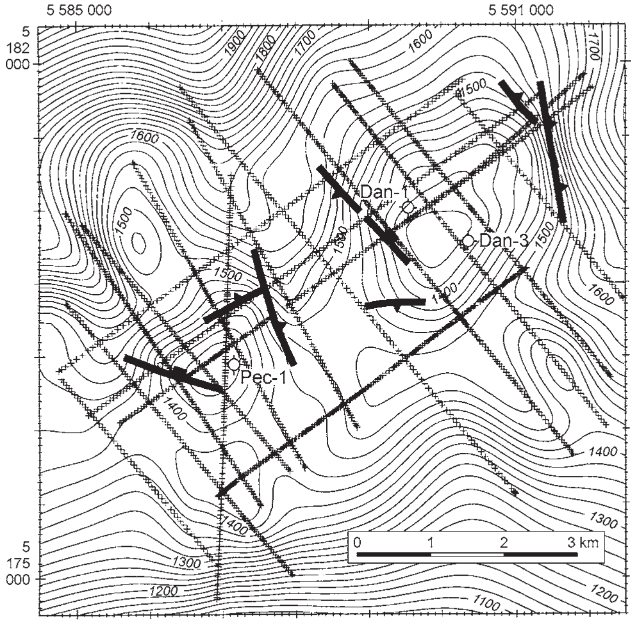


Fig. 10. Time structural map of the Pt horizon, equidistance = 20 ms, x — digitized points.

On the Pt horizon (Fig. 10), there are closed antiform structures at both locations. The reservoir rock is a layer of porous dolomite, approximately 70 m thick, overlying metamorphic rocks in the basement. At Dankovci, it is confined by the 1460 ms isochron, while the top of the structure is at 1350 ms. The area of the closed part is 5.42 km^2. At Pecarovci, the top of the structure is at 1350 ms and the antiform is confined by the 1400 ms isochron. The highest point of the opening is on the SW side. The area of the closed part is 1.576 km^2. The preliminary interpretation with a single fault on the NW side of the anticline is presented in the model in Fig. 10. According to raytracing modelling, the new interpretation with two normal faults is shown in Fig. 11, together with a prognostic geological profile. A minor reverse fault is also seen on the SW side of the structure.

On the basis of the time-to-depth conversion, structural depth maps were constructed for both horizons. The depth from the datum plane to the KB horizon is from 1100 m to 1200 m, and the depth to the Pt horizon is from 1900 m to 2000 m (Fig. 11b)

Of the three antiform structures, the Pecarovci (Pt) structure was selected for further investigations as the most promising for the construction of the gas storage facility. The structure at Dankovci (Pt) is too big for the desired storage volume, while the structure at Dankovci (KB) was found to be less reliable because of faults (Sadnikar 1993).

Conclusions

On the basis of the constructed models, the available storage volume in the Pecarovci (Pt) structure (Fig. 11) was estimated. The calculations were performed using the Evasit Program for the evaluation of porous gas storage facilities (Gaz de France 1990). The input data comprised the areas of closed isoch-

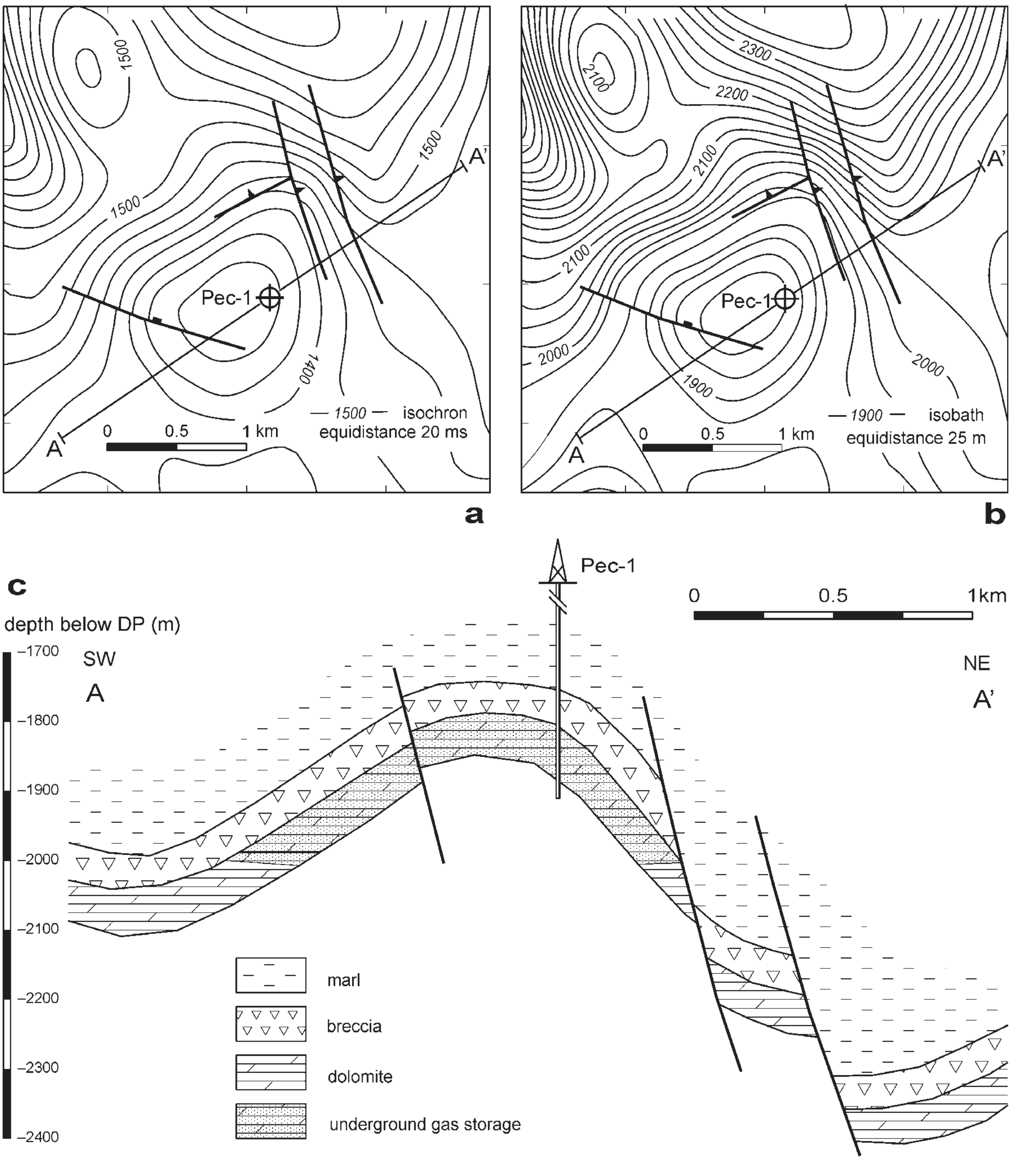


Fig. 11. Planned underground gas storage facility in the Pecarovci (Pt) structure: **a** — time structural map, **b** — depth structural map, **c** — prognostic geological profile A–A'.

rones and corresponding seismic velocities in the top rock. As the working volume, fifty percent of the total volume was taken. Using this data, the working volume in the Pecarovci (Pt) structure was estimated on 275–300 million m^3(n). This is above the desired minimum volume of 200 million m^3(n) selected for the project of gas storage in Slovenia (Sadnikar 1993).

Among all evaluated locations in Slovenia, the antiform structure in the pre-Tertiary basement at Pecarovci was proved to be the most promising for the construction of an underground gas storage facility. Its structure is defined by seven seismic profiles and one borehole. To prove the structural interpretation of seismic data and to test the hydrogeological parameters of the reservoir layer and the impermeable cap rock, another four boreholes are planned. The main disadvantage of this structure is the great depth of the storage layer, which requires compressors of higher power, and higher costs during operation.

Acknowledgments: The author is grateful to M. Bielik, F. Hubatka and J. Šefara for constructive reviews of the article. Part of this work was conducted while the author was receiving a grant from the University of Trieste. The assistance and many valuable suggestions of R. Nicolich are gratefully acknowledged. The author is indebted also to D. Ravnik, J. Sadnikar and S. Kranjc for their help and constructive remarks.

References

Dussaud M. 1989: Review of World Wide Storage Projects-France. In: Tek M.R. (Ed.): Underground Storage of Natural Gas. *Kluwer Academic Publishers*, Dordrecht, 23–29.

Fagin S.W. 1991: Seismic modelling of geological structures. *Society of Exploration Geophysicists,* Tulsa, 1–288.

Flanigan O. 1995: Underground gas storage facilities, design and implementation. *Gulf Publishing,* Huston, 1–179.

Gaussens P. 1986: Stockages souterrains de gas, Titre XIII. In: Manuel pour le transport et la distribution du gaz. *Association technique de l'industrie du gaz en France*, Paris, 1–333.

Gaz de France 1990: Evasit, PC Version, User's Manual. *Gaz de France*, Paris, 1–25.

Gosar A. 1995: Modelling of seismic reflection data for underground gas storage in the Pecarovci and Dankovci structures-Mura depression. *Geologija* 37–38, 483–549 (in Slovenian).

Gosar A. 2005: Geophysical and structural characteristics of the pre-Tertiary basement of the Mura Depression (SW Pannonian Basin, NE Slovenia). *Geol. Carpathica* 56, 2, 103–112.

May B.T. & Covey J.D. 1981: An inverse ray method for computing geological structures from seismic reflections: zero offset case. *Geophysics* 46, 4, 268–87.

Neidell N.S. 1981: Stratigraphic modelling and interpretation: geophysical principles and techniques. *Education Course Note Series 13. AAPG*, Tulsa, 1–141.

Sadnikar J. 1993: Investigations for underground gas storage in Slovenia. *Rud.-Metalur. Zbor.* 49, 1–2, 149–167 (in Slovenian).

Sheriff R.E. & Geldart L.P. 1995: Exploration seismology. *Cambridge University Press*, Cambridge*,* 1–592.

Sierra 1990: Quik raytracing, Release 3.2, User Manual. *Sierra Geophysics*, Seattle, 1–497.

SIS 1990: Vista 6.5, User Manual. *Seismic Image Software*, Calgary, 1–134.

Tek M.R. 1989: Underground storage of natural gas. *Kluwer Academic Publishers*, Dordrecht*,* 1–458.

Turk V. 1993: Reinterpretation of chronostratigraphic and lithostratigraphic correlations in the Mura depression. *Rud.-Metalur. Zbor.* 49, 1–2, 149–167 (in Slovenian).

Widess M.B. 1973: How thin is a thin bed? *Geophysics* 38, 6, 1176–1180.

Yilmaz O. 1987: Seismic data processing. *Society of Exploration Geophysicists*, Tulsa, 1–526.