Tectono-sedimentary features in 3D seismic data from the Moravian part of the Vienna Basin

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Abstract

By the end of the 20th century, the geology of the Moravian part of the Vienna Basin was fairly well known from hydrocarbon exploration; nevertheless, recently acquired seismic data have provided important new information. Some of the most interesting geological features derived from 3D seismic interpretation are presented in this article. The main focus is on the Badenian deposits which comprise the most important sedimentary succession in terms of thickness, rock volume, tectonic evolution, and hydrocarbon accumulations. Examples from other Neogene stratigraphic stages are also presented. 3D seismic data analysis has contributed to a better understanding of the basin's geological development in terms of the temporal and spatial relationships between tectonics, depositional environment, and sedimentation. The 3D data have enabled interpreters to identify new potential structural, stratigraphic, and combination hydrocarbon traps, some of which have been confirmed by wells.

Introduction

Understanding the geological development of sedimentary basins and the relationships between their tectonic and sedimentary history depends on both the quantity and quality of subsurface data. With the acquisition of new and more precise data, and the recent improvements in analytical methods, new information can be obtained even about basins that have already been well explored. The Moravian part of the Vienna Basin, where exploration for oil and gas has taken place for more than 80 years, is such an example. During this period, the geology was mainly determined from exploration drilling results that were latterly supplemented by geophysical data, especially seismic reflection profiles. Through well log interpretation, 2D seismic interpretation, and sedimentological, petrographic and micro-palaeontological analyses, it was possible to identify structural hydrocarbon traps and simple up-dip pinch-outs of sandy intervals. Several hydrocarbon reservoirs were discovered, from which ~3.4 million m^3 of oil and ~2.9 billion m^3 of gas have been recovered to date.

The majority of the known hydrocarbon fields in the Moravian part of the Vienna Basin were close to depletion by the end of the 20th century, and almost all of the opportunities for oil and gas exploration based on the interpretation of 2D seismic data and existing well data had been considered. These circumstances prompted the acquisition of 3D seismic data, and the interpretation of those data has produced new geological information that has greatly expanded our thinking about hydrocarbon plays in the basin. Detailed 3D seismic analysis has resulted in better understanding of the interaction between tectonics, depositional environment, and sedimentation, as well as the identification of new potential structural, stratigraphic, and combination hydrocarbon traps.

Summary of regional geology

The form of the Vienna Basin is a Miocene tectonic depression situated at the junction of the Alpine and the Carpathian orogens (Figures 1 and 2). Deep autochthonous basement in this area comprises crystalline (Precambrian) and sedimentary (Palaeozoic–Palaeogene) units of the North European Platform. These rocks are overthrust by the Alpine–Carpathian nappes, which directly underlie the Neogene sedimentary fill of the Vienna Basin and bound it at outcrop. The flysch nappes in the north are of Late Cretaceous–Palaeogene age, whereas the nappes of the Northern Calcareous Alps and the Central Western Carpathians in the south are of Late Palaeozoic–Palaeogene ages. The units in the north and south are separated by the narrow Pieniny Klippen Belt of Jurassic–Palaeogene age.

The sedimentary fill of the Vienna Basin attains a thickness of more than 5000 m, and consists predominantly of Miocene deposits. There are other sediments of Pliocene and Quaternary age. The geological structure comprises a complex of horsts and grabens divided by major fault systems (Figure 2). The Vienna Basin is elongated in the SW–NE direction with a length of ~ 200 km and a width of 55–60 km. It is located in Austria, the Czech Republic, and Slovakia (Figure 1).

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For this study, the area of interest lies in the northern part of the Vienna Basin and comprises approximately half of the Moravian (Czech) segment of the basin (Figure 3a). The geological structure of the Vienna Basin comprises several main tectonic blocks, bounded by major fault systems (e.g., Hamilton et al., 1990). Five of the most significant fault systems reach into our study area (Figure 3b): the Schrattenberg, Steinberg, Lanzhot-Hrusky, Farske, and Hodonin-Gbely fault systems. They divide the area into the following six blocks: Rakvice Block, Mistelbach Block, Central Moravian Depression, Hodonin-Gbely Horst, Kuty Depression, and Kopcany Depression.

Individual tectonic blocks differ in their lithostratigraphy as well as in the thickness of their sedimentary fill. In tectonic depressions, sedimentary fill exceeds several thousand metres, in contrast to the structural highs where the thickness of formations is considerably reduced (Figure 4). These variations are primarily the result of Badenian syn-sedimentary tectonics.

Figure 1 *Location of the Vienna Basin within the Alpine-Carpathian thrust belt.*

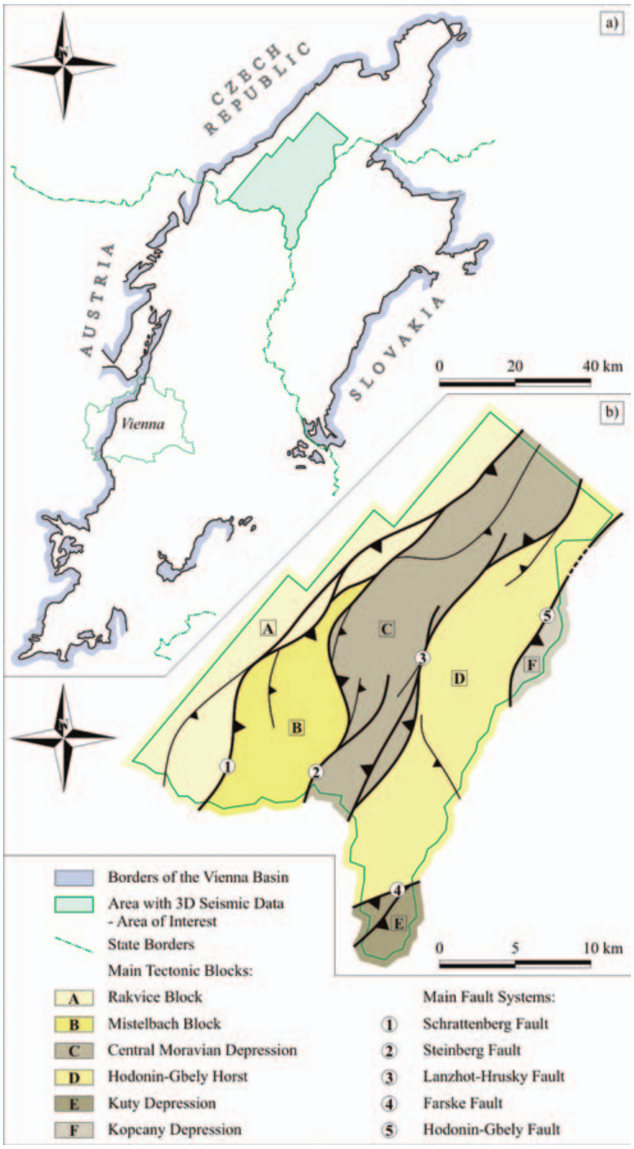

Figure 3 *(a) Location of the study area in the Vienna Basin. (b) Major faults and tectonic blocks in the area.*

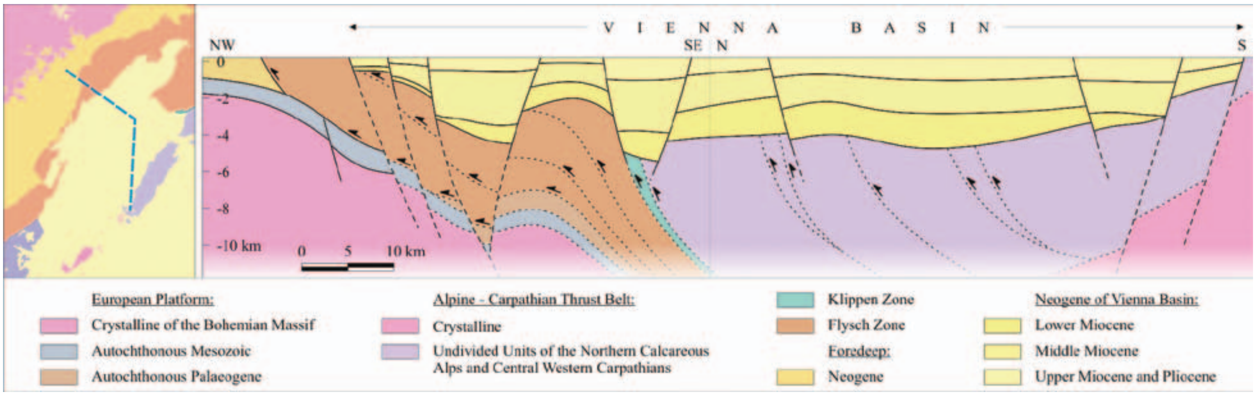

Figure 2 *Schematic geological section of the northern part of the Vienna Basin.*

Depressions bounded by Badenian growth faults form the deepest parts of the Moravian segment of the Vienna Basin.

Neogene sedimentary fill, overlying folded flysch units of Late Cretaceous–Palaeogene age, comprises vertically and laterally alternating successions of mainly clastic sediments deposited in marine, brackish, and freshwater environments. Carbonate rocks are present only to a limited extent. In the area of interest, a complete Miocene sedimentary record is developed; however, there are many unconformities, variations in thickness, and pinch-outs of formations, depending on locality.

Data used

Hydrocarbon exploration carried out in the 20th century was based on well data and 2D seismic data, and helped to identify faults, depositional settings, and the stratigraphy and lithology of both the Neogene sedimentary fill and the pre-Neogene succession in the study area. This exploration activity resulted in good knowledge of the geology and led to discovery of several hydrocarbon fields.

Geological knowledge obtained during previous phases of exploration can now be refined through detailed analysis of new subsurface data, which are predominantly 3D seismic data. Practically the entire area of interest is covered by 3D seismic surveys acquired during the last 10 years (Figure 3a). Approximately 400 km^2 of 3D seismic data and data from 1700 wells have been used for the purpose of geological interpretation and analysis of the study area.

Spatial mapping of faults, stratigraphic boundaries, and lithological boundaries, defined on the basis of the integration of well and 3D seismic data, has been an essential part of the interpretation. Seismic attribute analysis has been applied to various time windows above and below a number of mapped seismic horizons. Since depth (time) levels and gradients of stratigraphically equivalent boundaries within individual tectonic blocks differ significantly, the reflection strength has been analysed on seismic horizon slices as well.

3D seismic interpretation

In many cases, interpretation of new 3D seismic data has confirmed and enhanced existing information or assumptions regarding the geological structure of the study area determined from earlier exploration. However, 3D seismic data enable the geological features that were previously identified only in wells to be observed directly, and their spatial distribution to be established. Unconformities are important examples of such features, because they represent significant tectono-sedimentary events in the evolution of the Vienna Basin (Figure 5).

With the help of vertical and horizontal seismic sections, it has been possible to map faults in three dimensions, particularly in younger (Middle and Upper Miocene) sedimentary fill (Figure 6). In regions without sufficient well data, several previously unknown faults have been identified on the basis of 3D seismic interpretation.

The 3D data analysis procedures described above have mainly been used to identify depositional facies in the sedimentary fill and to predict the lithology of the sediments. In the following sections of this article, several facies identified mainly by seismic attributes are introduced. A number of attributes available in the software used were tested in order to highlight specific features. Those showing the best results are presented here as examples. Analysis of depositional facies and tectonics has contributed to an understanding of

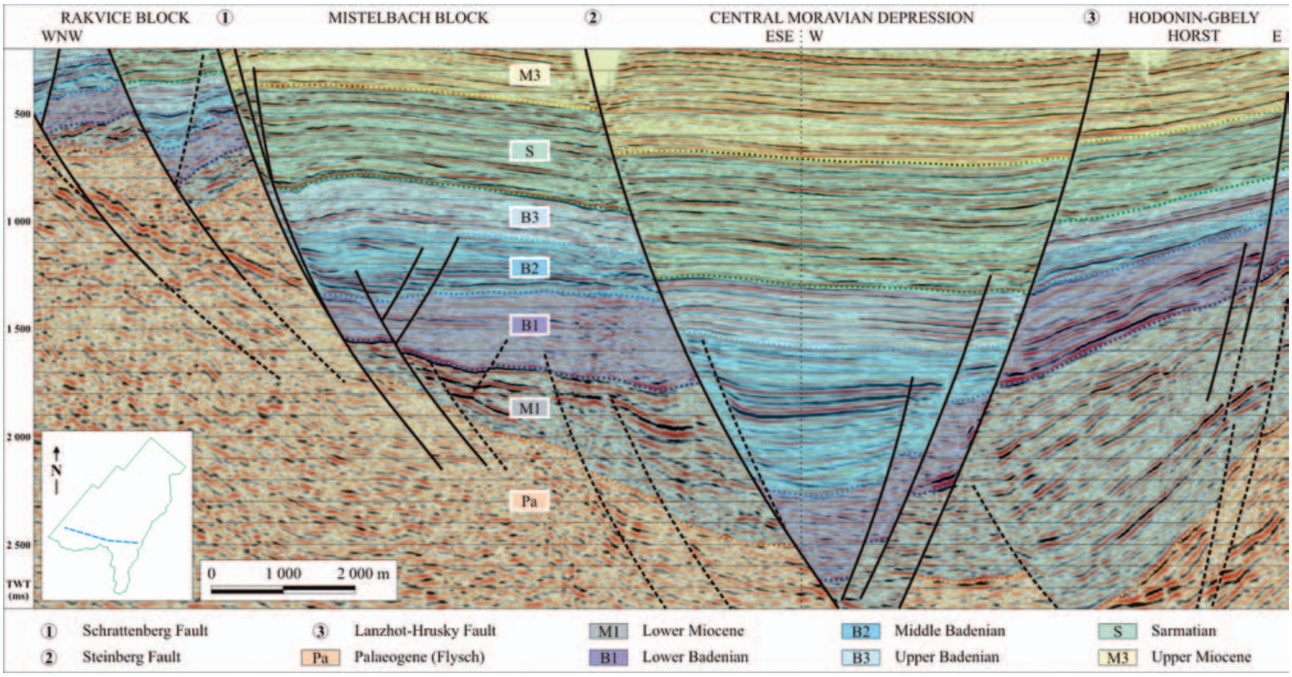

Figure 4 Characteristic seismic section from the study area.

the kinematics of some important fault systems, and consequently enabled the selection of several prospective areas.

Examples of depositional facies

3D seismic data have provided a basis for the identification of depositional facies. Some of the most significant depositional environments are channels, and most of them are directly recognizable in seismic profiles. The channels have commonly incised the underlying sediments, and are characteristic of the Pannonian and Sarmatian deposits (Figures 7 and 8). A few channel structures in Sarmatian sediments were partly known in the past from well data, and an underground gas storage facility was built in their sandy fill.

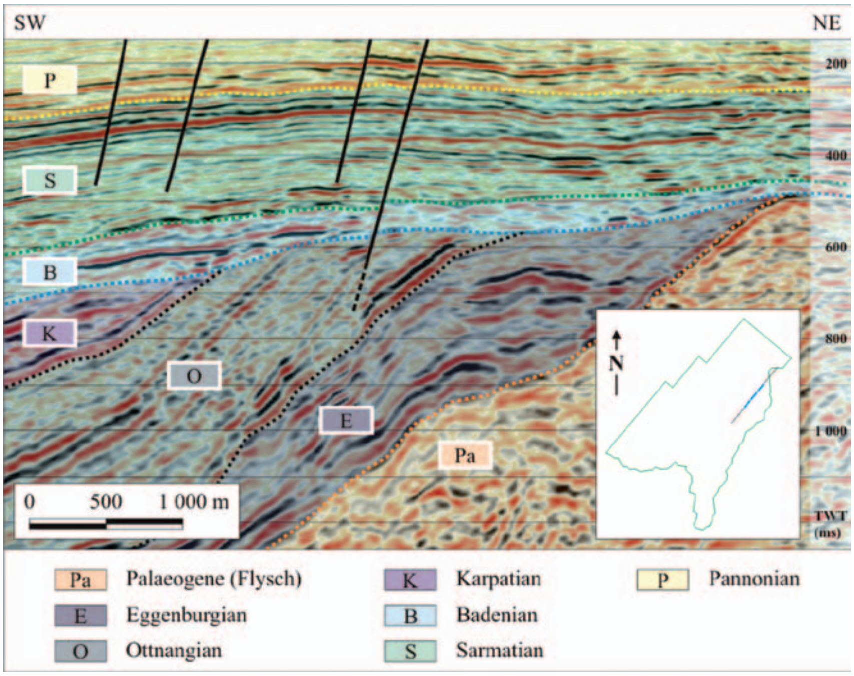

Figure 5 *Example of an unconformity in the sedimentary fill of the Vienna Basin between the Lower and Middle Miocene deposits on the Hodonin-Gbely Horst.*

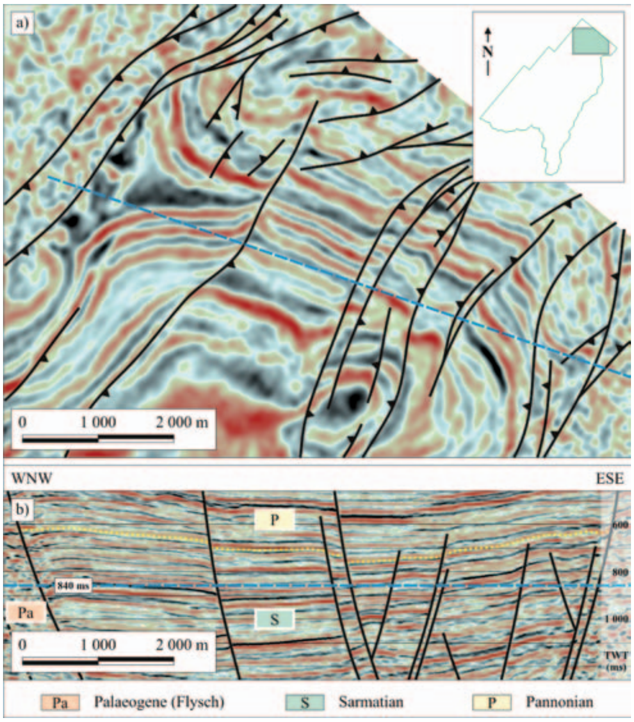

Figure 6 *(a) Timeslice at 840 ms, and (b) seismic section showing faulting in the northern part of the study area.*

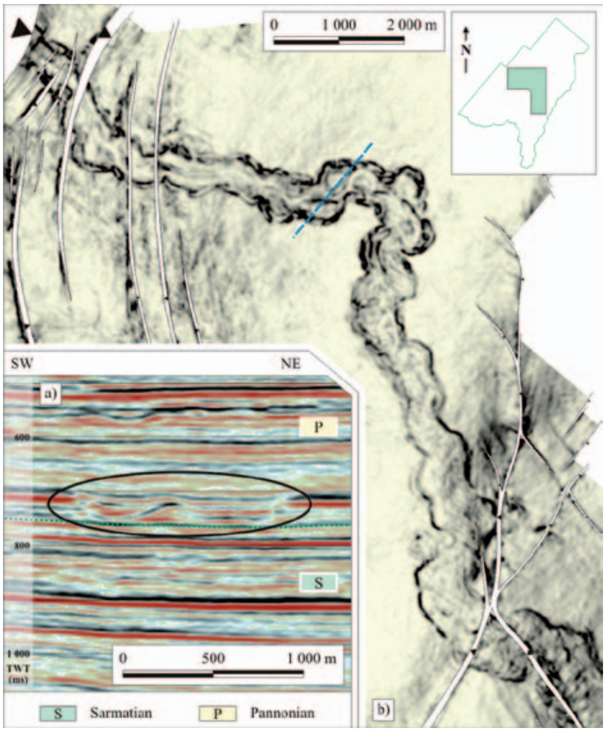

Figure 7 *Channel in the Pannonian deposits, crossing the Central Moravian Depression, displayed on (a) a seismic section and (b) a horizon slice with the variance attribute.*

3D seismic data analysis has shown that many previously unknown channels are also present in the Badenian sediments. They are not imaged as distinctly as the Sarmatian and Pannonian channels; nevertheless, these channels can be identified by means of seismic attributes and they can be located with some precision (Figure 9). They are mainly found in the Upper Badenian sediments, although some are also present in the upper parts of Middle Badenian formation.

Further examples of depositional facies revealed by suitable seismic attributes are the Middle Badenian lithothamnium (red algae) biostromes (Figure 10). These biostromes contain hydrocarbon accumulations, as was discovered by previous exploration drilling. In regions without sufficient well data, seismic attributes are a good tool for identification of these carbonate bodies, and mark their pinch-out boundaries quite accurately.

It is also possible to distinguish clinoform-shaped seismic reflections in the Badenian sediments (Figure 11), which indicate deltaic progradation predominantly to the north-east. Based on their shape, it is possible to consider the shift in base level during deposition. The deltaic succession in the lower part of the Middle Badenian formation (Figure 11b) shows patterns of sigmoidal clinoforms with topsets, interpreted as showing that deposition occurred during (tectonically controlled) normal regression. Oblique-to-shingled clinoforms without topsets in the upper part of the Middle Badenian deposits (Figure 11a), together with the channels (aggradation) in the directly overlying formation (Figure 9), indicate deposition during forced regression.

Notes on the fault kinematics

From earlier exploration in the Vienna Basin, it was deduced that the Miocene sedimentary fill was deposited in different

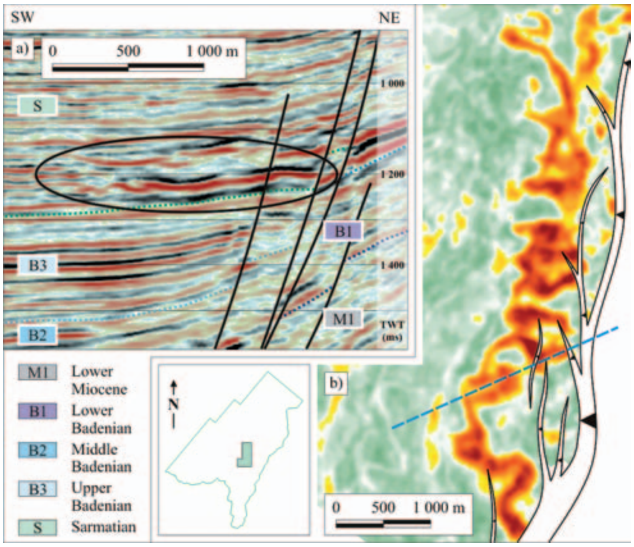

Figure 8 *Channel in the Sarmatian sedimentary fill on the eastern rim of the Central Moravian Depression displayed (a) on a seismic section, and (b) on the seismic attribute map of total absolute amplitude, for a window above the base of the Sarmatian deposits.*

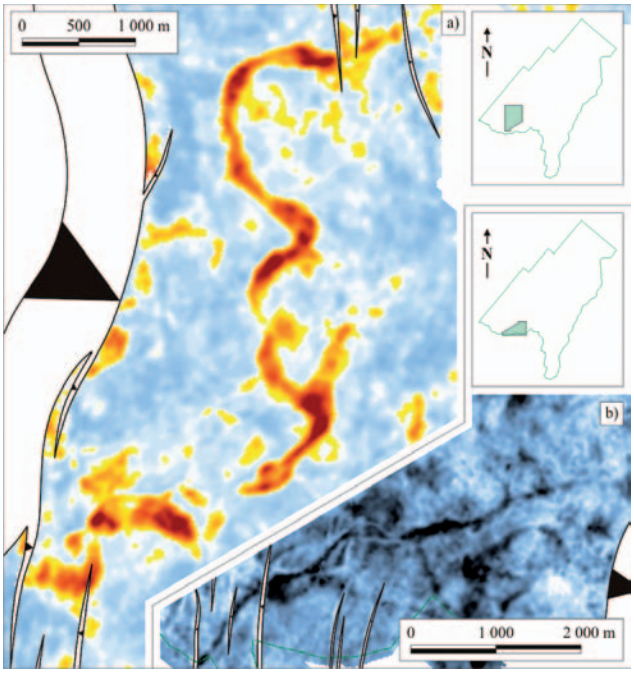

Figure 9 *Channels on the Mistelbach Block displayed on attribute maps extracted along a seismic horizon (a) in the Upper Badenian sediments with the attribute maximum absolute amplitude, and (b) in the Middle Badenian deposits with the attribute maximum trough amplitude.*

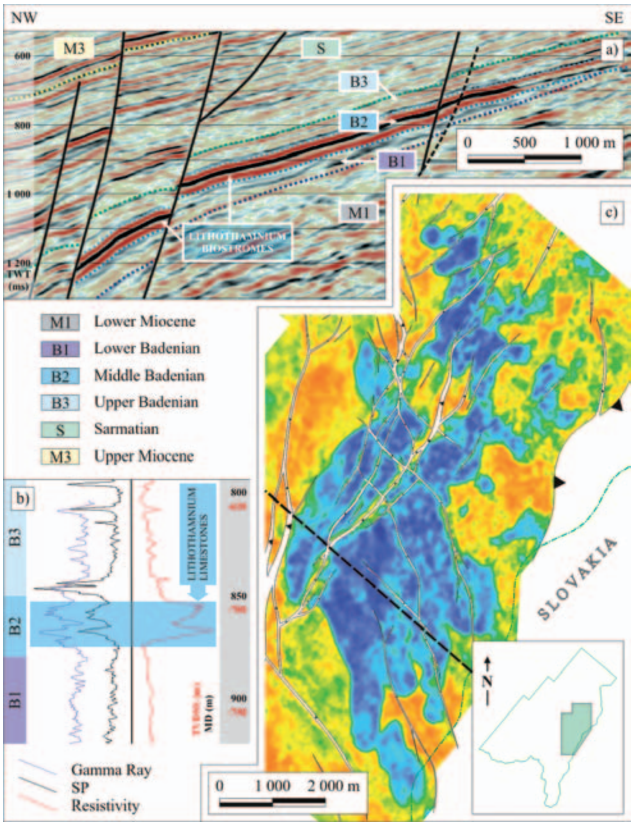

Figure 10 *Middle Badenian lithothamnium biostromes on the Hodonin-Gbely Horst displayed (a) on a seismic section, (b) on well logs, and (c) on the seismic attribute map of average absolute amplitude, for a window straddling the biostromes.*

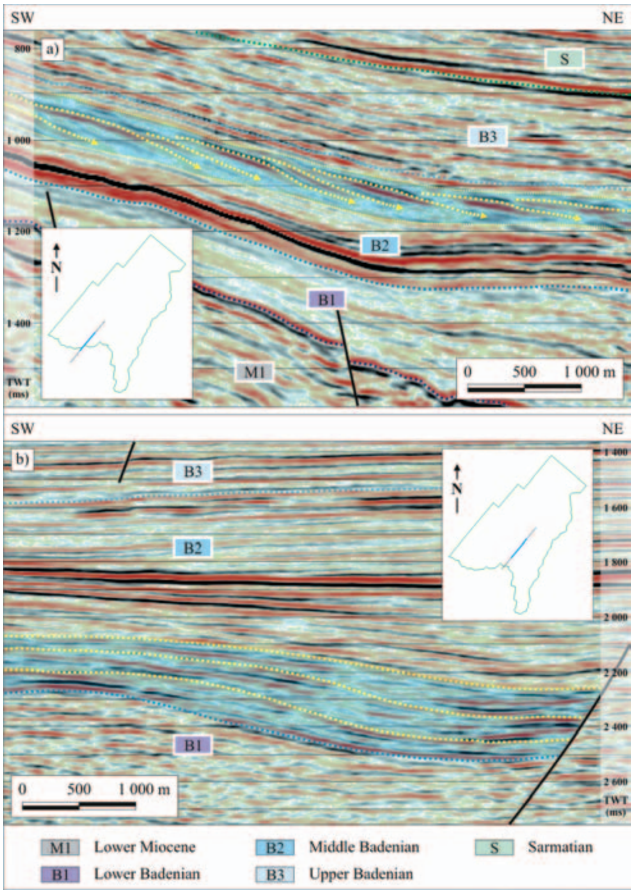

Figure 11 *Clinoform-shaped seismic reflections in (a) the upper part of the Middle Badenian deposits on the Mistelbach Block, and (b) the lower part of the Middle Badenian deposits in the Central Moravian Depression.*

tectonic settings in both space and time. At least two different Neogene tectonic regimes are commonly described (Early Miocene and Middle Miocene–Pliocene), associated with different stages of tectogenesis of the region between the Alps and the Carpathians (e.g., Ladwein et al., 1991). According to accepted models (e.g., Fodor, 1995), the later development of the Vienna Basin, particularly during the Middle Miocene, was affected by strike-slip faults in accordance with Royden's (1985) description of the Vienna Basin as a thin-skinned pull-apart basin. The Vienna Basin has been cited as a classic example of a trans-tensional pull-apart basin in several recent publications. Only Jiříček (1985, 2002) has expressed scepticism about this mode of basin formation.

Strike-slip tectonics are thought by several authors to be demonstrated by the rhombic shape of the Vienna Basin (e.g., Burchfiel and Royden, 1982); fault systems interpreted from seismic profiles as flower structures (e.g., Hinsch et al., 2005) or, in map view, as en echelon arrays (e.g., Ladwein et al., 1991); migration of depocentres over time (e.g., Royden, 1985); and the resemblance of the basin's tectonic style to structures modelled in trans-tensional conditions (e.g., Wu et al., 2009). However, no specific strike-slip offset of geological features across any fault has yet been proved.

Detailed analysis of depositional facies in relation to the tectonics can help to explain the fault kinematics and the basin formation mechanism. Some of the observed channels are disrupted tectonically, and it is possible to identify them on both the footwalls and hanging walls of faults, including the main fault systems. In such cases, they provide informa-

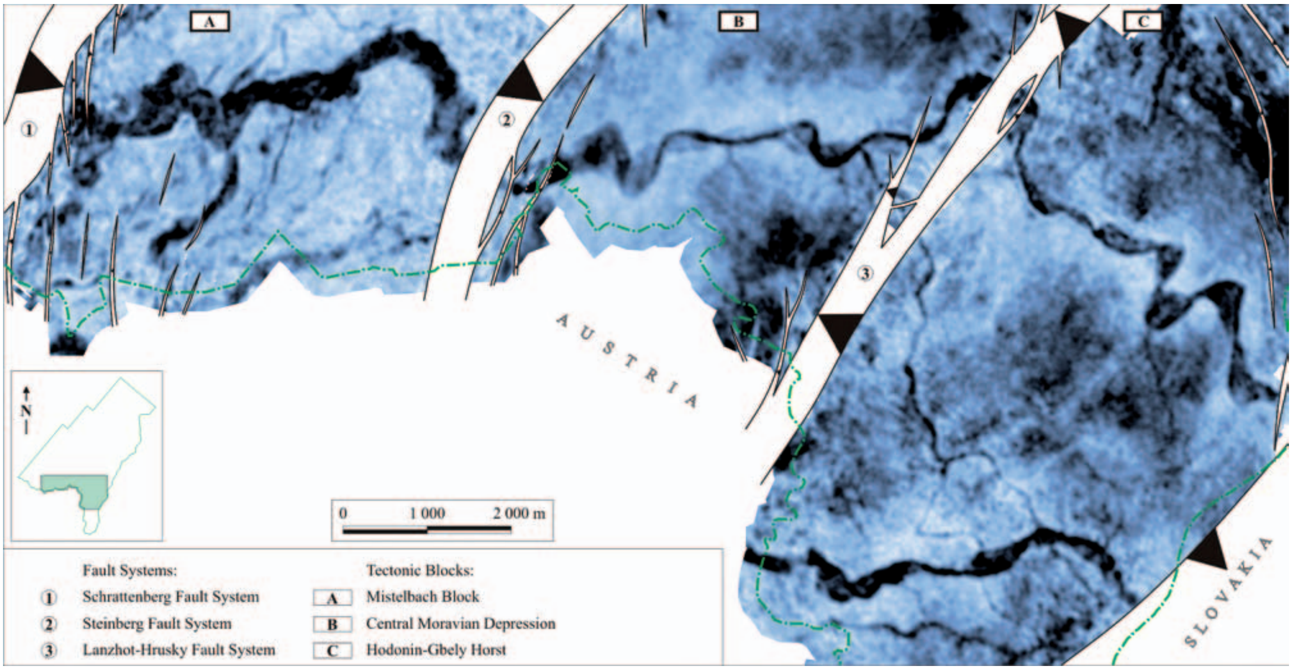

Figure 12 *Horizon slice with the attribute, root-mean-square amplitude, displaying a channel passing from the Mistelbach Block through the Central Moravian Depression onto the Hodonin-Gbely Horst.*

tion not only about the depositional environment, but also about the fault kinematics, because they allow the fault movement to be specified precisely in both space and time.

Channels crossing the main fault systems have been identified in sediments of Pannonian, Sarmatian, and Badenian age. They cross the faults without lateral offsets in the area of interest. The oldest channel recognized on more than one tectonic block occurs in Upper Badenian sediments, and crosses two main basinal fault systems without lateral offsets, i.e., the Steinberg and the Lanzhot-Hrusky faults (Figure 12). This observation excludes Upper Badenian and younger horizontal displacements along these faults, and indicates that during the opening of the study area depocentre (Central Moravian Depression) – at least since the late Badenian – strike-slip tectonics have not played a significant role.

Because of the limited extent of the study area, these fault kinematic results cannot be applied to the entire Vienna Basin, but they still unambiguously define the nature and timing (late Badenian and more recently) of fault development in the study area. The methods used to obtain the results presented here can be applied in any part of the basin or in any sedimentary basin where 3D seismic data are available. Seismic data volumes from other parts of the Vienna Basin may contain information that either supports or excludes proposed modes of basin genesis, and shows whether currently accepted concepts of basin formation are correct.

For kinematic analysis, channels have mainly been used in this paper, but theoretically, any tectonically disrupted geological structure identified by seismic attributes can be used for the same purpose. An example is the seismic attribute map of sediments underlying the so called 'Lab Horizon', one of the most important reservoir rocks in the Moravian part of the Vienna Basin, which displays one tectonically disturbed seismic facies that crosses several tectonic blocks (Figure 13).

New prospects for hydrocarbon exploration

Based on 3D seismic data analysis, new structures with potential hydrocarbon accumulations have been identified. New prospective targets (Figure 14) comprise various types of hydrocarbon traps: structural traps bounded by faults; stratigraphic traps in sandy intervals beneath unconformities or in lithologically restricted sand bodies detected by means of seismic attributes; and combination traps in the sandy fill of tectonically disturbed channels.

Fault positions specified through 3D seismic interpretation helped to design the optimal well trajectories in order to penetrate fault-bound prospects in crestal positions. Figure 15 illustrates such a proposed exploration well that was drilled in 2010 next to the Steinberg Fault.

It is estimated that recently identified prospective targets contain 1.5 million m^3 of oil and 1.6 billion m^3 of gas resources. Over 200 million m^3 of gas in such prospects have been proved by new wells so far.

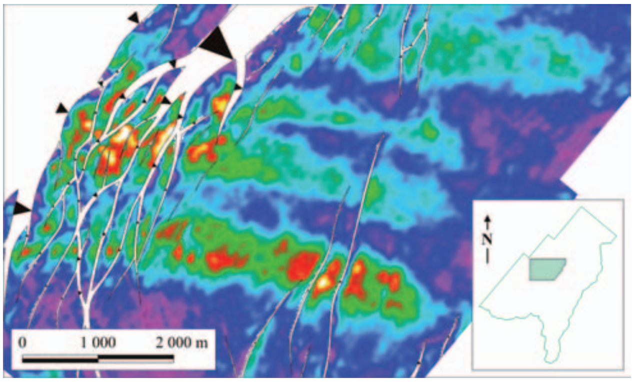

Figure 13 *The attribute RMS (root-mean-square) amplitude computed over a time window beneath the 'Lab Horizon' reservoir. The area displayed is located on the western flank and central part of the Central Moravian Depression, and crosses several fault-bounded blocks.*

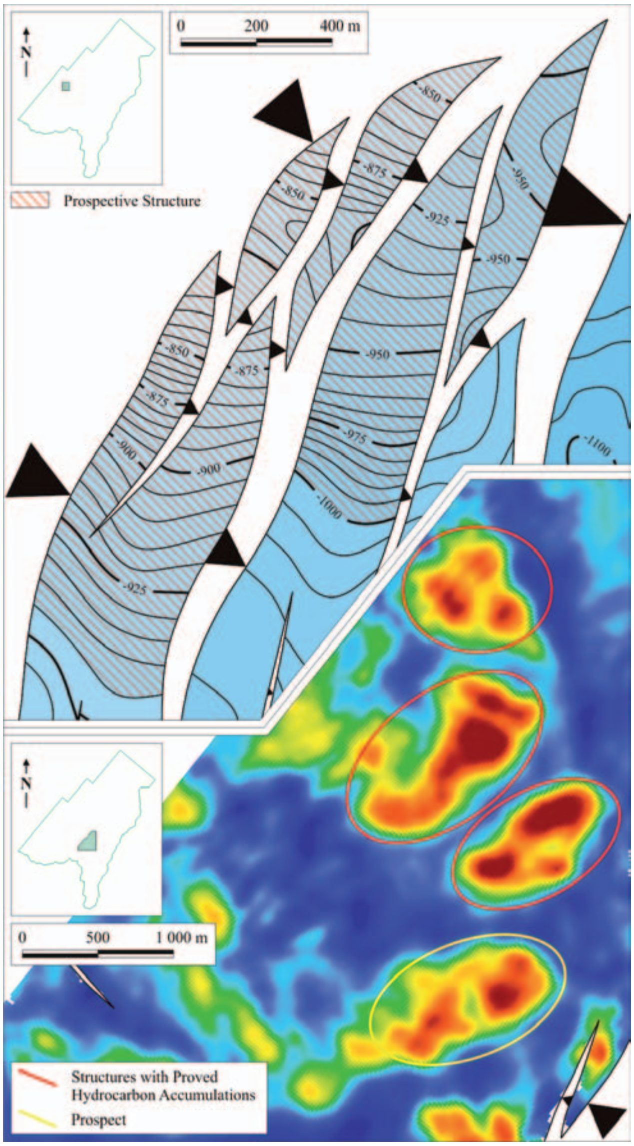

Figure 14 *Examples of prospective targets: (a) structural traps in the so-called '10th Badenian Horizon', and (b) lithological traps detected with the attribute, average absolute amplitude.*

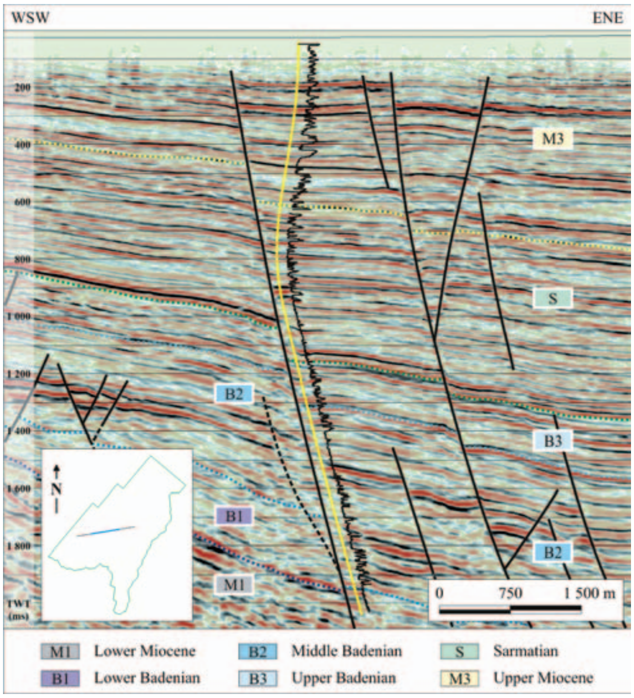

***Figure 15** Trajectory of the well adjacent to the Steinberg Fault on the western flank of the Central Moravian Depression.*

Conclusions

The role of seismic exploration has changed radically over recent years in the search for stratigraphic traps in the Vienna Basin. Information from other basins around the world show that the reserves in stratigraphic traps are comparable to those in structural traps, and the results of exploration have often led to renewed production in areas of depleted fields in structural traps.

These types of reservoirs have complex facies, and their identification is usually possible only where there is good coverage of high-quality seismic data and previous well data, and depends on the integration of all available data. Over most of the Vienna Basin, the geological conditions are favourable for the existence of stratigraphic traps, so the recent intensive exploration effort has been worthwhile.

The results of 3D seismic data analysis have contributed to a better understanding of the tectono-sedimentary evolution of the study area, but their main importance has been in the identification of new prospects. Based on the study of the temporal and spatial relationships between depositional facies, lithological development, and tectonics, a large number of prospects have been defined in the study area. Recoverable reserves proved by exploration wells in the new prospects demonstrate that detailed 3D seismic data analysis can be applied successfully in previously explored and tectonically complicated areas, such as the Moravian part of the Vienna Basin.

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