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International deep reflection survey along the Hungarian Geotraverse

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Low-frequency seismic reflection investigations of the lithosphere were conducted in SE Hungary with *Hungarian, Canadian and Swiss* cooperation during 1992. The profile PGT-4 (part of the Hungarian Geotraverse Project), starting at the eastern flank of the Algyő High (near the town of Szeged), crossed

—the Hódmezővásárhely-Makó Graben,
—the Pusztaföldvár-Battonya Ridge and
—the Békés Basin (Fig. 1).

The Neogene sediments of both the Hódmezővásárhely-Makó Graben and the Békés Basin have a thickness of 6–7 km. A NE dipping shear zone, which may be traced into the lower lithosphere, marks the eastern margin of the Algyő High.

Integrated interpretation of seismic (related profile PGT-1), regional geothermal, geomagnetic and gravity data reveals an elevation in the lower crust, the crust-mantle and the lithosphere–asthenosphere boundary, as well as magmatic intrusions which protrude as high as the upper crust beneath the Békés Basin. Deep reflection and magnetotelluric data along the PGT-4 indicate an anomalous rise of the lithosphere–asthenosphere boundary: a *domal uplift of the asthenosphere*, beginning at the NE termination of the profile. Beneath the Hódmezővásár-

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hely–Makó Graben both the crust–mantle and the lithosphere–asthenosphere boundaries form a minor uplift slightly westward from the Hódmezővásárhely-Makó Graben.

Low-frequency seismic reflection measurements within the Carpathian Basin outline a *sketch of the complete lithosphere*, suggestive of tectonic *development* described by low angle *extensional basin* forming models. Analogously to this Basin and Range type extensional model, the Hódmezővásárhely–Makó Graben and the Dorozsma Graben (to the southwest) were formed as a consequence of major penetrating shear zones and upswell of the lower crust and the lithosphere–asthenosphere boundary.

In addition to this *new tectonic model*, intriguing structures were mapped, at those depths which may be effective targets for *oil and gas* exploration.

Keywords: Mohorovičić discontinuity, Pannonian Geotraverse, lihosphere, reflection, seismic survey

1. Introduction

Deep seismic reflection experiments initiated in Hungary in the early 70's utilized low frequencies which penetrated the complete lithosphere and, in some localities, segments of the asthenosphere. One of the main objectives of these investigations was to generate observable signals at frequencies down to 2–4 Hz. Instead of adopting low cut filters, the signal to surface wave amplitude ratios were improved by placing explosive sources in 50–70 m boreholes and implementing specific velocity filtering. Processing with true amplitude recovery was achieved by applying spherical correction. Within the first experiments (line KA in *Fig. 1*), expanding spread survey configurations enabled us to infer that reflections can be received from the upper mantle. Relying on interval velocities derived from seismic signals, we were able to estimate the depth of the lithosphere–asthenosphere boundary [Posgay 1975]. Along the deep reflection profile KESZ-1 (Biharkeresztes area, near Debrecen, Fig. 1) seismic signatures suggested a deep fracture zone dissecting the entire lithosphere [Posgay et al. 1981, Posgay et al. 1986], and located in a region coinciding with a known major tectonic line of significant strike-slip component [Grow et al. 1989]. The results of the southern part of the reflection profile PGT-1 [Posgay et al. 1990] indicated an upswelling of the crust-mantle and the lithosphere–asthenosphere boundaries beneath the Békés Basin [Posgay et al. 1995].

Most recently these investigations were extended through an international seismic experiment with the collaboration of Hungarian, Canadian and

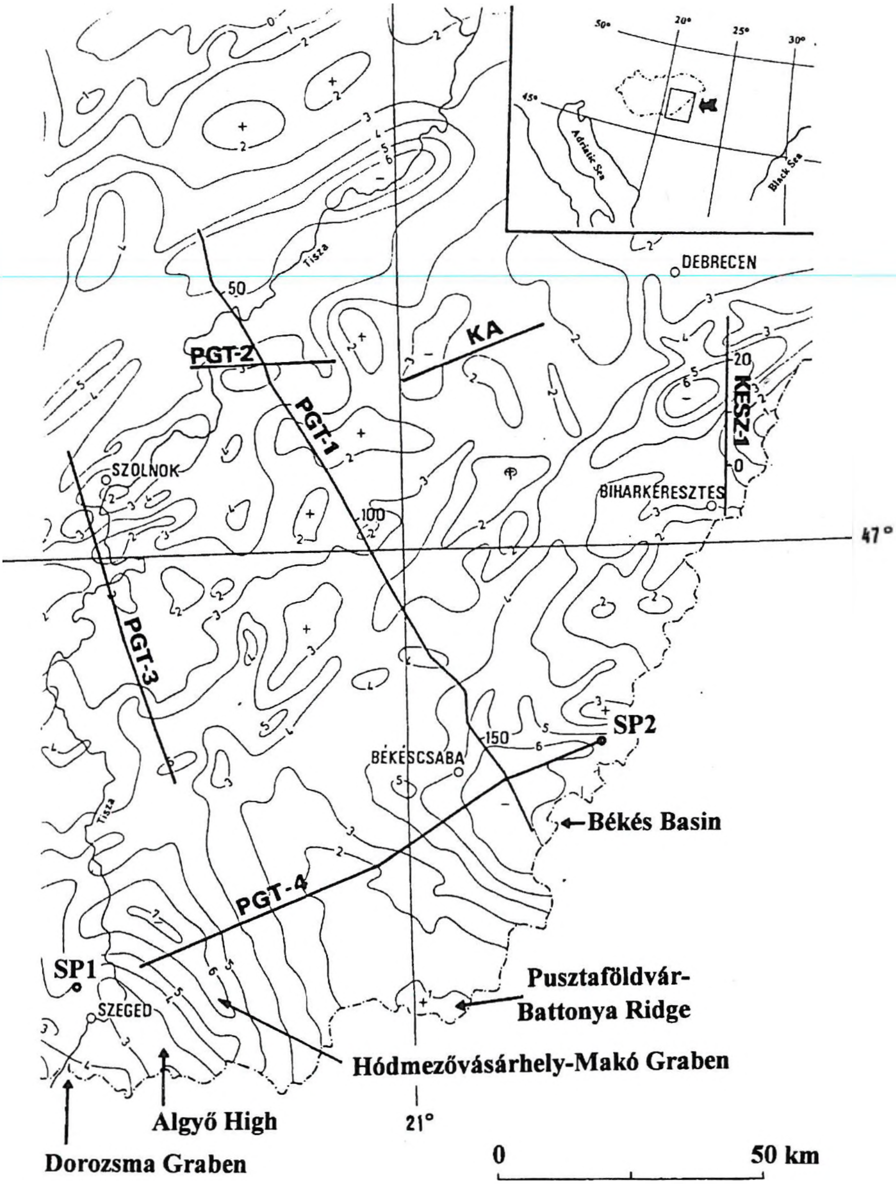


Fig. 1. Location of the deep seismic reflection lines in SE Hungary. Also shown is the contour map of the basement (pre-Tertiary rocks) compiled by KILÉNYI et al. [1991]. Contour lines of the basement in km

1. ábra. DK Magyarországon végzett mélyreflexiós kutatások helyszínrajza a pre-tercier medencealjzat [KILÉNYI et al., 1991] mélységtérképén. A szintvonalak értékközét km-ben írtuk fel

Swiss investigators. Efforts were made to further increase the penetration of deep reflection measurements by shifting the frequency range (approx. one octave) further towards lower frequencies. The data acquisitions were along the reflection profile PGT-4 (Fig. 1). This profile passes over two sub-basins of the inner Carpathians: the Hódmezővásárhely–Makó Graben and the Békés Basin, as well as the domal uplift separating them. The location of the survey line was chosen to map deep structures beneath this rapidly-developed region of the inner Carpathians. A special aim of the study was to gain a better insight on the origin and formation of the sedimentary sub-basins, their associated thermal and tectonic processes, injection of fluids, and the development structural traps within the lower segments of these features.

Researchers from a number of institutions contributed to the planning, execution, processing and interpretation of the data set:

—Eötvös Loránd Geophysical Institute (Hungary).
—LITHOPROBE, Canada,
—Department of Geological Sciences, University of Saskatchewan (Canada),
— Institut für Geophysik, Eidgenössische Technische Hochschule (Switzerland),
—Continental Geoscience Division, Geological Survey of Canada.

2. Seismic data acquisition and processing

The deep reflection data acquisition along seismic profile PGT-4 (Fig. 1) was conducted in September and October 1992. Seismic sources consisted of 50 kg chemical explosives, detonated in 70 m boreholes.The seismic signals were observed in three, coeval but different survey and recording configurations (*Fig. 2*).

In the first survey format 195 PRS (Portable Recording System, Canada) type recording units were deployed. Spacing of the detectors was 100 m. Each twenty first unit had three-component signal detection capability (PRS-4). The seismometers of the PRS units had an unattenuated natural frequency of 2 Hz. The low-frequency transmission limit of this recording equipment started practically at 0 Hz. The digital sampling frequency was 120 Hz with an observation time of 60 s. To achieve a more favourable signal to noise ratio field operations were performed at nights only. During this

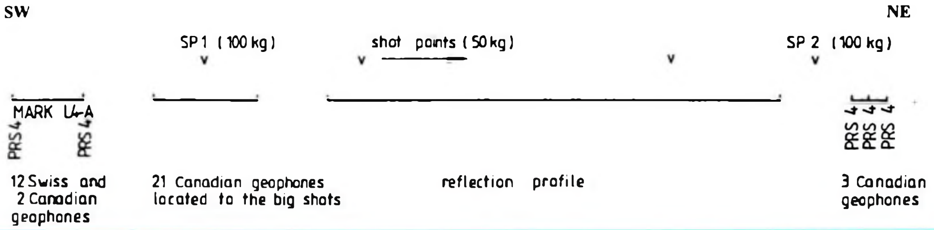


Fig. 2. Reflection survey configuration of deep reflection profile PGT-4 along the Hungarian Geotraverse. Shots were observed in 3 different arrangements

2. ábra. A Magyar geotraverz menti, PGT-4 mélyreflexiós szelvény észlelési vázlata. A robbantásokat 3 rendszerben észleltük

time-period the spread remained stationary, with detonations at alternate source locations. A total of 288 shots were observed along 15 spreads.

In the second survey arrangement observations were conducted with a 160 channel MDS-18 type (Halliburton Geophysical Services, USA) telemetric instrument and detector array spacing of 50 m. Each detector array was formed by 5 seismometers, having an unattenuated natural frequency of 4.5 Hz. The digital data sampling rate was 4 ms (high cut filter of 93 Hz), the recording time 48 s. Survey spreads of this data acquisition format were laid out parallel with the previous configuration.

The third data collection was provided by two stationary seismic arrays at the west and east ends of the survey line. At the west end 2 PRS-4 units and 12 L4-A detectors (MARK Products, USA) were deployed with ELGI's telemetric system; at the east end 3 PRS-4 units provided the data acquisition. The ELGI system (low-frequency transmission characteristics: at 1 Hz was –3 dB) recorded 48 s of data with a sampling rate of 8 ms. All PRS-4 units observed 100 s of data. The survey was completed with the detonation of 100 kg charges at both ends of the profile (Fig. 2).

The different data sets were processed and interpreted in the laboratories of the cooperating institutions. ELGI's staff processed the data observed by the first and second systems, with special attention to structures of Neogene sediments and of the underlying lithosphere. This presentation relies only on results generated by the Hungarian participants. Processing and consequent presentation of the results of the first system were provided by the Canadian contributors in a special issue of Tectonophysics [HAJNAL et al. 1996].

Synthesis of the stationary and transverse data — gathered in the third system — was the task of the Swiss members. The results are still being worked on.

In the course of processing reflection data at ELGI's laboratory, an attempt was made to obtain true amplitude images (no automatic amplitude control was applied). These data were subjected to velocity and wide-band (2–5, 29–32 Hz) filtering, spherical divergence correction and editing. (Efforts were directed towards suppressing surface waves through specially developed coherent noise adaptive filtering and through a more careful cutting of the surface wave prior to summing, thereby to avoid the weakening of low frequency deep reflections by low-cut filtration). Velocity depth functions of the Neogene sedimentary complexes were established from refraction arrivals — appearing in the 18 km long spreads — and utilization of the areal velocity–depth functions of hydrocarbon exploration, from the same area of consideration. Where wireline well logging data were not available, and in the crystalline crust and the upper mantle, interval velocities were determined from the expanding spread data of profile KESZ-1 [POSGAY et al. 1981, POSGAY et al. 1995]. Stacked data were subjected to *f–k* domain filtration, *f–x* deconvolution and the weighted 2D median filtering. One of the post stack processing steps was the application of 45° finite-difference time migration.

The first 6 s of the information of the second system was processed with frequency band limits of 4-60 Hz (Figs. 3–6). No *f–k* domain filtering was applied and a minimum phase predictive deconvolution filtering was implemented to replace *f–x* deconvolution and weighted 2D median filtering.

3. Regional structural sketch

The pre-Neogene floor of the Carpathian Basin is constituted by tectonic 'terranes' formed in various parts of the Tethys sea. The region of this investigation falls on the Tisza terrane. The origin and present site of this unit were established through concentrated paleogeographic, biostratigraphic, paleomagnetic, paleokinematic, sedimentologic and facies studies [KOVÁCS 1982, BALLA 1984, CSONTOS et al. 1992]. Although there are a number of contentious issues still remaining to be solved, all the investigators agree that the Tisza terrane more likely originates from the European (northern) side of the Tethys, at the time of the Alpine-Carpathian orogeny [STEGENA et al. 1975, MÁRTON 1981, HORVÁTH and ROYDEN 1981]. In that part of the Tisza terrane which falls within the survey area, the pre-Neogene basement includes continuation of the Codru nappe system, which is exposed in the outcrops in the Apuseni Mountain of the Transylvanian Middle Range [SZEDERKÉNYI et al. 1991]. The upthrusts of these units occurred in the upper Cretaceous (Middle-Upper Turonian, GYÖRFI 1994), with a N vergence, during the impact of the Alpine compressional phases. On the basis of the stratigraphic and facies character of these strata, five structural units can be distinguished. They are, from the bottom upwards: Mecsek–northern part of the Great Hungarian Plain zone, Villány–Bihar zone, Papuk–Békés-Lower Codru zone, Northern Bácska–Upper Codru zone, and Nagybihar zone. These structural units contain both Mesozoic and metamorphic Paleozoic and older series, except the Nagybihar zone, where no Mesozoic formations are known.

The pre-Neogene basement of the Carpathian Basin was formed in the Paleogene. Along the boundaries of the developing terranes (and within their interior as well) major shear zones were formed as a consequence of the irregular transpressional movements between the various units. Results of deep seismic measurements reveal that these wrench faults dissect the entire crust and in some cases penetrate the lithospheric segment of the mantle [POSGAY and SZENTGYÖRGYI 1991].

At the end of Paleogene—beginning of Miocene, the Tisza terrane may have reached its present location [CSONTOS et al. 1992]. Tectonic processes leading to the formation of the Carpathian Basin (Pannonian Basin system) were initiated in the Late Oligocene and/or in the Early Miocene and culminated during the Middle Miocene [CSONTOS et al. 1991, HORVÁTH 1993]. The 'back arc' extension of the Carpathian Basin is contemporaneous with the formation of the Outer-Carpathian flysch belt. The synrift phase (active extension) within the Carpathian Basin — according to one estimate — started from 22 Ma [GROW et al. 1994], the other estimate [TARI et al. 1992] is 17.5 Ma, and extended either to 12 Ma [HORVÁTH and POGÁCSÁS 1988], or to 10.5 Ma [TARI et al. 1992, HORVÁTH et al. 1988]. The postrift phase is still going on.

Numerical modelling of the evolution of the Great Hungarian Plain shows that a moderate crustal extension (stretching parameter less than 2.2), combined with a major thinning (or heating) of the mantle lithosphere (the stretching parameter is bigger by one order of magnitude), has controlled the formation of the basin [HORVÁTH et al. 1988]. Modelling of the subsidence of the sedimentary sequences of the Hódmezővásárhely-I deep borehole provided figures between 11 Ma and 0 Ma with values of $\beta_c=2.2$ for the crust, and $\beta_m=19$ for the mantle lithosphere [HORVÁTH 1986].

4. The Neogene complex

The depth section derived from data recorded with PRS stations — in the first observation system — is shown in *Encl. 1*. One possible interpretation of it is presented in *Encl. 2*. The depth section obtained from data of the MDS-18 equipment — second system — is provided in *Encl. 3*. Interpretation of these data is given in *Encl. 4* with some interpretive concepts taken from Encl. 2. The differences in instrument responses and spread parameters are reflected in the sections. The PRS section gives a more conspicuous image of the deep structure, while the MDS section highlights the sedimentary strata, the floor of the basin and the fractures within the sub-basin sequences. Magnetotelluric results are also given in Encls. 2 and 4. Crosses in the vicinity of the bottom of the Neogene basin are indicative of the high resistivity beneath the basin.

An accurate correlation of Neogene sediments, deposited in the Hódmezővásárhely–Makó Graben and in the Békés Basin, would be of interest for the reconstruction and comparison of the development of these two basins. However, sediments deposited at greater depths cannot be directly correlated along the profile because the Pusztaföldvár–Battonya pre-Neogene ridge separates them (*Fig. 3*). A number of relevant studies based on earlier data sets are, however, available in the literature. Incorporation of these concepts into the present synthesis is revealed in *Fig. 4*. Age data received from seismo-, sequence- and magnetostratigraphy, as well as radiometric age determinations were marked at the end of the profile, based on data from VAKARCS et al. [1994]; at the crossing of PGT-1 and PGT-4 the information is from MATTICK et al. [1994]. The interpretation at the deep drilling site 1 is taken from MATTICK et al. [1988]. As the scope of understanding on the sedimentary infill within the basins has increased, so the regional correlation of individual complexes has also progressed. It is now recognised that sedimentation was provided to the basins from a variety of directions NE, N, NW, W and S [MATTICK et al. 1994]. In that it was unlikely that there would be any direct correlation of all the phases within the two basins, direct correlation was not attempted. As a consequence of these complexities the most comprehensive interpretation of the sedimentary sequences along

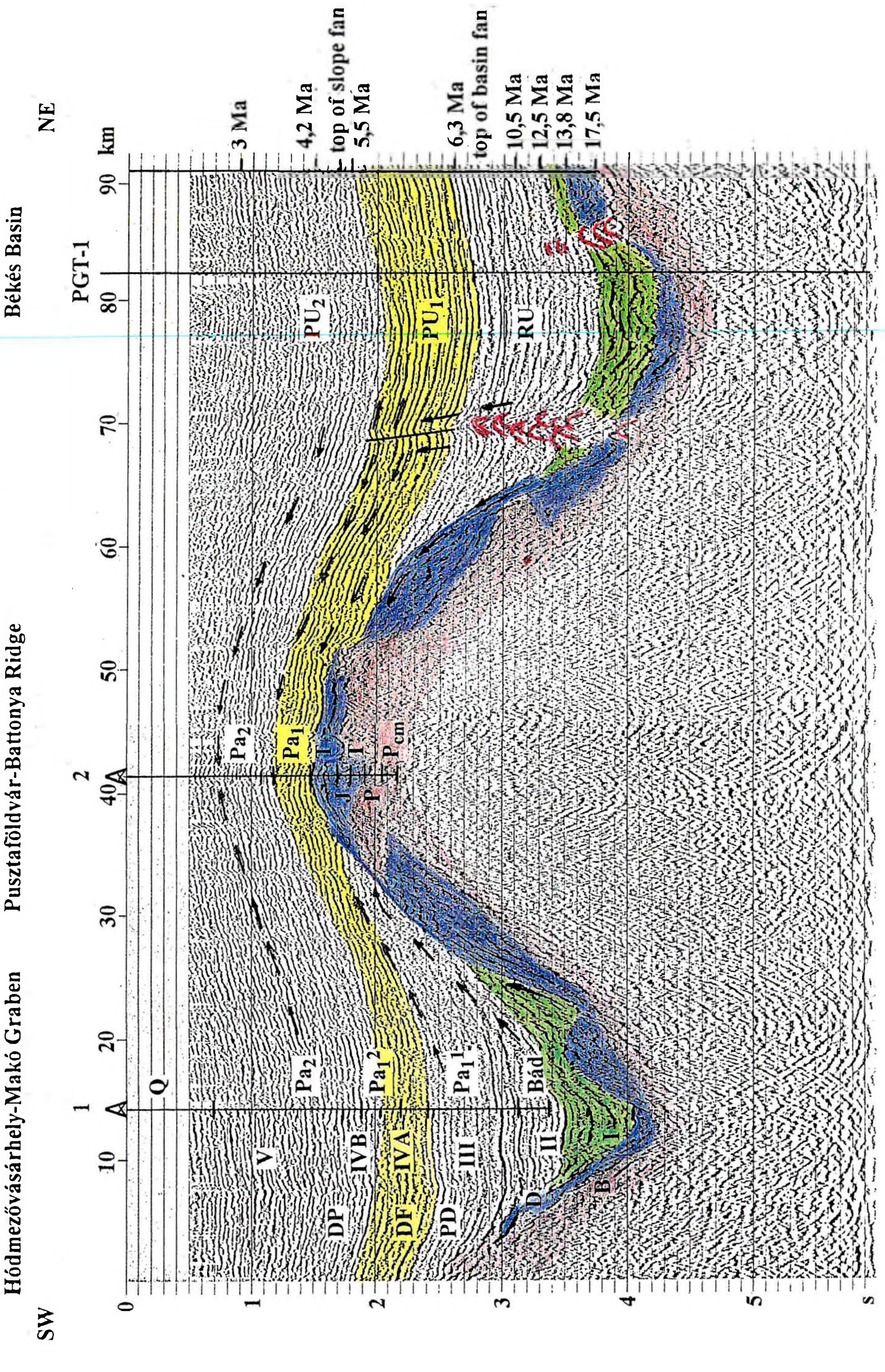

SW
NE
Hódmezővásárhely-Makó Graben
Pusztaföldvár-Battonya Ridge
Békés Basin
PGT-1
km
10
20
30
40
50
60
70
80
90
A1
A2
0
1
2
3
4
5
s
3 Ma
4,2 Ma
top of slope fan
5,5 Ma
6,3 Ma
top of basin fan
10,5 Ma
12,5 Ma
13,8 Ma
17,5 Ma
Q
V
DP
IVB
IVA
DF
III
PD
II
D
I
B
Pa2
Pa1 2
Pa1 1
Bád
Pa1
J
T
P
Pcm
PU2
PU1
RU

Fig. 4. Interpretation of the section of Fig. 3. Delta sediments are indicated in yellow, a complex interpreted as Lower Badenian–Lower Miocene in green, and the Mesozoic sediments of the pre-Neogene basement in blue. Black arrows show the assumed direction of oil and gas migration. It can be assumed that from high pressure beds of the Békés Basin hydrocarbon migrated in fractured, fissured reservoirs formed on elevated parts of the pre-Neogene basement, further on, in reservoirs formed in Neogene sediments

4. ábra. A 3. ábrán látható szelvény értelmezése. A delta üledékeket sárga, egy értelmezésünk szerinti alsóbádeni–alsómiocén összletet zöld és a preneogén medencealjzat mezozoós üledékeit kék színnel jelöltük. Fekete nyilakkal a olaj és gáz migráció feltételezett irányát érzékeltettük. Feltételezhető, hogy a Békési medence nagynyomású rétegeiből szénhidrogén migrált a preneogén medencealjzat magasabb részein kialakult töréses, repedezett, továbbá a neogén üledékekben kialakult tárolókba.

PGT-4 and more specifically within the two basins demanded the establishment of local stratigraphic concepts. In *Table 1* the names generally accepted in seismostratigraphic investigations are shown together with the international chronostratigraphic boundaries most widely known in Hungary, and with those used in the practice of hydrocarbon exploration.

The last substantial phase of basin infill — the *Late Progradational Unit* (*PU_2*, MATTICK et al. 1994) — corresponds to the *Delta Plain Facies*, i.e. to the sequencies *IV.B and V* of MATTICK et al. [1988]. Sediments deposited during this period (over 4 Ma) are present along the whole length of the profile (Encls. 1 - 4, also Figs. 3 and 4).

In the middle of the Pannonian epoch (6–7 Ma) delta sediments began to fill in the Békés Basin [POGÁCSÁS et al. 1994] and the Hódmezővásárhely–Makó Graben. At the beginning of the epoch the decrease of water depth may have exceeded 200 m. A relatively intensive sedimentation in the Hódmezővásárhely–Makó Graben started somewhat earlier than in the Békés Basin [VAKARCS et al. 1994]. The *Early Progradational Unit* (*PU_1*, MATTICK et al. 1994) was interpreted by us as a contemporaneous deposit to the *Delta Front Facies* or *sequence IV.A* [MATTICK et al. 1988]. Reflection signatures which originated from this sedimentary interval of the subsurface appear with significant amplitudes and characteristic stratal termination patterns and stratal discontinuities. In Encls. 2 and 4 as well as in Fig. 4 these band reflections are marked in yellow. The lower levels of the sequence onlap the Pusztaföldvár–Battonya Ridge. The ridge may have subsided below the interior lake level approximately 6 million years ago. Submersion of portions of the basins must have progressed at a quicker pace since that period as a number of equivalent strata occur in the basins at a greater depth than over the ridge.

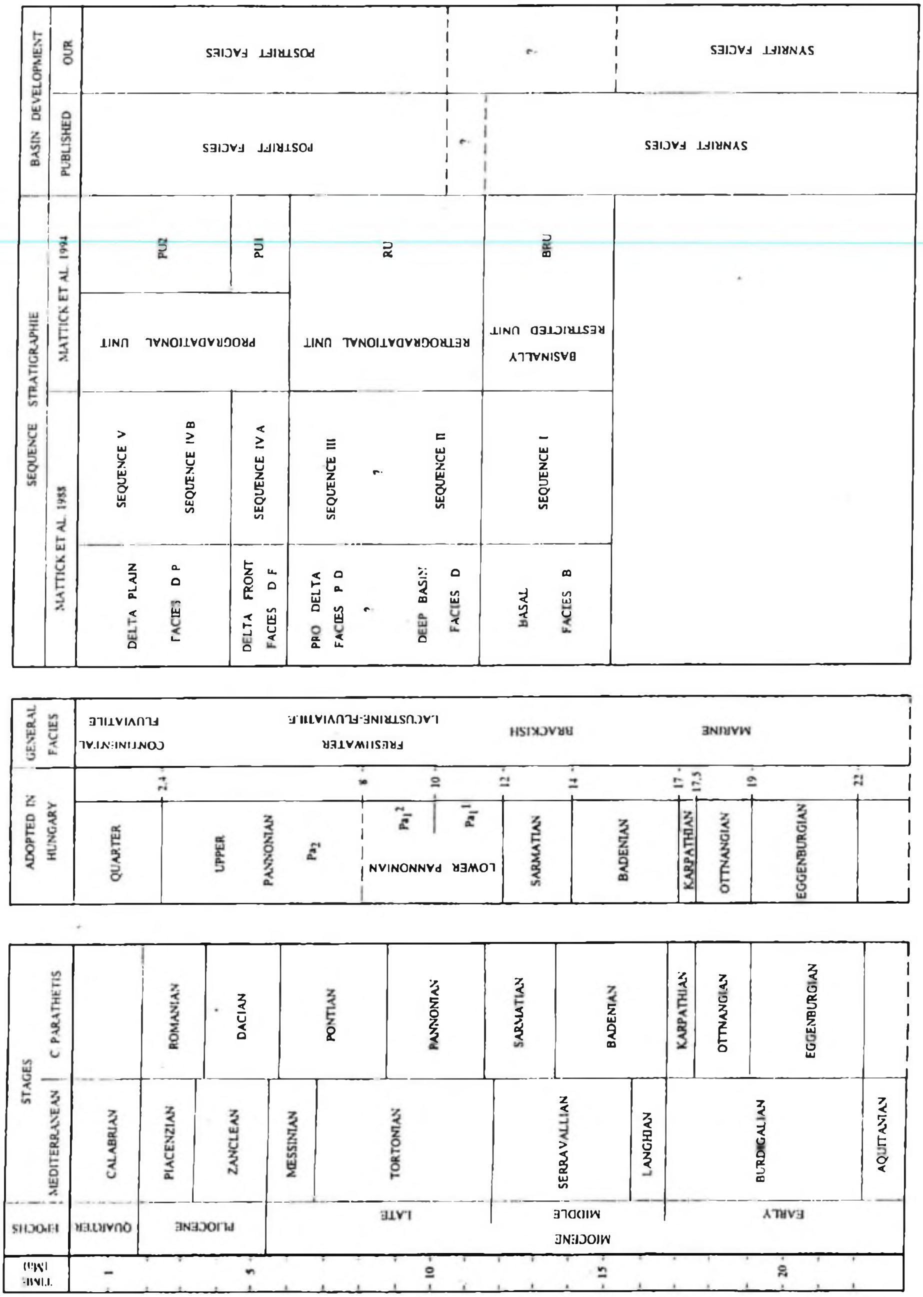
According to the results of seismostratigraphic, sequence-stratigraphic, magnetostratigraphic investigations and radiometric age determinations [VAKARCS et al. 1994] the shallow sea of the inner Carpathians was isolated from the world oceans and reduced to a lake at the boundary of the Sarmatian and Pannonian stages (11.5 Ma). At that time the water depth began to increase and progressively reached 800 to 1000 m. At the end of the Sarmatian and the beginning of the Pannonian stage the subsidence of the Hódmezővásárhely–Makó Graben and of the Békés Basin was quicker than the accumulation of sediments, thus it was relatively starved of sedimentary fill [POGÁCSÁS et al. 1989, KÓKAI and POGÁCSÁS 1991]. The *Retrogradational Unit* (*Ru*, MATTICK et al. 1994), which contains readily traceable reflection horizons, was correlated by us to the earlier described *Deep Basin Facies* and *Prodelta Facies* [MATTICK et al. 1988], i.e. approximately corresponding to *sequences III and II* .

An extended (time)segment of the (MDS-18) seismic section images the central region of the Békés Basin (*Fig. 5*). Interpretation of this partial section reveals a number of seismic signal characteristics some of which are regional in nature; the others are confined to a specific segment of the subsurface (*Fig. 6*). The prevailing, laterally well correlatable subparallel reflections, with visible decrease in frequency content and gentle overall easterly dip — down to 2.75 s travel times on the southwest and 4 s arrival times on the northeast — are clear manifestations of the characteristic seismic images of the Neogene sediments. In the lower central regions of the sections (Figs. 5, 6), approximately 70 km southwest from the northeast end of the survey line, just below 2.5 s travel time, extending below 4 s, there are a number of directly recognizable congruous, highly curved, laterally limited and locally distinct reflection patterns. The nature of these reflectivity patterns and the draping of the overlying sedimentary strata are suggestive of a *young magmatic intrusion* which locally protruded the basin. Originating as a consequence of differential compaction a steeply east dipping *listric fault* and a *roll-over structure* are traceable from 1.8 s to a significant depth, along the NE side of the magmatic intrusion. Based on the geochronological age of the affected sediments the inferred age of the strata directly overlying the magmatic body is 6-7 Ma.

In the Apuseni Mountain (an area 60–150 km eastward from the investigated anomaly) rhyolitic volcanism was active in the Upper Badenian, dacitic and andesitic in the Sarmatian, while basaltic at the beginning of the Lower Pannonian. In the eastern part of the Pannonian Basin there are

Table I. International chronostratigraphic boundaries best known in Hungary and used in the practice of oil and gas exploration [HORVÁTH 1986], and nomenclature established in sequence-stratigraphical investigations [MATTICK et al.1988, 1994]. As our interpretation shows, in Encls. 2 and 4 it is assumed that the synrift sediments deposited in the Lower-Miocene and at the beginning of the Middle-Miocene, and the postrift phase began 10–15 million years ago ➪

I. táblázat. A Magyarországon legismertebb nemzetközi, továbbá a szénhidrogénkutatás gyakorlatában használt korbeosztások [HORVÁTH 1986], és a szekvenciasztratigráfiai vizsgálatoknál kialakult elnevezések [MATTICK et al. 1988, 1994]. A 2. és 4. mellékleteken látható értelmezésünk szerint feltételezzük, hogy a szinrift üledékek az alsó miocénben és a középső miocén elején keletkeztek és a posztrift fázis 10–15 millió évvel ezelőtt kezdődött ➪


TIME (Ma)
1
5
10
15
20
EPOCHS
QUARTER
PLIOCENE
MIOCENE
LATE
MIDDLE
EARLY
STAGES
MEDITERRANEAN
CALABRIAN
PIACENZIAN
ZANCLEAN
MESSINIAN
TORTONIAN
SERRAVALLIAN
LANGHIAN
BURDIGALIAN
AQUITANIAN
C. PARATHETIS
ROMANIAN
DACIAN
PONTIAN
PANNONIAN
SARMATIAN
BADENIAN
KARPATHIAN
OTTNANGIAN
EGGENBURGIAN
ADOPTED IN HUNGARY
QUARTER
UPPER PANNONIAN
Pa_2
LOWER PANNONIAN
Pa_1^2
Pa_1^1
SARMATIAN
BADENIAN
KARPATHIAN
OTTNANGIAN
EGGENBURGIAN
2.4
8
10
12
14
17
17.5
19
22
GENERAL FACIES
CONTINENTAL FLUVIATILE
FRESHWATER LACUSTRINE-FLUVIATILE
BRACKISH
MARINE
SEQUENCE STRATIGRAPHIE
MATTICK ET AL. 1988
DELTA PLAIN FACIES D P
DELTA FRONT FACIES D F
PRO DELTA FACIES P D
?
DEEP BASIN FACIES D
BASAL FACIES B
SEQUENCE V
SEQUENCE IV B
SEQUENCE IV A
SEQUENCE III
?
SEQUENCE II
SEQUENCE I
MATTICK ET AL. 1994
PROGRADATIONAL UNIT
RETROGRADATIONAL UNIT
BASINALLY RESTRICTED UNIT
PU2
PU1
RU
BRU
BASIN DEVELOPMENT
PUBLISHED
POSTRIFT FACIES
?
SYNRIFT FACIES
OUR
POSTRIFT FACIES
?
SYNRIFT FACIES

ignimbrites and pyroclastic of rhyolitic composition (11–12 Ma), in its central and southern parts submarine basalts are encountered [7–10 Ma, PÓKA 1988]. According to KŐRÖSSY [1992] products of basaltic volcanism, recognized in boreholes, around Kecel (~ 150 km to the west of the anomaly), formed a more than 600 m thick pyroclastic complex with basaltic beds and veins. Within this sequence volcanic rocks alternate with fossiliferous Lower Pannonian marl and argillaceous marl. The respective ages of these volcanics, as determined by the K/Ar method, are 8.13± 0.71 and 8.47±0.77 Ma [BALOGH and JÁMBOR 1987]. Supported by the above evidence the magmatic intrusion in the Békés Basin was interpreted as *Upper Miocene* (*Lower Pannonian*) *basalt*.

The comparable characteristic upwarping of the reflection horizons, at about profile kilometer 85, between 3.3 and 3.5 s (smaller sets can be observed on Encls. 1 through 4) is also suggestive of magmatic origin. Seismic patterns of overlying younger sedimentary horizons, indicative of a listric fault, are also present on the SW side of the magmatic body (Encls. 3 and 4). At both locations of the section, seismic signatures traced the intrusive structures down into the crust.

The *time of synrift formation* in the basin [GROW et al. 1994 and in Table I] is coeval with the deposition of the *Basinally-Restricted Unit* (*BRU*, MATTICK et al. 1994), or the *Basal Facies* of the Hódmezővásárhely-Makó Graben [*sequence I*, MATTICK et al. 1988]. Encls. 2 , 4 and Fig. 4 show our interpretation which somewhat deviates from the published basin development models (Table I). It is assumed that the Middle Miocene (Upper Badenian) beds intersected by the deep drilling, denoted by 1, had already been formed as a postrift facies. (If too high velocities were used for depth determination, this error may have contributed to the deviating interpretation; if, however, our notion is correct, then the beginning of the postrift facies formation may be put between 10 and 15 Ma). According to our model, in the deep part of both basins *Lower Miocene* (perhaps Paleogene) sediments may also have accumulated under the Badenian beds. This synrift formation is characterized by a slightly fractured texture and has a significant thickness of about 1500 m. Seismically it is manifested by high amplitude and low frequency. In enclosures 2 and 4, as well as in Figs. 4 and 6 this series is shown in green. On the basis of magnetotelluric studies the resistivity of the previous sedimentary zone is assumed to be over 200 Ωm [VARGA and NEMESI 1994]. On the basis of an integrated seismic and magnetotelluric

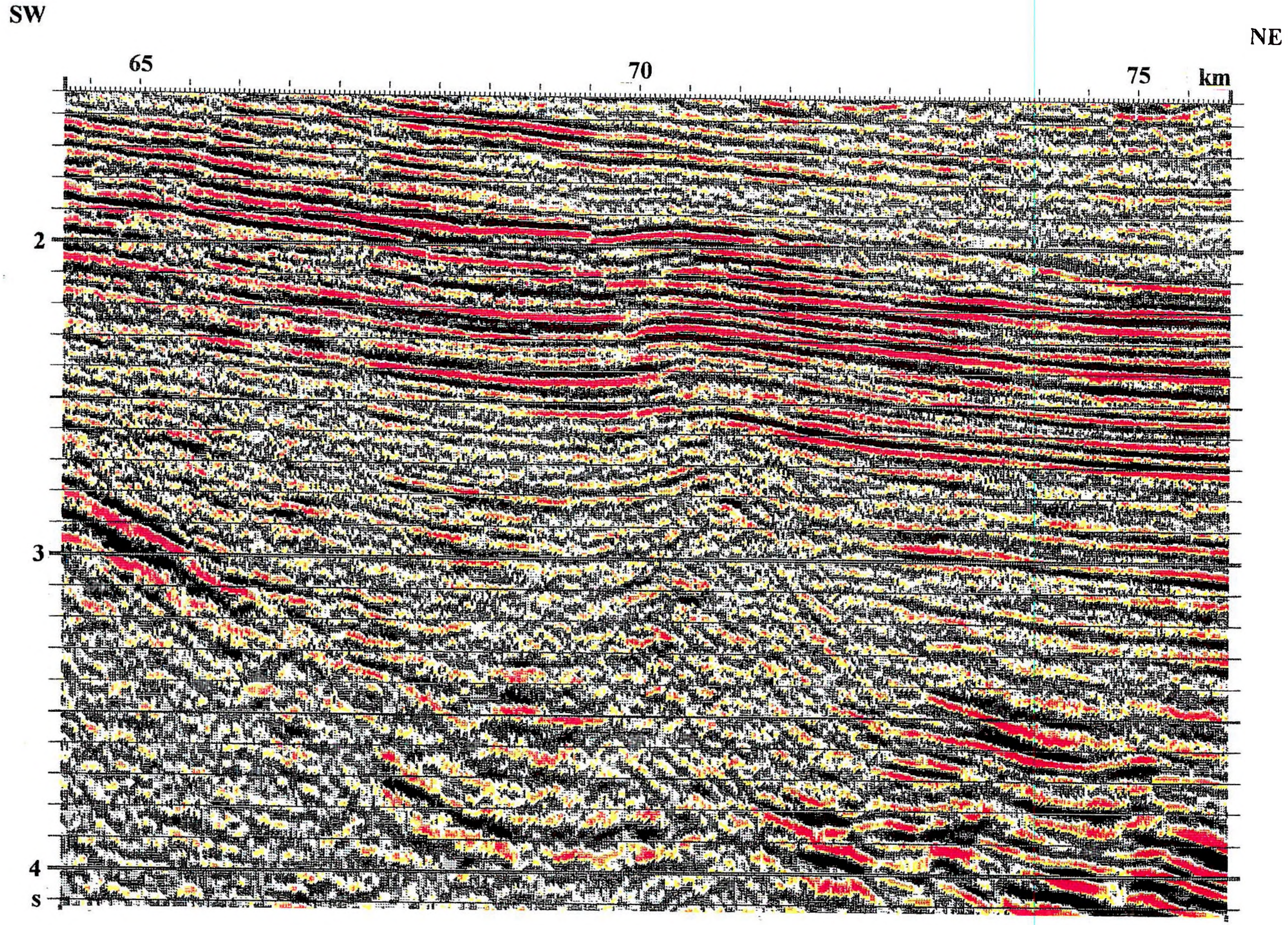

SW
NE
65
70
75
km
2
3
4
s

Fig. 5. Part of the time section from data recorded — based on the chapter 'Seismic data acquisition and processing' in the second survey arrangement — by MDS-18 telemetric seismic equipment

5. ábra. A — „Seismic data acquisition and processing" c. fejezet szerinti — második rendszerben, MDS-18 tipusú telemetrikus szeizmikus berendezéssel regisztrált adatokból kapott időszelvény egy részlete

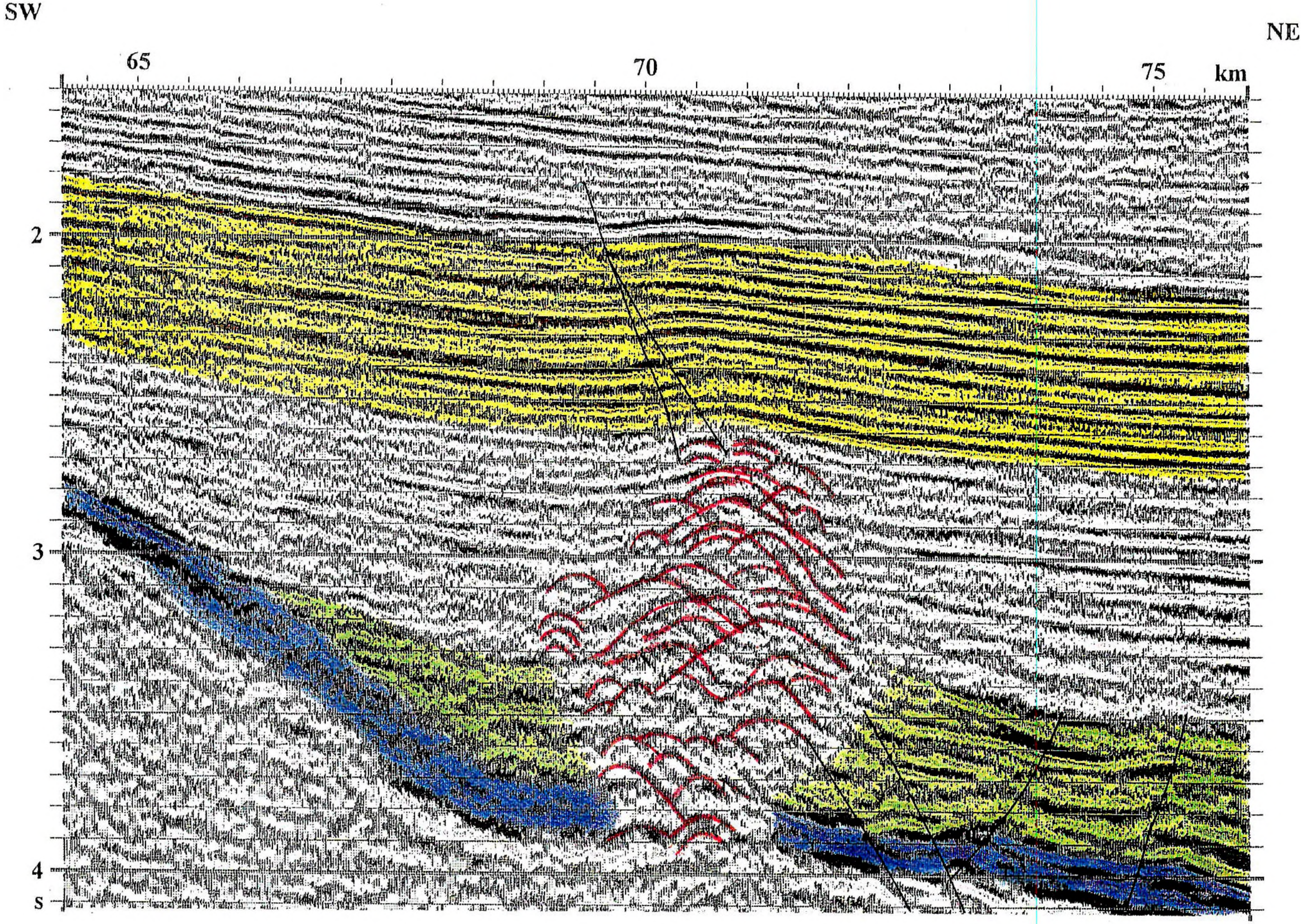

SW
NE
65
70
75
km
2
3
4
s

Fig. 6. Interpretation of the section part in Fig. 5. Delta sediments are indicated in yellow, the series interpreted as Lower Badenian–Lower Miocene in green, layers assumed to be Mesozoic in blue and the magmatic intrusions in red. Above the basic intrusion of assumed Lower Pannonian age a listric fault has formed which is dipping towards the side of the intrusion facing the basin

6. ábra. Az 5. ábrán látható szelvényrészlet értelmezése. A deltaüledékeket sárga, az alsó-bádeni–alsó-miocénnek értelmezett rétegsort zöld, a mezozoósnak feltételezett rétegeket kék és a magmatikus benyomulásokat piros színnel jelöltük. A feltételezett alsó-pannon korú bázikus benyomulás felett lisztrikus vető alakult ki, mely a benyomulás medence felé eső oldala felé lejt

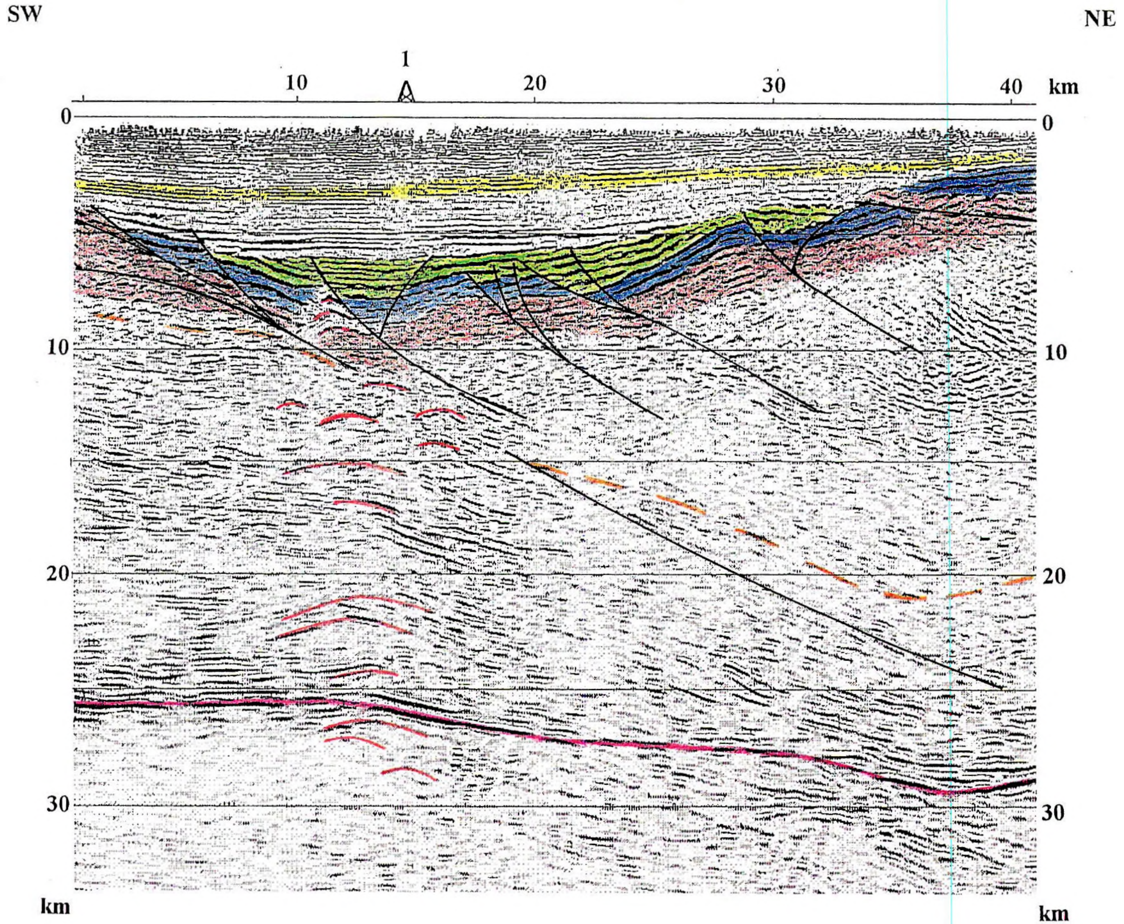

SW
NE
1
10
20
30
40
km
0
10
20
30
km
0
10
20
30
km

Fig. 7. Results shown in Encls. 1 and 3 may suggest an evolution of the Hódmezővásárhely-Makó Graben slightly deviating from that presented in Encls. 2 and 4. Between profile kilometers 29 and 34 a *third graben* may also have formed, containing synrift sediments as well

7. ábra. Az 1. és 3. mellékleten ábrázolt eredmények alapján a Hódmezővásárhely-Makói ároknak — a 2. és 4. mellékleten ábrázoltaktól — kissé eltérő kifejlődése is elképzelhető. Lehetséges, hogy a 29 és 34 szelvénykilométer között egy harmadik árok is kialakult és ebben is találhatók szinrift üledékek és az itt észlelt amplitúdó anomália ezekből származik interpretation these deposits may represent *thick beds of limestone*, or *sandstone with quartz cement*.

In the Hódmezővásárhely–Makó Graben the younger sediments of the synrift complex onlap on older deposits. Such a regression of the series of strata towards the basin, as they turn 'younger', may indicate that the subsidence of the graben must have declined at that time. No such phenomenon was observed in the Békés Basin.

Fractures crossing the synrift sediments in the two basins are different. The Hódmezővásárhely–Makó Graben was bisected during the Lower Miocene. The relief of the ridge separating the *two portions* can be estimated to extend several hundred meters (in the section). In the development of both graben parts the deep fracture zones and the attached smaller faults on their SW side (in the section) may also have played a significant role. At the time of the Lower Badenian the sea may have risen over the ridge thereby initiating a sedimentary basin.

The results shown in Encls. 1 and 3 may suggest evolution of the Hódmezővásárhely–Makó Graben (slightly deviating from that presented in Encls. 2 and 4). Between profile kilometers 29 and 34 a *third graben* may also have formed, containing synrift sediments as well (*Fig. 7*).

In the synrift period, faults dipping towards the basin's interior were formed in the Békés Basin. The fault zone with a throw of many hundred meters that can be detected between profile kilometers 85 and 87 has offset even the Lower Miocene beds. Such a significant throw can be inferred from both the seismic pattern and the changes in the depth of the high-resistivity layer detected by magnetotelluric measurements (Encls. 2 and 4).

5. Amplitude anomalies observed in the pre-Neogene basement

On the deep reflection profile PGT-4 along the Hungarian Geotraverse surveyed with the MDS-18 instrument between profile kilometers 29 and 32 and between 57 and 60 km a nearly horizontal amplitude anomaly protruding laterally was observed. The part of the section shown in *Figs. 8* and *9* was prepared by filtering between 2 and 40 Hz. The amplitude anomaly observed between profile kilometers 57 and 60 was studied in more detail.

When this portion of the data is filtered with a 10 Hz low-cut filter the anomalies are no longer apparent (*Fig. 10*). The anomalously high amplitude levels must therefore receive contributions from frequency components between 2 and 10 Hz. This amplitude behaviour is a clear indication that *exploration of the deeper part of the sedimentary segment requires specially designed low-frequency survey methods.* The anomaly — presumably below the surface of the Mesozoic basement (about 2.1 s) — was observed at a two-way travel time (TWT) of 2.4 s. TAKÁCS [1996] conducted amplitude versus offset (AVO) modelling of this anomaly (Fig. 13) with a number of velocity estimates (*Fig. 11*). True amplitude recovery of the original seismic data was established by utilizing the PROMAX data enhancement software system (Advance Geophysical Corporation Products, USA) and through the implementation of processing steps of offset dependent amplitude recovery, surface-consistent amplitude correction, surface-consistent deconvolution and Q compensation. The modelling was carried out with a program especially designed for this purpose.

The values of the best fit velocity model ranges from 3300 m/s to 5600 m/s (Fig. 11) in the travel time interval of 2–2.6 s. The match between the computed synthetic traces (*st*) and the observed traces (*mt*) is excellent. A reasonably high reflection coefficient (*rc*) value of -0.074 was required to find the best correlation between the two seismic trace sets at 2.39 s TWT.

Preliminary interpretation of the derived low-velocity field (2.39 s - 2.575 s) is that the lowest velocity zone (4400 m/s) represents calcareous rocks with gas saturated secondary porosity. The increase to 4800 m/s and the location of the reflection coefficient +0.044 are indicative of the gas–fluid contact. The point at +0.077 reflection coefficient marks the ending of fracture porosity. The equivalent seismic section and amplitude anomalies are shown in *Fig. 12*, where red represents the zone of predicted gas saturation, blue is indicative of the fluid-bearing zone.

Maintaining the modelling generated *P*-wave velocities constant, the matching of the observed amplitude variations with their theoretical equivalent required [TAKÁCS 1996]: for the upper layer (4400 m/s) a Poisson's ratio of 0.115 and for the zone beneath it 0.333 (*Fig. 13*). According to HARVEY [1993] and OSTRANDER [1984], the distinctly low value is a further indication of gas saturated rock whereas the higher ratio represents fluid saturation.

A comparable anomaly, associated with oil-water contact [ALBU and PÁPA 1992], was detected at the northern margin of the Békés Basin in a fractured metamorphic basement reservoir.

Below a depth of 1800 m most reservoirs are overpressured in the Békés Basin. SPENCER et al. [1994] postulate that the carbon dioxide orginating from the metamorphosis of the calcareous rocks in the deeper part of the

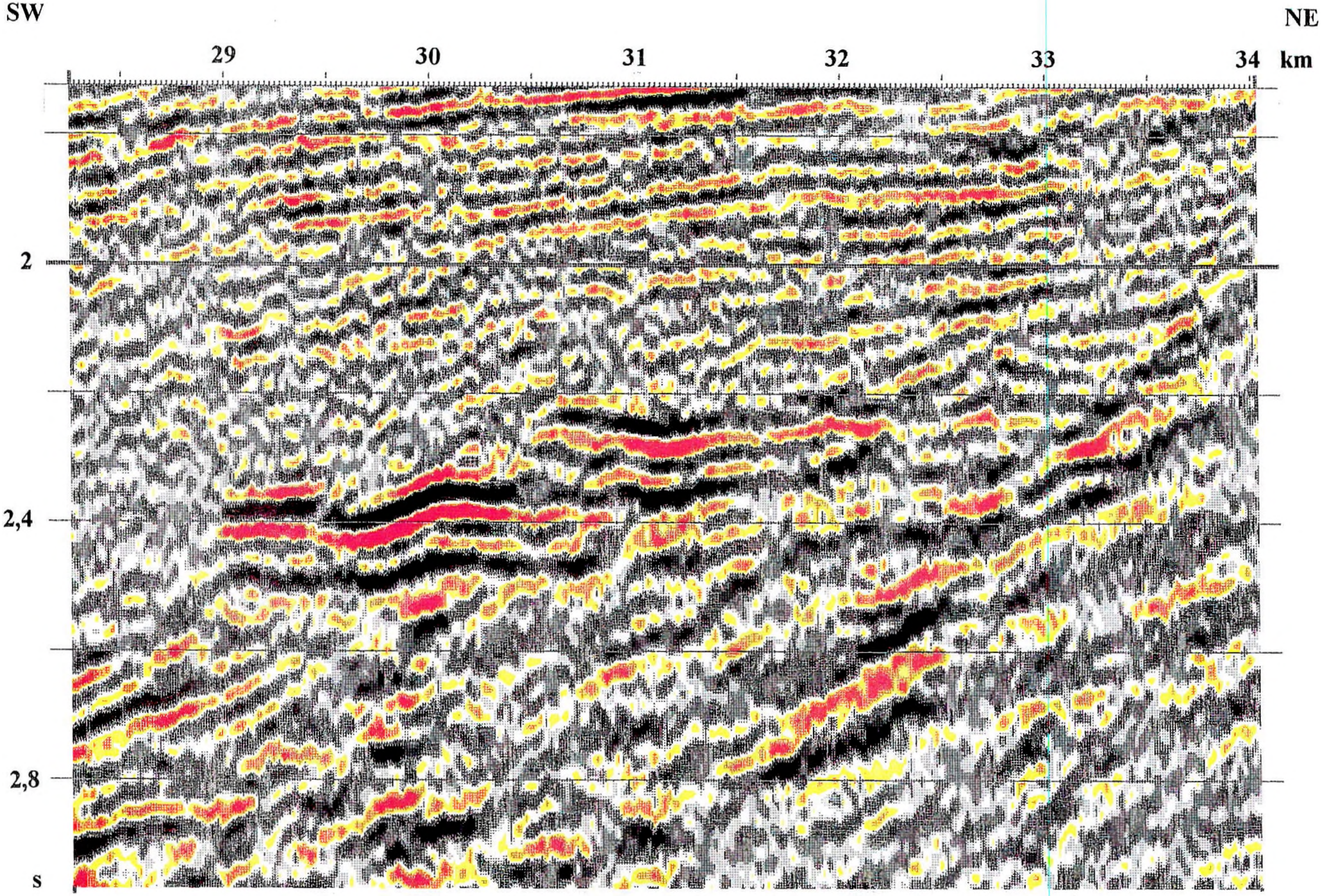

SW
NE
29
30
31
32
33
34
km
2
2,4
2,8
s

Fig. 8. Amplitude anomaly observed between profile kilometers 29 and 32 of the deep reflection line PGT-4 by low-frequency recording. For the detail of the section given here 2–40 Hz band-pass filtering was used

8. ábra. A PGT-4 mélyreflexiós vonal 29–32 szelvénykilométere között, kis-frekvenciás metodikával észlelt amplitúdó anomália. A szelvényrészlet 2–40 Hz közötti szűréssel készült

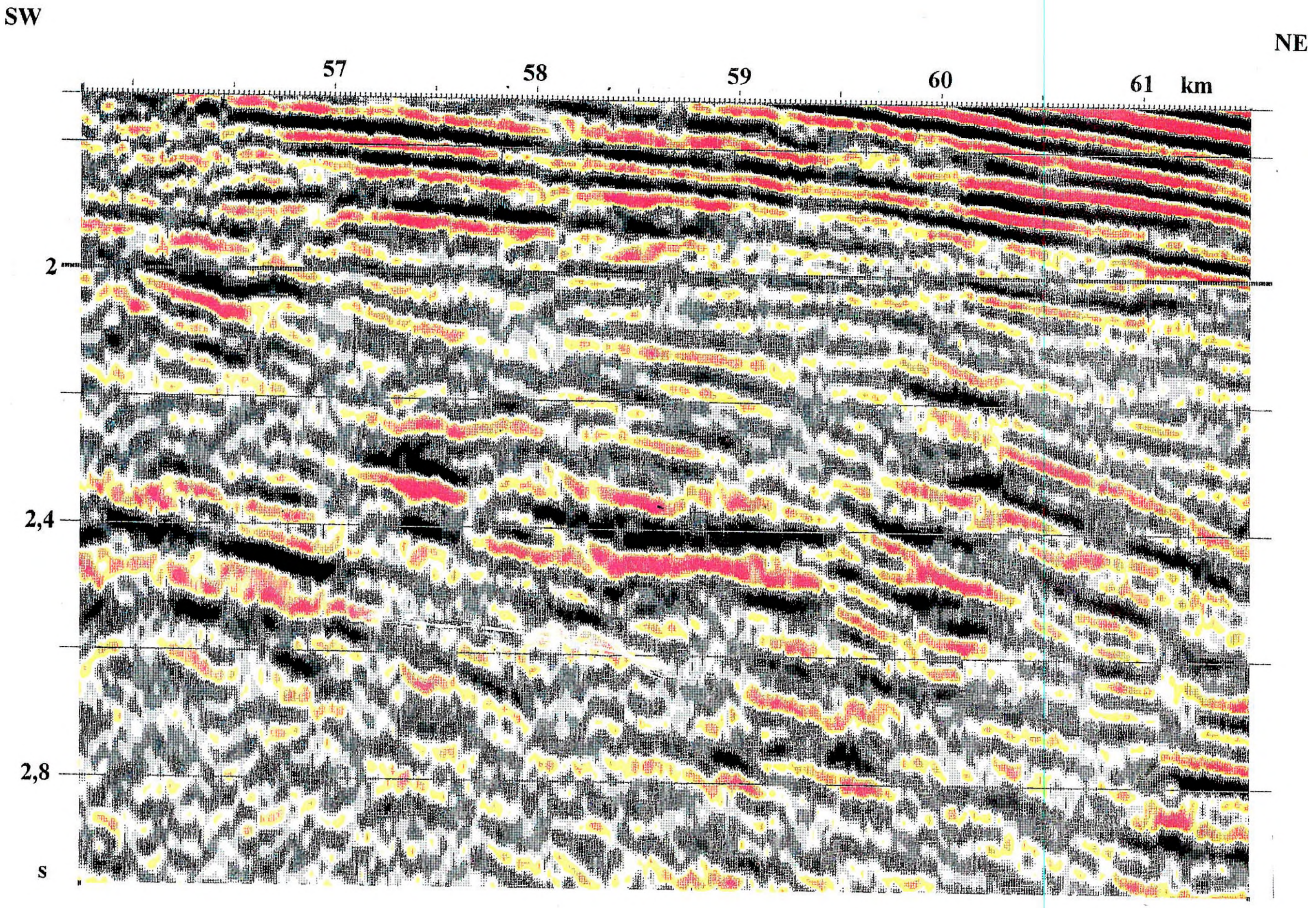

SW
NE
57
58
59
60
61
km
2
2,4
2,8
s

Fig. 9. Amplitude anomaly observed between profile kilometers 57 and 60 of the deep reflection line PGT-4 — from the depth of the basement of assumed Mesozoic age — using low-frequency recording. For the detail of the section given here 2–40 Hz band-pass filtering was used

9. ábra. A PGT-4 mélyreflexiós vonal 57–60 szelvénykilométere között, kis-frekvenciás metodikával — a feltételezhetően mezozoós korú medencealjzat mélységéből — észlelt amplitúdó anomália. A szelvényrészlet 2-40 Hz közötti szűréssel készült

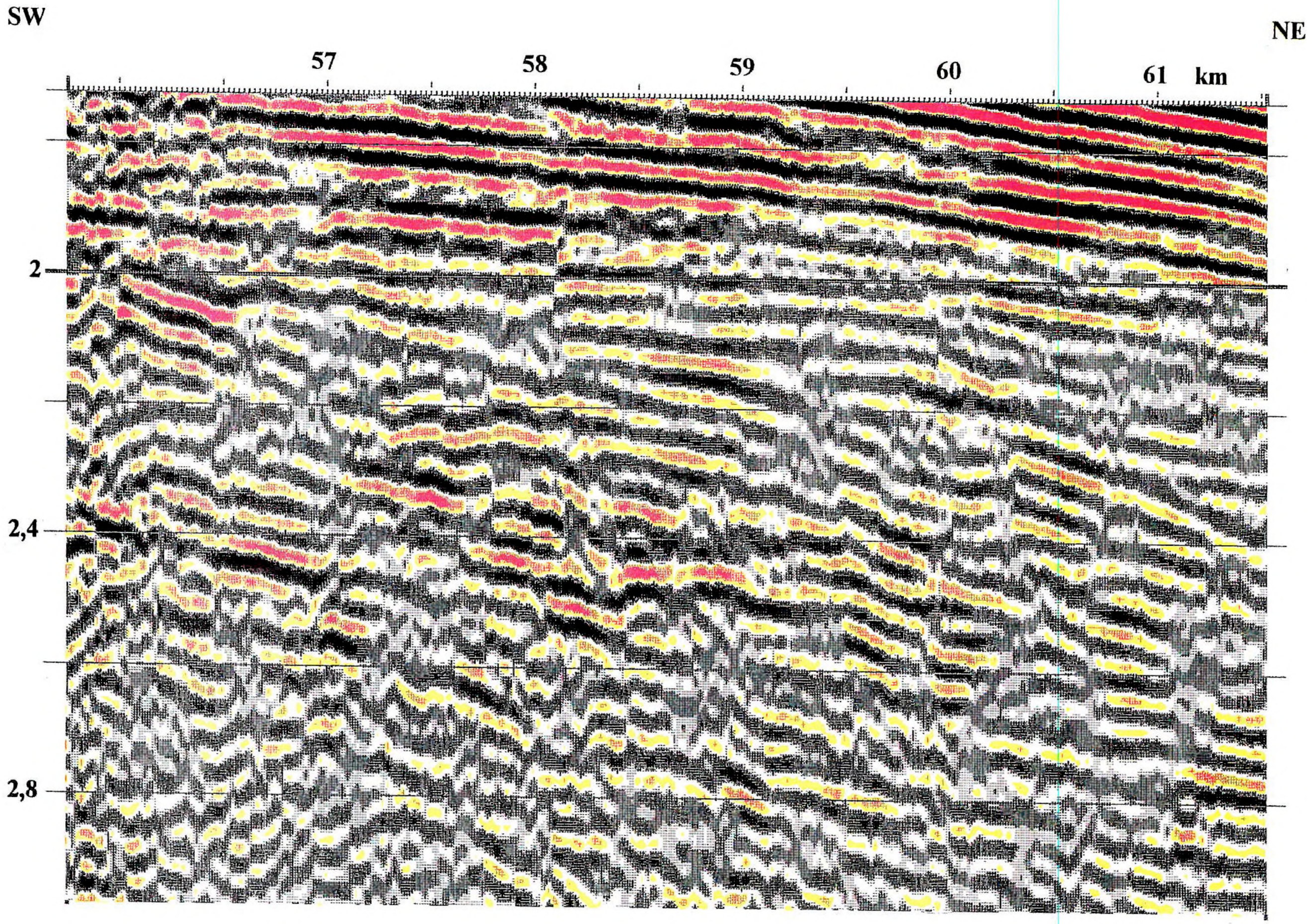

SW
NE
57
58
59
60
61 km
2
2,4
2,8

Fig. 10. Detail of the section shown in Fig. 9 after low-cut filtering at 10 Hz. The amplitude anomaly is absent. The difference of the two figures suggests that exploration of pre-Neogene basement structures requires specially designed low-frequency surveying

10. ábra. A 9. ábrán látható szelvényrészlet 10 Hz-es alulvágás után. Az amplitúdó anomália nem figyelhető meg. A két ábra különbségéből arra következtettünk, hogy a kisfrekvenciás metodika a pre-neogén medencealjzat szerkezeteinek felkutatásában is előnyös

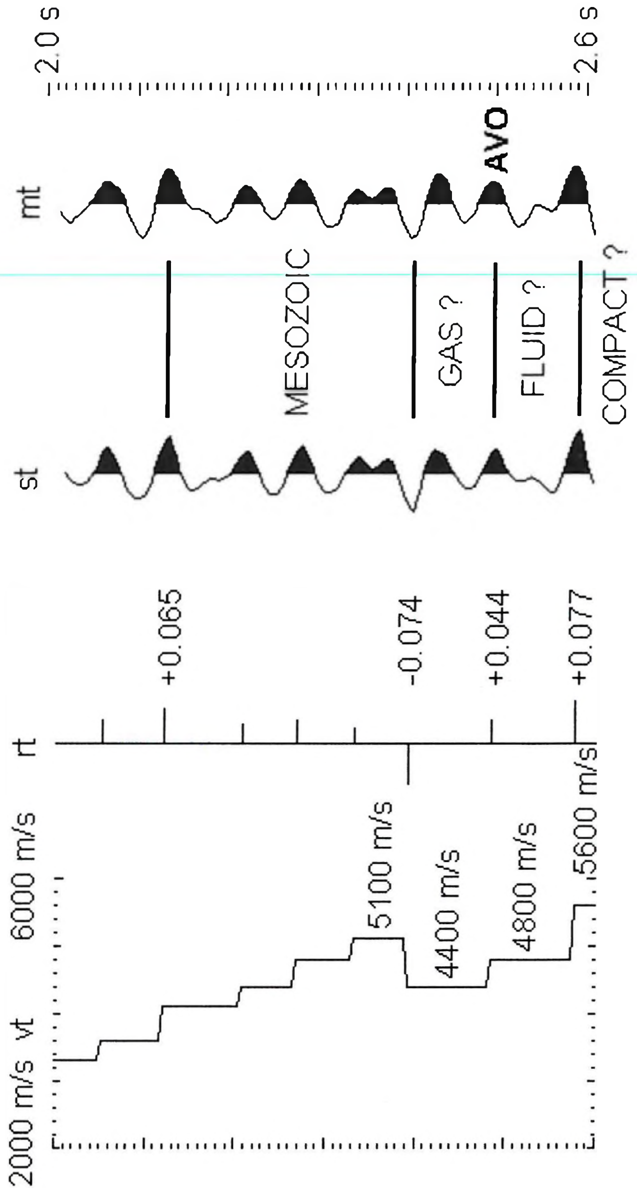


Fig. 11. Result of seismic trace modelling: *vt*—velocity model; *rc*—reflection coefficient; *st*—synthetic trace; *mt*— measured trace [TAKÁCS 1996]

11. ábra. Szeizmikus csatorna modellezés eredménye: *vt*—a sebesség modell; *rc*—a reflexiós tényező; *st*—a szintetikus csatorna; *mt*—a mért csatorna [TAKÁCS 1996] basin may also contribute to the excessive formation pressure. In porous rocks the velocity of seismic waves decreases substantially when the pressure of fluid, filling up the pores, approximates the rock matrix pressure. Such a decrease is even more conspicuous in fractured rocks [CHRISTENSEN 1989]. For identical pressure conditions and identical pore volume the higher the aspect ratio of pores, the more significant is the decrease in velocity. On this basis the relatively low velocities and the velocity inversion, in segments of the PGT-4 profile, may be ascribed not only to formation saturation, but also to the substantial pressure.

The amplitude anomaly (on PGT-4 between 57 and 60 km) is located on the east flank of the elevated Pusztaföldvár–Battonya Ridge at a depth of 2.5–3 km. In the neighbouring Békés Basin the thickness of Neogene sediments is about 8 km (Fig. 4). It is probable therefore that hydrocarbon migrated from the high pressure beds within the Békés Basin into the reservoir space — due to fractures and faults — formed on the upper segment of the pre-Neogene basement (Fig. 4). Thus, the anomalous reflection amplitude of the seismic section may have been caused by *carbon dioxide and water*, or *hydrocarbon gas and hydrocarbon fluid*, or any other combinations of them.

To support the interpretation of the above analysis, the amplitude anomaly of the PGT-1 (Fig. 1) survey is also commented on. Acoustic logs and areal magnetotelluric surveys were available for the modelling of these seismic data. The amplitude anomaly (*Fig. 14*) with 6–10 dB above the background was observed at a depth of 5–5.5 km (*Fig. 15*). To determine the character and regional extent of the anomaly the deep reflection cross-line — PGT-2 — was also surveyed (*Fig. 16*). Subsequently, seismic modelling was conducted by TAKÁCS [1996], and magnetotelluric soundings by VARGA [1992].

Direct sonic and density data were utilized from borehole W-2 (Fig. 14). Additional sonic and density information for deep wells W-1 and W-3 were assembled from an assortment of comparable data from boreholes in nearby localities. Synthetic seismic traces produced from these data were compared to corresponding traces of the profile S-1 (Fig. 14) [SZEIDOVITZ 1990]. Composite subsurface sections (*Fig. 17*) were prepared by applying interval velocities calculated from VSP data of borehole W-4 (Fig. 14). By refining the parameters of the above initial model, an amplitude anomaly was generated which was directly comparable to the observed traces of profile PGT-1.

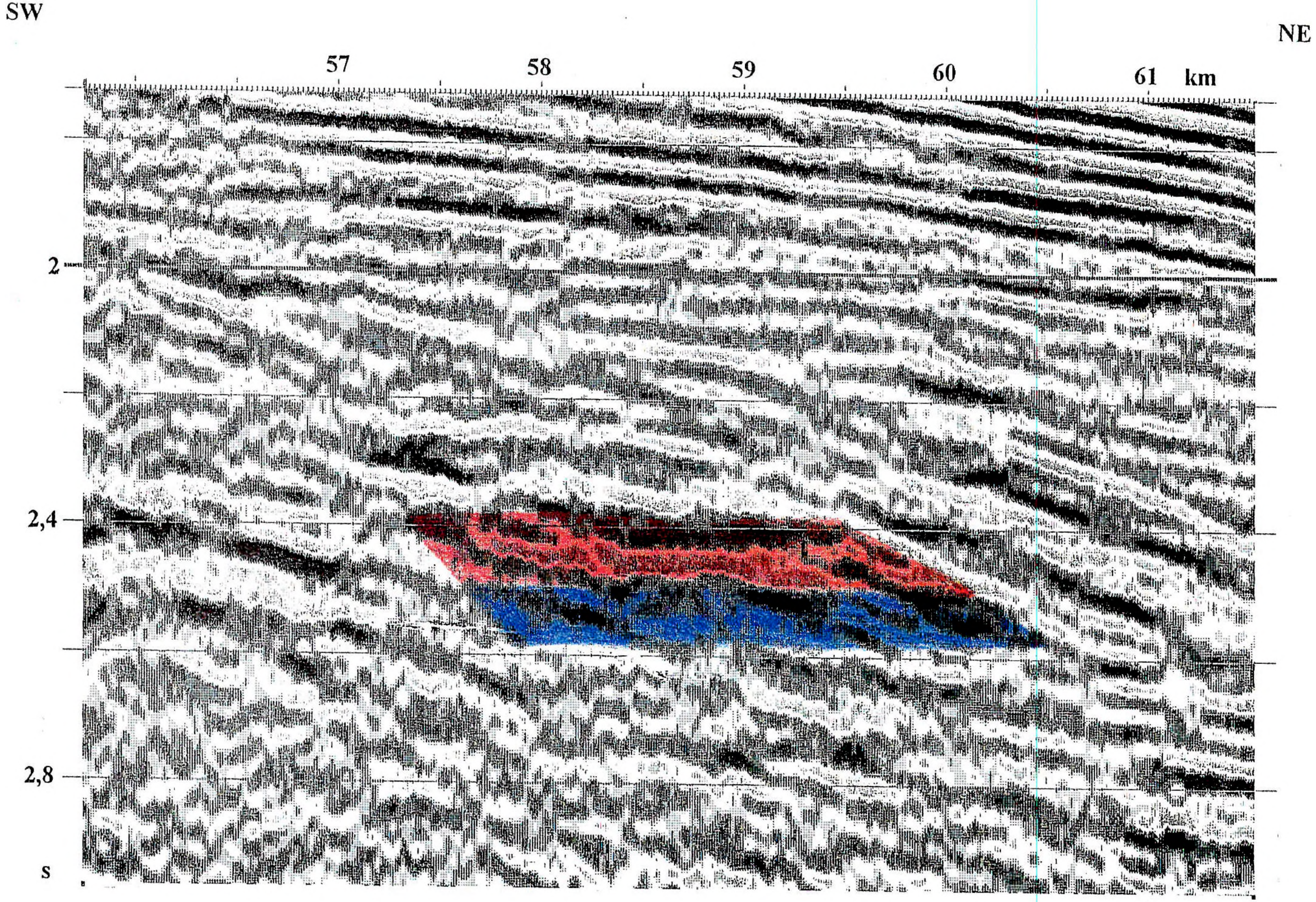

SW
NE
57
58
59
60
61
km
2
2,4
2,8
s

Fig. 12. Interpretation of the amplitude anomaly observed between profile kilometers 57 and 60 of the line PGT-4 on the basis of model investigations. Red is used to indicate the zone assumed to contain gas, blue to indicate the fluid containing zone

12. ábra. A PGT-4 vonal 57–60 szelvénykilométere között észlelt amplitúdó anomália értelmezése a modellezési vizsgálatok alapján. Piros színnel a feltételezésünk szerint gáztartalmú, kékkel a folyadéktartalmú zónát jelöltük

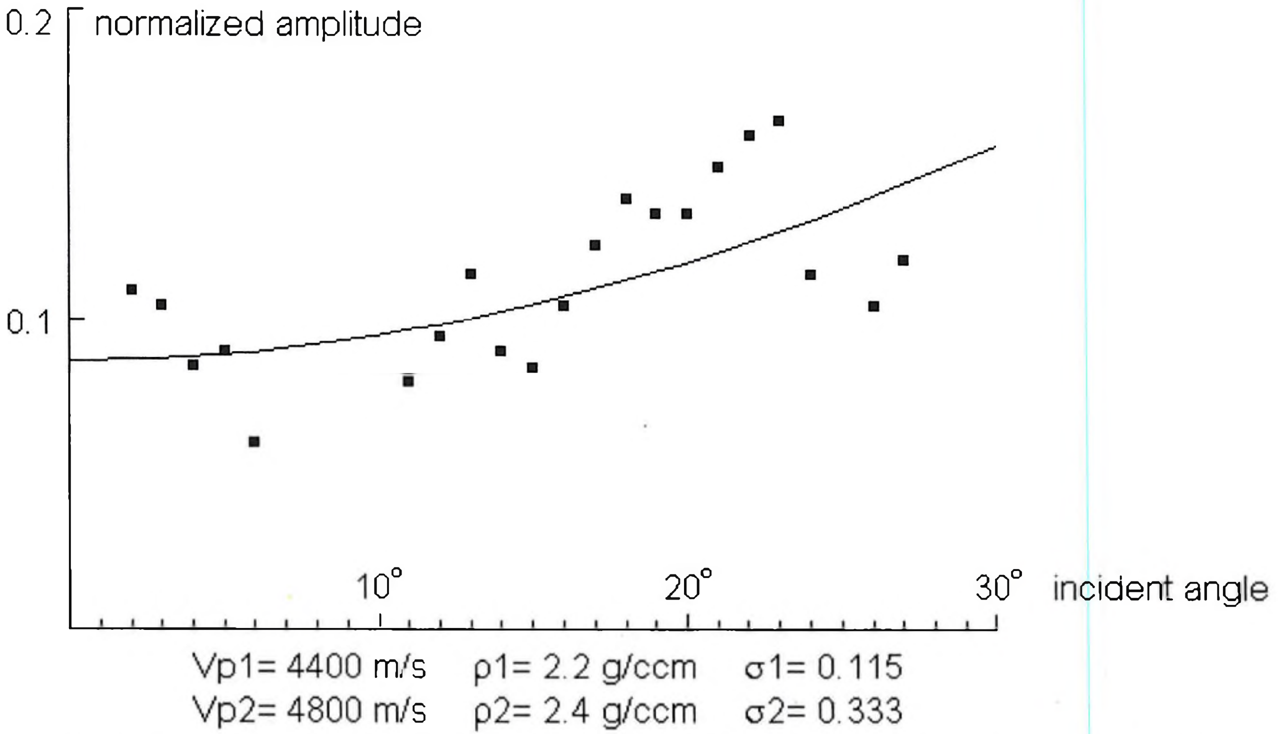


Fig. 13. Result of the AVO analysis of the amplitude anomaly [Takács 1996]. The Poisson ratio for the upper layer (σ_1) is anomalously low (0.115), which may correspond to rock with gas saturated pore volume. The Poisson ratio for the lower layer (σ_2=0.333, in extremity) may indicate a porous zone saturated with fluid

13. ábra. Az amplitudó anomália AVO analízisének eredménye [Takács 1996]. A felső réteg Poisson aránya (σ_1) anomálisan kicsire (0,115) adódott, ami megfelelhet a gázzal telített pórustérfogatú kőzetnek. Az alsó rétegre kapott Poisson arány (σ_2=0,333, határesetben) jelezhet folyadékkal telített porózus zónát

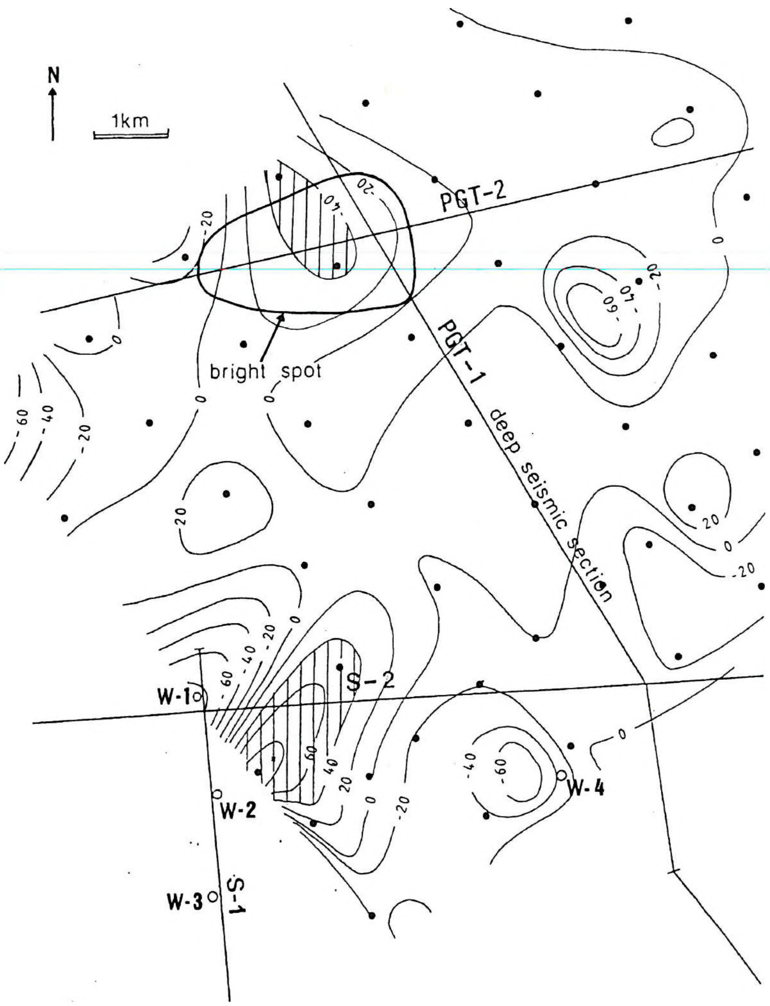


Fig. 14. Sketch of the amplitude anomaly observed on the seismic deep reflection profiles PGT-1 and PGT-2 and contour map of estimated probability of oil and gas occurrence, plotted by applying multi-variable statistical analysis of magnetotelluric data [NAGY 1992)] The seismic amplitude anomaly shows fairly good agreement with a probability maximum. *PGT*—is used to mark the deep reflection profiles; *S*—seismic profiles of hydrocarbon exploration; •—magnetotelluric measuring points; *W*—deep wells

14. ábra. A PGT-1 és PGT-2 szeizmikus, mélyreflexiós szelvényeken észlelt amplitúdó anomália vázlata és a szénhidrogén előfordulás becsült valószínűségének — a magnetotellurikus adatok sokváltozós statisztikai analízise alapján szerkesztett — szintvonalas térképe. A szeizmikus amplitúdó anomália elég jó egyezést mutat egy valószínűség maximummal. *PGT*— mélyreflexiós szelvények; *S*—szénhidrogénkutató szeizmikus szelvények; •—magnetotellurikus mérési helyek; *W*—mélyfúrások

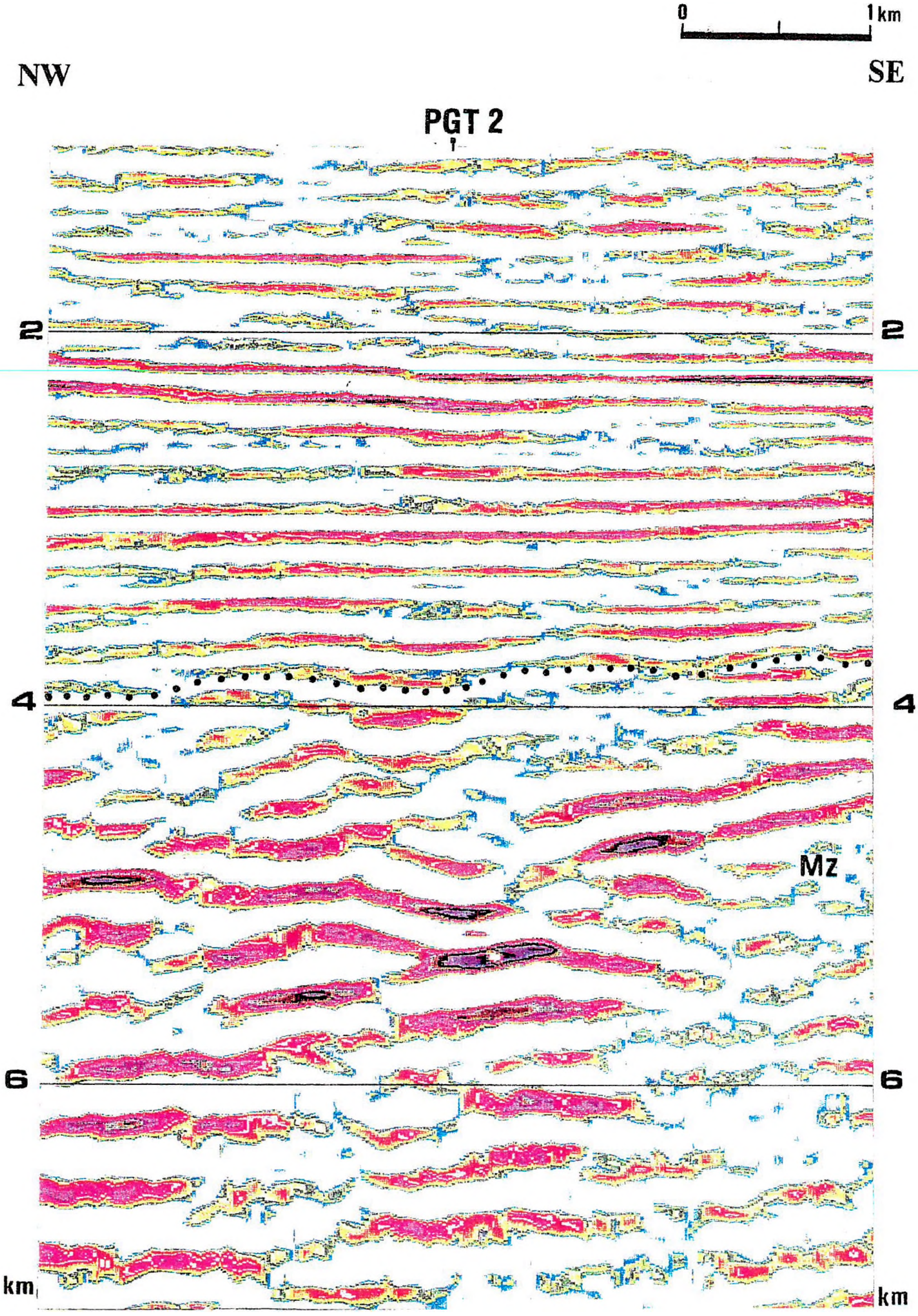

0
1 km
NW
SE
PGT 2
2
2
4
4
Mz
6
6
km
km

Fig. 15. Detail of the migrated depth section of geotraverse PGT-1 for lithosphere investigation. An amplitude anomaly with 6–10 dB above background was observed at a depth of 5–5.5 km. Dotted line indicates the surface of the basement, presumably of Mesozoic age

15. ábra. A PGT-1 litoszférakutató geotraverz migrált mélységszelvényének részlete. 5–5,5 km mélységben, a környezetéből 6–10 dB kiugró amplitudó anomáliát észleltünk. Pontozással a mezozoósnak értelmezett medencealjzat felszínét jelöltük

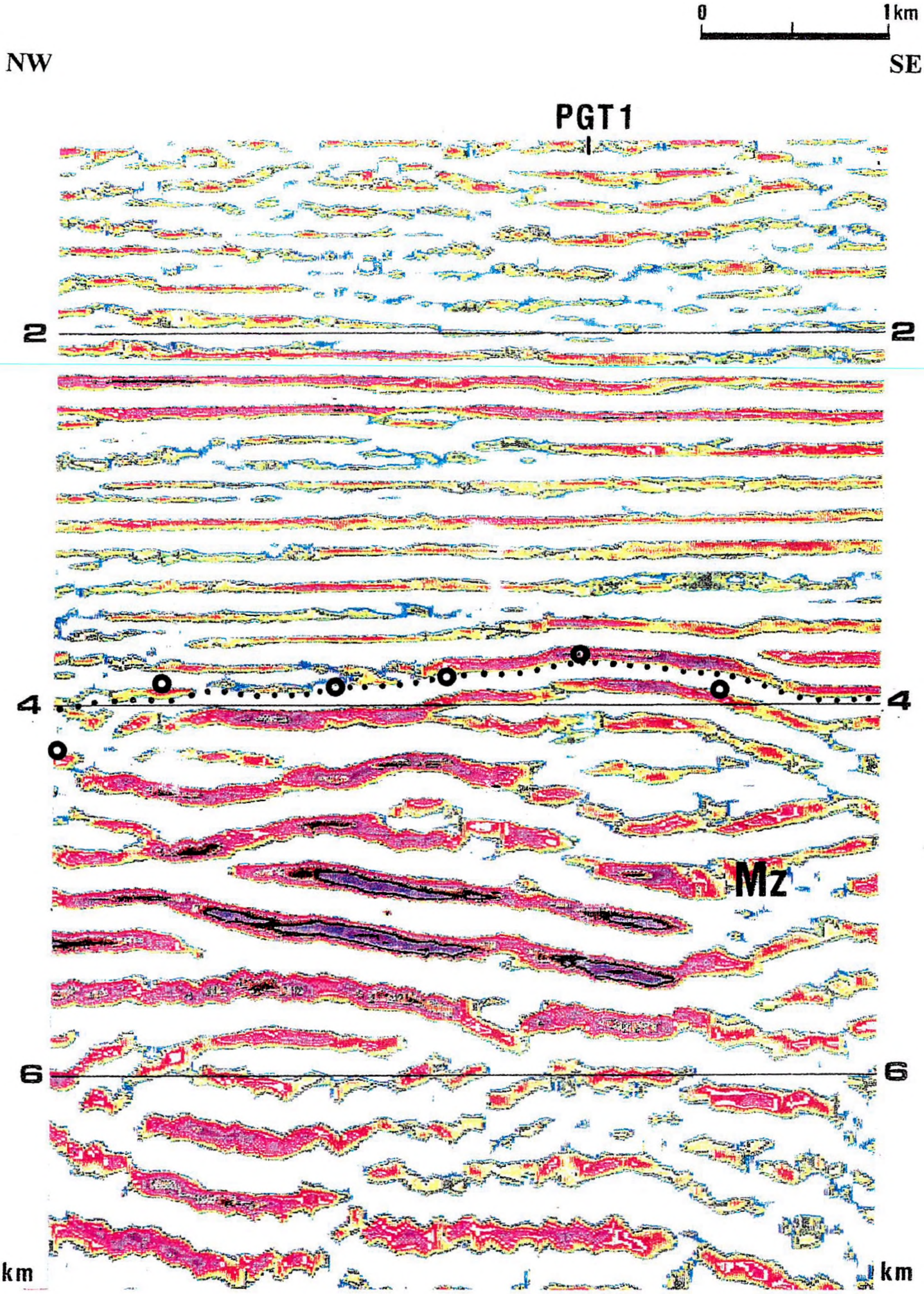

0
1km
NW
SE
PGT1
2
2
4
4
Mz
6
6
km
km

Fig. 16. Detail of the migrated depth section of geotraverse PGT-2 for lithosphere investigation. Dotted line indicates the surface of the basement, presumably of Mesozoic age, bigger points the surface of the high resistivity (100–200 Ωm) basement, determined by magnetotelluric measurements [VARGA 1992]

16. ábra. A PGT-2 jelű mélyreflexiós geotraverz migrációval készitett mélységszelvényének részlete. Sűrű pontozással a mezozoósnak értelmezett medencealjzat felszínét, nagyobb pontokkal a nagyellenállású (100–200 Ωm) aljzat — magnetotellurikus mérésekkel meghatározott [VARGA 1992] — felszínét jelöltük

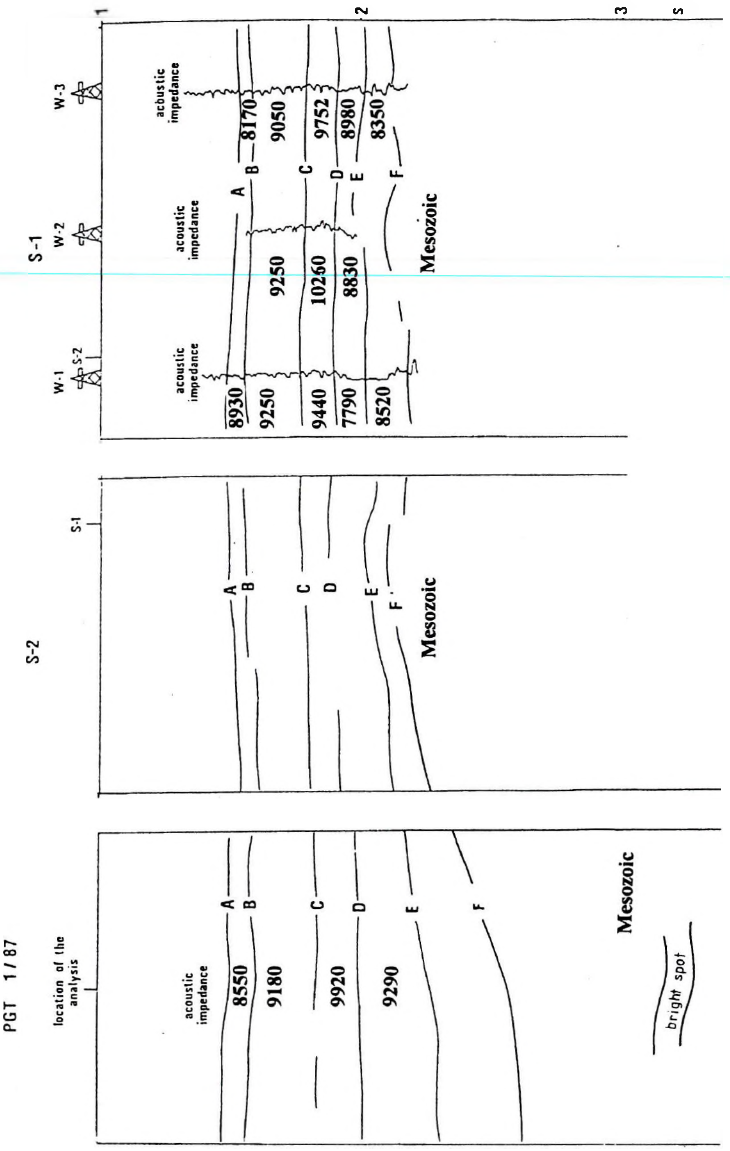


Fig. 17. Composite sections determined with the help of geophysical well logging in oil and gas exploration wells, seismic data, and the deep reflection geotraverse PGT-1 [Takács 1996]. Here the marker horizons and the acoustic impedance values taken on between them, as well as the acoustic impedance logs at the locations of deep drilling are indicated

17. ábra. Szénhidrogénkutató mélyfúrásgeofizikai és szeizmikus adatok, továbbá a PGT-1 mélyreflexiós geotraverz alapján meghatározott kompozit szelvények [Takács 1996]. Ezeken a markerszintek és a közöttük felvett akusztikus impedanciaértékek, továbbá a mélyfúrások helyén az akusztikus impedancia szelvények is feltüntetésre kerültek

The final acoustic impedance values, the reflection coefficient series, the synthetic and observed traces are shown in *Fig. 18*. Marker *E* is interpreted as a Middle Miocene complex, *F* as the pre-Neogene basement contact. In the upper several hundred milli-seconds depth interval of this pre-Neogene basement, presumably of Mesozoic age, there are no significant variations in impedance or reflection coefficients. These synthetic values were derived to match the observed weak arrivals, seen between 4 km depth and the amplitude anomaly at the intersection of profiles PGT-1 and PGT-2 (Figs. 15 and 16). There is an abrupt change in the reflection wave form at this depth. The higher frequency and subparallel Neogene reflections are replaced by low-frequency wave forms.

The equivalent model to the amplitude anomaly at the intersection of the two seismic profiles is given in *Fig. 19*. This theoretical response suggests two fluid layers under the gas-saturated zone. The low reflection coefficient (0.043) is attributed to the karstic characteristics of the presumed Mesozoic limestone and dolomite caprock. At the gas–fluid contact the reflection coefficient is significant (0.098). The reflection coefficient at the contact of the two fluids is also significant (0.074). The gradual decrease in porosity with increasing depth is associated with the reflection coefficient of 0.033.

Along PGT-2, magnetotelluric (MT) measurements [VARGA 1992] indicated a highly resistive pre-Tertiary basement at about 4 km depth below the low-resistive (2–6 Ωm) Neogene strata (circles in Fig. 16). This above depth is coincident with the sudden change in character of the seismic reflection images. Within the pre-Tertiary basement no highly conductive zone was detected.

The results of the areal magnetotelluric surveys have also been interpreted with the aim of evaluating the amplitude anomalies from the aspect of oil and gas prospecting. The principle of evaluation is the recognition that vertical migration of oil and gas fluids causes characteristic changes in the geoelectric parameters of the rocks around the periphery of oil and gas deposits [HUGHES et al. 1985, KARUS et al. 1985]. Thus the detection and recognition of the geoelectric parameters by magnetotelluric surveys is suitable for tracing oil and gas deposits [NAGY 1992]. The problem to be solved is to distinguish significant characteristics for oil and gas deposits in measured electromagnetic (EM) data. The WEGA-D system established by DZWINEL [1983] provides the solution of the problem in the case of a particular EM dipole source field generation. During the 1980's the capabilities of this system were tested in the Carpathian Basin, too [DZWINEL and

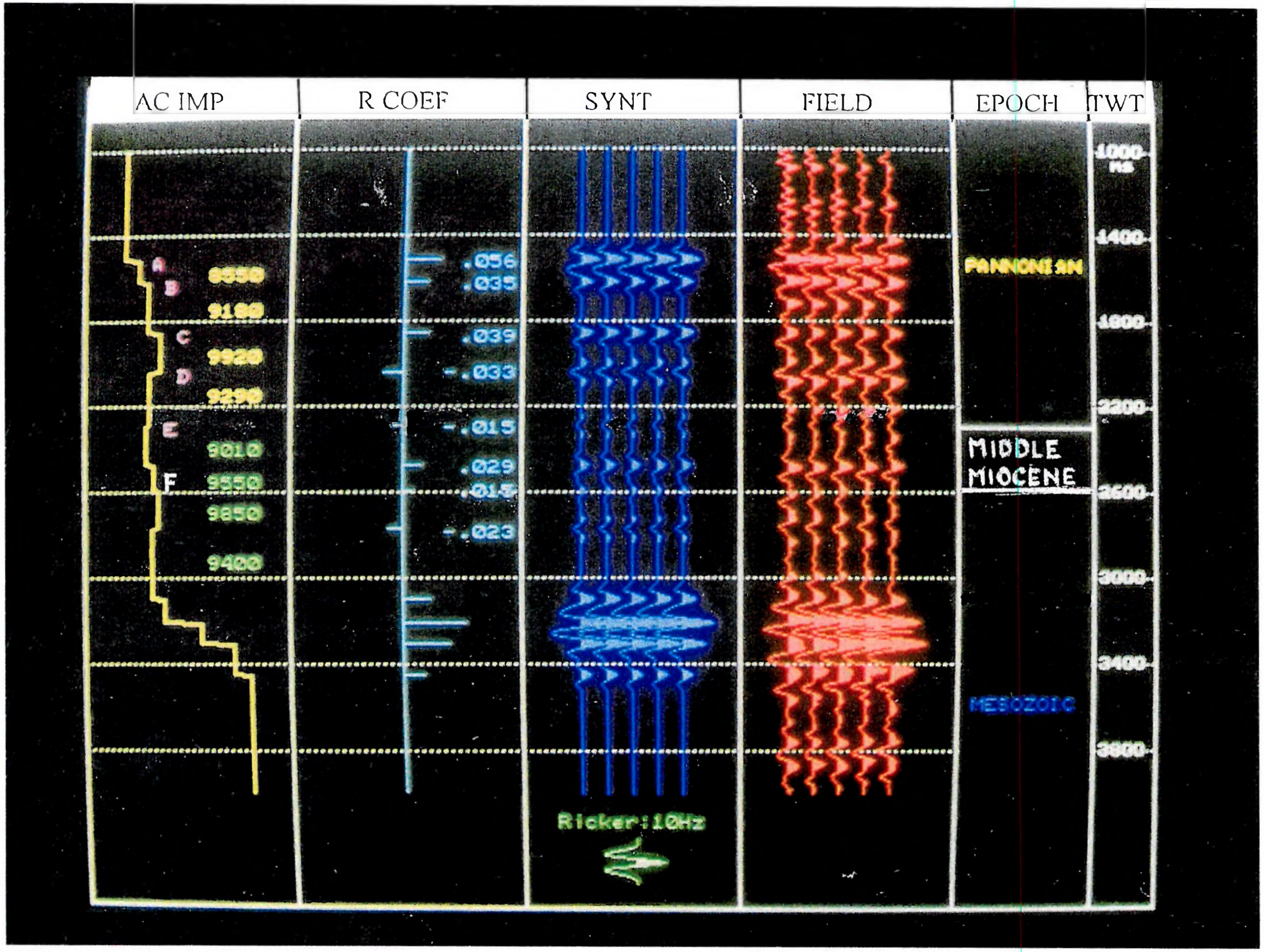
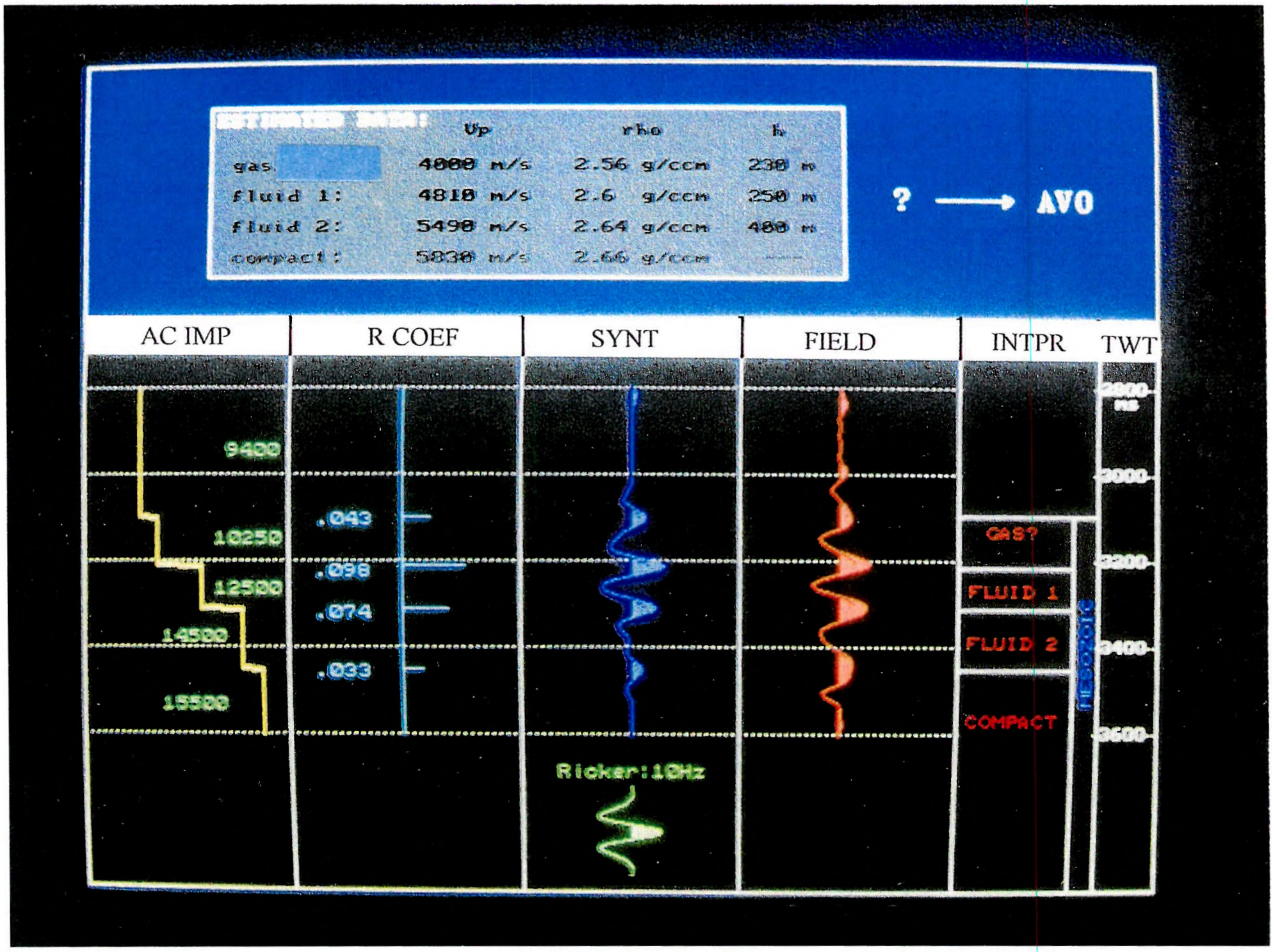

AC IMP
R COEF
SYNT
FIELD
EPOCH
TWT
A
B
C
D
E
F
9550
9190
9920
9290
9010
9550
9850
9400
.056
.035
.039
-.033
-.015
.029
.015
-.023
Ricker:10Hz
PANNONIAN
MIDDLE
MIOCENE
MESOZOIC
1000
ms
1400
1800
2200
2600
3000
3400
3800

Fig. 18. Acoustic impedance model of the amplitude anomaly, its series of reflection coefficients, a synthetic trace calculated for the model and the field seismic trace

18. ábra. Az amplitúdó anomália akusztikus impedanciamodellje, reflexiós tényező sorozata, a modellre számított szintetikus csatorna és a terepi szeizmikus csatorna



[illegible]	Vp	rho	h
gas	4000 m/s	2.56 g/ccm	230 m
fluid 1:	4810 m/s	2.6 g/ccm	250 m
fluid 2:	5490 m/s	2.64 g/ccm	400 m
compact:	5830 m/s	2.66 g/ccm	-----

Fig. 19. Impedance model, values of reflection coefficients, detail of the synthetic and the field trace, and a possible interpretation at the depth of the amplitude anomaly. Significant reflection coefficient can be assumed at the gas-fluid and at the fluid-fluid boundary [Takács 1996]

19. ábra. Az amplitúdó anomália mélységében látható az impedanciamodell, a reflexiós tényező értékek, a szintetikus és az észlelt csatorna részlete, továbbá egy értelmezési lehetőség. Jelentős reflexiós tényező a gáz-folyadék és a folyadék-folyadék határon tételezhető fel [Takács 1996]

NAGY 1985]. In EM measurements, impedance and phase data determined at a number of frequencies from EM field vectors running in various directions form a characteristic multi-dimensioned vector for each field measurement site. Multi-dimensional vectors are carriers of the information searched for. The data of reference measurements performed on productive and non-productive wells serve as a basis for cluster analysis to be carried out to distinguish significant information characteristic of oil and gas deposits. Pattern recognition on the basis of cluster separation considers the multi-dimensional vectors belonging to the weight centre of clusters as such information that characterizes the occurrence or lack of oil and gas deposits. Weight centres of separated clusters determine the probability values of $p=+100\%$ and -100% for occurrence, respectively. On the basis of deviations of the multi-dimensional information vectors characteristic of the field sites of the survey from the vectors characteristic of the weight centres (point of gravity) of the clusters, probability values — diagnostic for the occurrence of hydrocarbons — are estimated in per cent.

Similar multivariable statistical analysis is applicable for the data of magnetotelluric surveys, too. Fig. 14 shows the locations of MT field sites (black dots) in the vicinity of the seismic amplitude anomaly and the contour map of estimated probability of hydrocarbon occurrence — plotted on the basis of the statistical analysis of MT data with multiple variables. Borehole W2 intersected a gas-producing bed of Miocene age at a depth of about 2600 m. On the map a probability anomaly of +70% is found near the well site, while close to the non-productive wells the probability reduces to negative values. The seismic amplitude anomaly reveals a probability maximum of +40% in fairly good agreement with the MT probability anomaly, thus the combined synthesis of the two geophysical data sets supports the interpretive inference of *oil and gas occurrence within the pre-Tertiary basement.*

The amplitude anomaly observed within PGT-4 (region of profile kilometer 60, see Encls. 2 and 4) may originate from — similarly to conditions resolved at the intersection of profiles PGT-1 and PGT-2 — the presence of Mesozoic calcareous rocks. At the depth of the amplitude anomaly observed around profile kilometer 30 of PGT-4, Mesozoic calcareous rocks can be assumed, too (Encls. 2 and 4). If a partial graben formed also between profile kilometers 29 and 34 at the formation of the Hódmezővásárhely–Makó Graben with synrift sediments deposited in it, then it can be imagined that the amplitude anomaly observed here has been caused by them (Fig. 7).

Particularly on PGT-4, the marginally explored basement depth and the seismic acoustic parameter environment *are indicative of oil and gas accumulation* in producing areas of the Carpathian Basin.

6. Structure of the consolidated lithosphere

The pre-Neogene basement is delineated by the striking change in the geophysical parameters beneath orderly arranged signatures of the overlying younger clastic deposits. These juvenile strata are seismically associated with comparatively flat seismic horizons, and large signal amplitudes characteristic of young sediments that can be correlated over long distances. With increasing depth the above features are replaced by a character suggestive of predominantly folded and faulted tectonic pattern (Encls. 1 through 4). The average level of amplitudes is also reduced. Electrically, the conductive young sedimentary series are replaced by series whose resistivity is substantial increased. Beyond the sedimentary cover the upper crust is characterized by shorter irregular reflectivity patterns. Passing from the upper towards the lower crust, coherent reflectivity can be traced over longer distances outlining the previous lamellae characteristic of the lower crust.

Over a substantial portion of PGT-4, the bottom of the crust is imaged by prominent reflections of high amplitude traceable for long distances. In the mantle lithosphere (lithospheric part of the mantle) the average signal amplitudes are reduced. Due to the lack of velocity determinations with increasing depth of penetration (along the PGT-4), the bottom of the lithosphere can only be inferred from fragmented reflections and further decrease of their average amplitudes. From magnetotelluric surveys the surface of a deep, highly conductive layer is inferred as the asthenosphere. Magnetotelluric studies in addition indicate a small quantity of melt around the upper levels of the asthenosphere by a significant increase in conductivity (the depth of this interface is marked with crosses on Encls. 2 and 4). The Békés Basin is coupled with the highest conductivity region within the Hungarian segment of the Carpathian Basin. Since the interpretation of the magnetotelluric data assumed 2D-structures, the derived depth values are only estimates [ÁDÁM et al. 1993].

Key-factors in establishing an overall interpretation of the PGT-4 related information (Encls. 1–4) were:

- — the fault zones extending from shallow to considerable crustal depth,
- — the extended crust beneath the Békés Basin,
- — the relatively thick lithosphere beneath the Hódmezővásárhely–Makó Graben
- — the projected thinning of the lithosphere in the NE part of the profile.

At the SW end of the section, from the eastern flank of the Algyő High, zones of reduced amplitude descend to the NE. These zones are defined by numerous, subparallel reflecting surfaces (Encls. 1–4) outlining a number of significant *shear zones* of varying thickness. Along the intersecting PGT-1, the projections of these shear zones also have smaller seismic amplitude and from the 7 km thick fracture zone beneath the Szolnok–Máramaros flysch strike-slip movements can be inferred [POSGAY and SZENTGYÖRGYI 1991, POSGAY 1993]. It is assumed that in the ruptured fragmentary zones the reflecting surfaces are also destroyed/interrupted, hence in such a zone a smaller number of shorter reflecting surfaces are preserved. This may be why only shorter arrivals of lower energy are found in the zones under consideration. From reflections in the shear zone, which reflections run parallel to it, it has been concluded that glide zones generated by tectonic displacements are also reflectors. Several of these shear zones can be traced, with slight local displacements, to the bottom of the lithosphere. These local disruptions may be correlated with local causes (e.g. magmatic intrusions). The extent of the zone perpendicular to the plane of the profile (in rough approximation) may be of tens of kilometers. Displacements along the zone of considerable thickness and width could be influenced only locally by smaller objects, but could not essentially be prevented. Several of these fractured zones can be visually traced on the section, and are marked by continuous lines on Encls. 2 and 4.

At the SW, 0 and 15 km of the profile, curving series of reflections are evident at a depth of 9–11 km (Encls. 1–4). This inferred Dorozsma fractured zone extends beneath the Algyő High and southwestwards to the Dorozsma Graben (Fig. 1). This projected fractured zone may have played a major role in the development of the Dorozsma Graben, thus the tectonic evolution of the Hódmezővásárhely–Makó Graben, the Dorozsma Graben, and the Algyő High can be portrayed by a *single tectonic framework.*

The Dorozsma fault zone, dipping to the NE, joins to a major shear zone which extends from the eastern margin of the Algyő High, to the NE, beneath the Hódmezővásárhely–Makó Graben. This major shear zone is delineated by a complex reflection pattern. It is several km thick and may have played a dominant role in the formation of the graben. This *extraordinary zone of weakness* can be followed laterally to the east of profile kilometer 40 and to a depth of about 24 km, where it is interrupted by a number of arcuate short sets of reflectivity. These localized, vertically arranged reflections are attributed to a magmatic intrusion developed in the lower crust at a point of reduced strength and viscosity [STREHLAU and MEISSNER 1987]. The reduction in strength of the lower crust and the uppermost domain of the mantle is a result of the thermal effects due to an intrusion ascending from a considerable depth [FOUNTAIN 1989]. This process is probably responsible for a number of intrusions of magmatic bodies into the uppermost mantle of the region [POSGAY 1993]. Beyond the intrusive body at 59 and 75 km and depth of 26–27 km, the strong and slightly dipping reflections are (Encls. 1 and 2) interpreted as a depthward continuation of the fracture zone.

From 70 to 80 km and below a depth of 35 km the reflection energy of the seismic section decreases significantly and the dip becomes more gentle. Beyond 80 to 85 km the predominant pattern of reflectivity turns subhorizontal. The high conductivity layer (crosses in Encls. 2 and 4) rises steeply to a depth of about 35 km beyond 70 km. This highly conductive domal body and zone of seismic transparency is interpreted as a major *uplift of the asthenosphere*. Comparable geophysical signatures were recognized along the relevant intersecting portion of PGT-1 [POSGAY et al. 1995]. It appears that the apex of this domal uplift is further to the east beyond the survey line. It is probable that the fracture zone originating at the margin of the Algyő High terminates adjacent to this structure. The synrift phase of the lithospheric extension contributed to the generation of the Hódmezővásárhely–Makó Graben, the metamorphic core complex associated with the Algyő High and a consequent development of the Dorozsma Graben at a later stage of tectonic progression. An extraordinary thinning of the lithosphere around the NE part of the profile led to an anomalously high rise of the asthenosphere. The rapid cooling of this uplifted segment of the asthenosphere led to fracturing and additional subsidence within the Hódmezővásárhely–Makó Graben and the Dorozsma Graben. Most of the seismically recognizable NE dipping faults, which may have played a substantial role in the formation of the grabens, may have formed in the synrift phase of the tectonic development of the region. To make the phenomenon physically more perceptible several additional possible fracture zones have been interpreted on the seismic sections (Encls. 2 and 4).

Under the Békés Basin, at a variety of depths of the lithosphere, a composite set of arcuate reflectivity patterns can be identified consisting of characteristically upward convex reflecting surfaces. These localized patterns of arrivals are thought to be images of sequences of *magmatic intrusions*. Evidently the magmatism was reactivated several times and its latest stages penetrated the lower sedimentary deposits of the basins. As a local phenomenon, towards the NE end of the profile (as far as 60 km) the crust-mantle boundary appears — that from 0 to about 60 km can be characterized by a strikingly robust reflecting surface — only occasionally. It is assumed that the magmatism did not permit the complete formation of a solid boundary. Along PGT-1 the crust-mantle boundary can be identified fairly unambiguously [POSGAY et al. 1995]. Thus the location of the crust-mantle boundary, beneath the basin is marked according to the indication of the PGT-1 cross profile. We infer that beneath the Békés Basin the crust suffered extensive attenuation. Apart from the thick, young sedimentary series, and the significant rise of the crust-mantle boundary, it is difficult to account for the excess of magmatic material in the crust [SCLATER et al. 1980, PINET and COLLETTA 1990].

The profile of deep penetration permits one to draw conclusions also on the complexity of the nappe system formed during the Alpine orogeny. The Mesozoic formations forming the basement of the Pusztaföldvár–Battonya Ridge are identified on the seismic section by characteristic parallel reflections of high amplitudes, indicative of layered strata. The deep well marked with 2 allowed us to infer the lower-Codru nappe thrust over upper-Codru beds [GYÖRFI 1994]. The section leads us to assume that the overthrust plane can be encountered at the bottom of Neogene formations around 36 and 64 km of PGT-4. The seismic pattern reveals partial folding and fracturing of these rocks. The locally highly correlatable units are abruptly disrupted by visually evident displacements. Contacts between blocks of depositionally unrelated rock masses can be realized by abrupt changes of reflectivity characteristics. Any geological identification of these allochtonous nappes is highly contradictory [GYÖRFI 1994, GROW et al. 1994]. A number of crossing profiles or 3-D surveys (with specially designed low-frequency survey methods) are required to image these complex rock units with sufficient distinctness.

7. Schematic model of basin evolution

When the formation of the basin was initiated (about *20-25 Ma ago, Fig. 20a*) the original *crust of 30 km thickness* was perceived to be a consequence of the last great metamorphic event [MEISSNER 1986] of the terrane, the Hercynian-Variscan orogeny [FÜLÖP et al. 1987].

In assuming the lithospheric thickness of the initial model the key points of consideration had to be as follows:

- the thickness of the lithosphere should show an empirical inverse relationship to the superficial density of heat flow [ÁDÁM 1980],
- attention should also be given to the relationship between the heat flow and the tectono-thermal age [ČERMÁK 1979].

Taking into account the above factors, the *thickness of the entire lithosphere* of the initial model was estimated to be *100 km* (this corresponds to about 300 Ma and 50 mW/m^2) of which 70 km was contributed by the lithospheric mantle .

The ratio of the estimated initial thickness of the crust to the crustal thickness of segments of the interpreted seismic profile varies between 1.2 and 2.1. The same (i.e. calculated vs. actual) ratio for the mantle lithosphere is between 1.8 and 5.4. It can be assumed that at the beginning of basin formation the zones of the upper and lower lithosphere were heterogeneous locally [COWARD 1986] and this may also have interfered with the deformation of individual structural entities of the region. It is also probable that the mechanical strength of certain zones underwent modification as a result of variation in temperature, and the development of fracture zones during the course of basin formation. For example retrograde phase changes (amphibolitization, serpentinization of dry rocks) may have led to a local weakening of basic and ultrabasic rocks.

Relating the *mean extension* to the whole profile section, values of *1.5 and 2.5* were obtained for the *crust and the mantle lithosphere,* respectively. Consequently the extension of the mantle lithosphere appears to be areally smaller than that of the crust [COWARD 1986]. A number of symmetrically aligned echelons of basins is known along the direction of the PGT-4 survey (*Fig. 21*). The outer basins developed as half-grabens and their main faults dip towards the Békés Basin. The basin and their ridges of separation, from W to E are as follows: Dorozsma Graben, Algyő High, Hódmezővásárhely–Makó Graben, Pusztaföldvár–Battonya Ridge, Békés Basin, Zarand

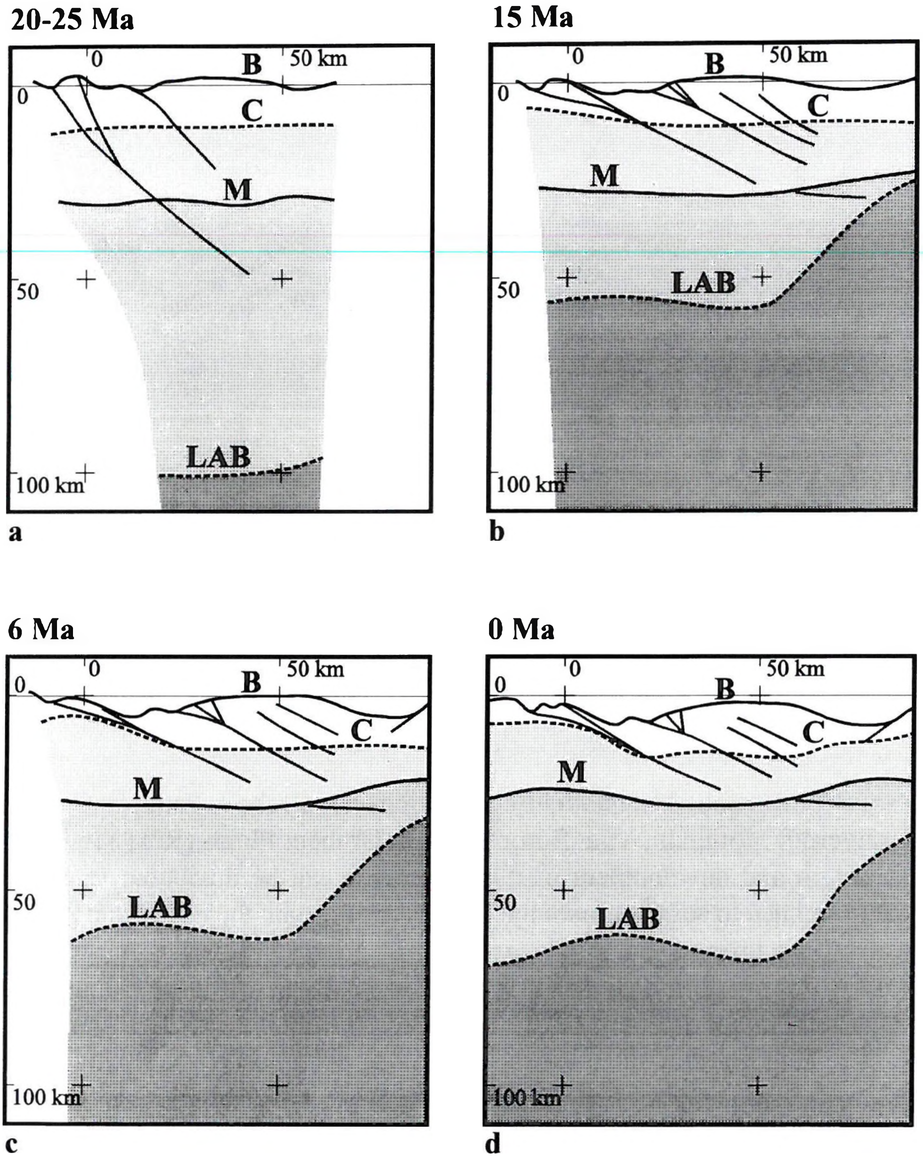


Fig. 20. Basin formation models of the Dorozsma Graben, the Hódmezővásárhely–Makó Graben and the Békén Basin assumed for 20–25, 15, 6 Ma and for the present date

20. ábra. A Dorozsmai árok, a Hódmezővásárhely–Makói árok és a Békési medence 20–25, 15, 6 millió évvel ezelőttre és a mai időpontra feltételezett kifejlődési modellje

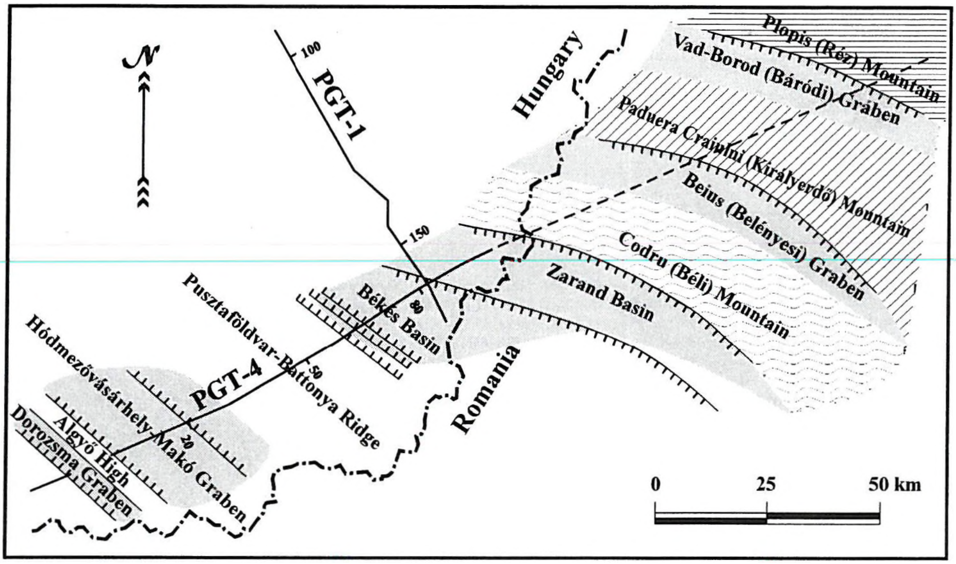


Fig. 21. Sketch of symmetrically aligned echelon of basins along the direction of the PGT-4 survey, modified after GYÖRFI [1994]. The outer basins developed as half-grabens and their main faults dip towards the Békés Basin and the neighbouring Zarand Basin

21. ábra. A PGT-4 szelvény irányában elhelyezkedő medencesor helyszín vázlata módosítva GYÖRFI [1994] után. A külső medencék félárokként fejlődtek ki és fő töréseik a Békési és a szomszédos Zarándi medence felé lejtenek

Basin, Codru (Béli) Mountain, Beius (Belényesi) Graben, Paduera Craiului (Királyerdő) Mountain, Vad–Borod (Báródi) Graben, Plopis (Réz) Mountain. The origin and development of this basin row can be attributed to a fault system, related to attenuation of the lithosphere beneath the Békés and Zarand Basins. This process led to the extension of a crustal portion *about 100 to about 150 km long,* which was identical (by and large) with the extension of a substantially shorter portion of the mantle lithosphere.

The length of the initial model crust along profile PGT-4 study is 60 km and, with its comparable upper mantle depth, is indicated in Fig. 20a. The depths of the fault-zones denoted on the model suggest that at this stage the maximum stress regime reached the maximum load-bearing capacity stress guide zones of the crust and mantle lithosphere [LISTER and DAVIS 1989, CHEN and MOLNÁR 1983]. In estimating the thickness of the stress guide in the mantle lithosphere, an additional eclogitic zone [MORGAN et al. 1994] was also assumed. Compared to theoretical models [WERNICKE 1981 and

1985, COWARD 1986] the assumed dip of the fault zones of the initial model appears to be relatively steeper.

For the model, about *15 Ma ago* (Fig. 20b) a major catastrophic event has been assumed to have taken place during the time interval which elapsed from the time of faulting of the initial model and the stress guides. Beneath the Békés and Zarand Basins the crust and lithospheric mantle were already subjected to fracturing and thinning, and a considerable mass of magma intruded, accompanied by an intensive warming period. The *mantle lithosphere* must have been heavily involved in this event so that its structure and physicochemical properties were changed significantly. As a consequence (beneath the Békés and Zarand Basins almost in its whole thickness) it probably *became similar to the asthenosphere*.

Through reduction of strength in depth the upper crust slipped along the fault zone which separates the Algyő High from the Hódmezővásárhely-Makó Graben. *The extent of separation may have reached about 15 km.* The movement was greater adjacent to the weakened fault zone and led to the formation of a half-graben. Mesozoic beds — as implied by borehole data along the profile and result of a grid of exploration seismic surveys [GROW et al. 1989 and 1994] — may have slipped down from the Algyő high at the same time. Due to the *slip of the upper crust the load on the lower crust was reduced* [WERNICKE 1985] and the Algyő area rose isostatically. Such a rise manifest itself by the metamorphic pre-Neogene basement in the area, by the domal uplift of the lower crust suggested by the seismic section, and by the characteristic gravity and magnetic anomalies of the region [POSGAY 1963, 1967, and KOVÁCSVÖLGYI 1995]. The domal uplift of 7–8 km on the boundary between the upper and lower crust allows us to infer that due to isostatic emergence of the Algyő area a part of the metamorphic basement was subjected to denudation, too.

In the Hódmezővásárhely–Makó Graben and the Békés Basin, 1–2 km thickness of synrift sediments were deposited (Encls. 2 and 4, see also in Figs. 4 and 6). At the beginning of this process the Hódmezővásárhely–Makó Graben may have been a double (or triple) graben. The dividing ridge(s) developed in submarine environment during the continuing extension of the lithosphere.

Structural attitudes of the postrift sediments suggest the early complex evolutionary phase of the graben. A factor which appeared earlier in the studied area and which is believed to be more significant was the faster cooling and contraction of the asthenosphere at a smaller depth beneath the Békés and Zarand Basins. Contraction of the asthenosphere at an anomalous depth (on a regional scale) beneath the Carpathian Basin must have appeared later and to a lower extent. The first effect resulted in the unusually thick accumulation of Neogene sediments in the Hódmezővásárhely–Makó Graben and the Békés Basin. It is understood that *the fractured zones* played a major role in the development of the Hódmezővásárhely–Makó Graben. They *formed a weakened portion of the lithosphere that transmitted the contraction of the asthenosphere beneath the Békés and Zaránd Basins towards the graben even during the thermal phase.* This explains the formation of anomalously thick Tertiary sedimentary deposits in the Hódmezővásárhely–Makó Graben although the asthenosphere there lies at the average depth characteristic of the Carpathian Basin. This view also seems to be supported by the observation that the maximum thickness of sediments is found in the southwestern part of the graben, which allows one to assume the preservation of its origin of formation as a half-graben.

The magmatic activity continued in the postrift phase. Seismic evidence (Encls.2 and 4) dates the last phase of the magmatism as Upper Miocene. The seismic section beneath the Békés Basin suggests that a great amount of magma intruded into the lithosphere from the asthenosphere and accumulated in a shallow depth, contrary to the postulation of constant volume of the lithosphere [PINET and COLLETTA 1990].

The subsidence and inundation of the Algyő Ridge and of the Pusztaföldvár–Battonya Ridge *5–7 million years ago* is attributed to regional contraction of the asthenosphere in the Carpathian Basin (Fig. 20c). The delta fronts reached the region of PGT-4 in this period too [VAKARCS et al. 1994] blanketing the ridges with the bulk of delta sediments. Earlier these ridges were above the water level of the inland lake.

The contraction of the higher portion of the asthenosphere beneath the Békés and Zarand Basins continued to contribute to the relief depression caused by contraction of the asthenosphere on a regional scale. Thus the Hódmezővárásrhely–Makó Graben and the Békés Basin subsided at a faster pace than the ridges which were in an elevated position earlier (Figs. 3, 4 and Fig. 20d). Geodetic surveys reveal that the subsidence of the Hódmezővásárhely–Makó Graben is still an ongoing process in recent times [JOÓ et al. 1991].

8. Application in prospecting for oil and gas

One of the mandates of the lithosphere–asthenosphere research programme is to establish a method that images the subsurface from young sedimentary strata down to the asthenospheric depth. Such a method aims at

- —identifying structures in the young Neogene sedimentary complex and mapping the pre-Neogene basement. (Roll-over structures connected to the listric fault in the Békés Basin. Seismic amplitude anomalies related to Mesozoic structures in the pre-Neogene basement);
- —detecting fractures penetrating deeply into the lithosphere thereby helping the understanding of both tectonic patterns and local structures,
- —inferring an attenuation of the crust and the lithosphere under young basins that furnishes a fundamental clue to theories on the origin of basins,
- —providing information concerning the shape of the asthenospheric updoming and of its magmatic activity which may contribute to the improvement of our understanding of basin subsidence and hydrocarbon maturation models.

The pre-Neogene basement has recently played an important role in hydrocarbon exploration. Results of deep seismic surveys can therefore act as initial guide lines in this process. There is a high probability that the pre-Neogene basement may contain a significant amount of oil and gas. The vertically exaggerated section of PGT-4 (Fig. 4) reveals intriguing sedimentological and genetic features. Units I-II are the main hydrocarbon-generating formations. Geochemical investigations point to the fact that calcareous marl members of unit IV generated young immature/moderately mature oil at a shallow depth (about 2 km). Another oil generation process at greater depth took place when units I-II were at a depth of 3–4 km. During the short distance of migration the immature oil was trapped in the fractured weathered top zone of the uplifted basement or in the basal conglomerate — silty calcareous marl formation, which overlay it.

The mature oil with a longer migration path may have moved in two different ways: it could have migrated in the turbidite unit (III) along faults and became trapped in wedging out sandstones or moved along the pre-Neogene unconformities and accumulated in tectonic traps of the basment slope.

The amplitude of a dim spot anomaly indicates a very probable presence of Mesozoic reservoir at that particular depth.

Prediction of migration of gas is more difficult. Mature gas of high CO_2 content discovered in the basement may originate from different Mesozoic sequences. CO_2 may have been generated in metamorphic carbonates and migrated along overthrusts within the basement. The gas found in the Lower Pannonian (Upper Miocene) sandstones may have migrated in the turbidite unit III from the Hódmezővásárhely–Makó Graben. Alternatively, it may have followed listric faults, from the deeper zone of the basement into unit IV, where it was trapped in sandstone wedges of domal uplift.

9. Summary

Interpretation of the 1992 international deep seismic reflection profiling furnished interesting results from the young sediments to the asthenosphere. This cooperative study supplemented a series of experiments that had been conducted very successfully by the Eötvös Loránd Geophysical Institute of Hungary (ELGI) for the past quarter of this century, aiming to extend the depth penetration of seismic reflection surveys to study the *upper mantle*. The purpose of all of the programmes was to develop field procedures and data processing methods to utilize frequencies several octaves lower than the frequency range traditionally applied by seismic prospecting. An additional aim of the 1992 international survey was the testing of the Canadian equipment (PRS model), originally designed for refraction surveys, for its suitability in seismic reflection mode. This experiment was concluded with success. The exploitable seismic frequency limit was reduced to *1–2 Hz* in a survey which imaged the entire lithosphere.

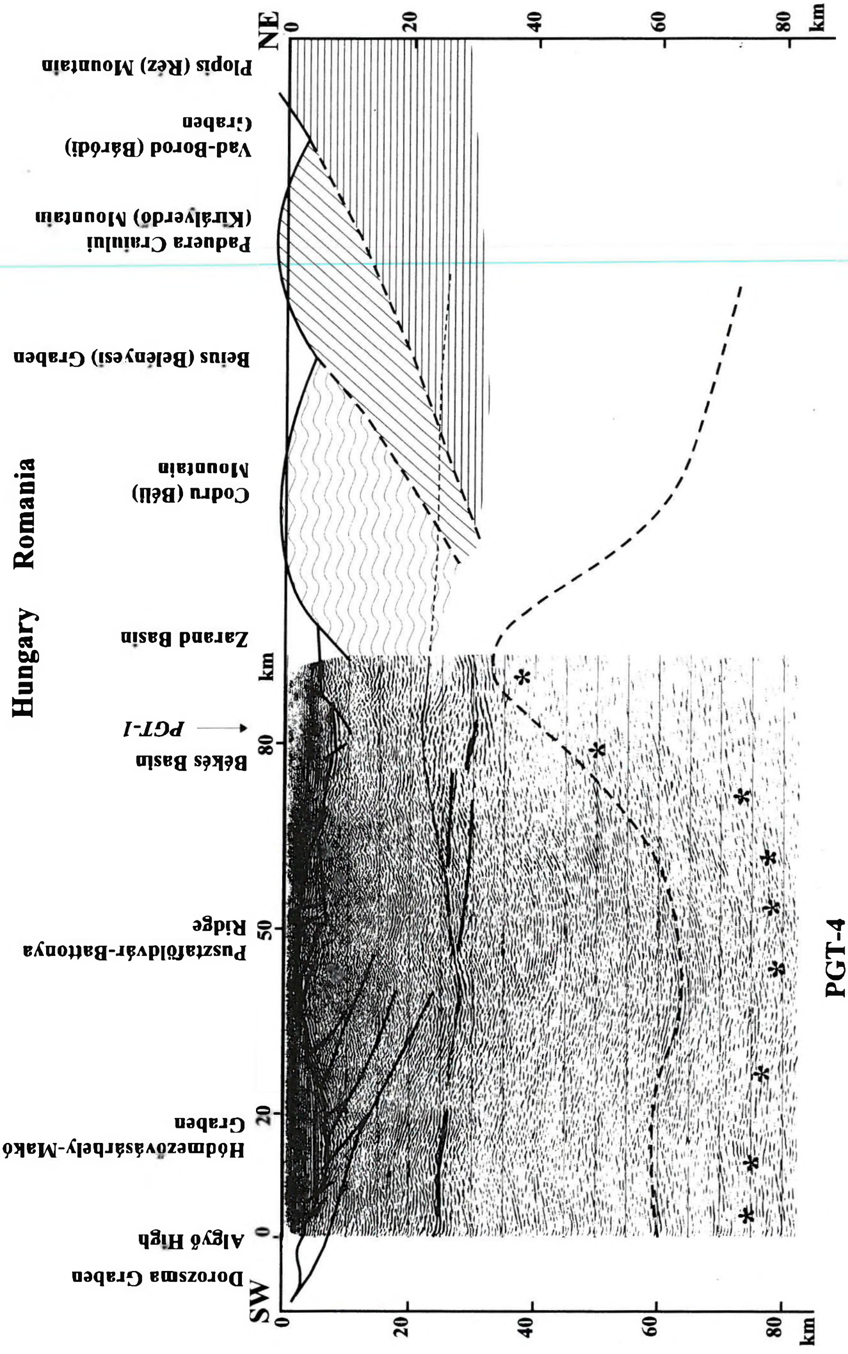
The reflection depth section of the PRS recorded data with ELGI processing is displayed in a part of *Fig. 22*. Prominent features of the section were extrapolated into an interpretive model which outlines the tectonic framework of a series of basins in the region of investigation. Profile PGT-4 is a part of the Hungarian Geotraverse Project. It crosses the Hódmezővásárhely–Makó Graben, the Békés Basin (both of which are filled with thick sequences of Neogene sediments), and the Pusztaföldvár–Battonya pre-Neogene domal uplift. On the seismic depth section the depth of the asthenosphere determined by magnetotelluric survey is marked with crosses.

It is evident that due to extensive horizontal stresses that arose in the synrift phase stage, the load-bearing stress guide zones of the lithosphere were ruptured. A great amount of magma intruded into the lithosphere and transformed the lithospheric mantle to such an extent that its physicochemical properties became comparable (beneath the Békés and Zarand Basins almost throughout its whole thickness) to the asthenosphere. The extension of a relatively short (about 60 km) portion of the lithospheric mantle induced the extension of a significantly longer (about 100 km) segment of the upper crust (to about 150 km). We infer that this tectonic process led to the formation of an inward dipping *fault system*. The individual fault zones dip towards the *domal uplift of the asthenosphere*. In the early synrift phase the upper crust downthrusted along a set of faults. Along some fault zones the movement was more extensive forming half-grabens: Dorozsma Graben, Hódmezővásárhely–Makó Graben, Beius (Belényesi) Graben and Vad–Borod (Báródi) Graben. Beneath the central (Békés and Zarand) basins the crust weakened to a level that magma intruded and replaced a major portion of the lithospheric mantle.

During the phase of cooling and contraction of the magma infested region (in the postrift phase) the fault zones acted as zones of mechanical weakness. The asthenosphere rose to its highest position beneath the central basins and the cooling there was extremely intensive. Contraction of the domal structure caused not only the subsidence of the central basins but, through a number of *fault zones, generated the half-graben-like basins along its margins*. Within the Carpathian Basin the lithosphere was also subjected to regional extension, because of which the asthenosphere reached an anomalously shallow depth. Subsidence of the tectonic high in between the basin sequences below the level of the interior lake and the beginning of sedimentation in the area is attributed to the *regional* cooling of the asthenosphere.

The results and methodologies of this successful experiment present an excellent guide for mineral exploration of the pre-Neogene basement. A number of local seismic amplitude anomalies have been recognized which could be possible future targets for *oil and gas exploration*. New data could also be added to the *nappe structure* system formed at the time of the Alpine orogeny.

The very thick (7–8 km) Neogene basin sediments were also presented with new perspectives. Underlying the already known sedimentary strata, limestone (or quartz-cemented sandstone) beds of *Lower Badenian and Lower Miocene* (perhaps Paleogene) age are assumed. The *magma* intruded into the


Hungary
Romania
SW
NE
Doroszma Graben
Algyő High
Hódmezovásárhely-Makó Graben
Pusztafoldvár-Battonya Ridge
Békés Basin
PGT-1
Zarand Basin
Codru (Bélí) Mountain
Beius (Belenyesi) Graben
Padurea Craiului (Királyerdő) Mountain
Vad-Borod (Báródi) Graben
Plopis (Rez) Mountain
0
20
50
80
km
0
20
40
60
80
km
PGT-4

Neogene complex and the roll-over structure along a *listric fault* is also a new revelation.

Low-frequency deep penetrating seismic surveys combined with magnetotelluric studies offer a powerful tool for oil and gas exploration. Seismic amplitude analysis may also be utilized to detect deep seated oil and gas accumulations. Within the present data set the combined seismic amplitudes and magnetotelluric investigations led to the inference of target areas with possible hydrocarbon saturation. At greater depths, *stratigraphic traps* on the flanks of the uplifted structure and the *roll-over structures* formed on the NE side of the listric fault may present new exploration targets as well.

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in Canada:
— Geological Survey of Canada,
— LITHOPROBE,

Fig. 22. Extension of the results of the Hungarian Geotraverse for the basin echelon known along the direction of the PGT-4 survey [modified after GYÖRFI 1994]. On the seismic depth section, crosses are drawn to indicate the depth of the asthenosphere as determined by magnetotelluric survey. The basin system is attributed to a deep fault system, related to attenuation of the lithosphere beneath the Békés and the Zarand Basin

22. ábra. A Magyar geotraverz eredményeinek kiterjesztése a szelvény irányába eső medencesorra [módosítva GYÖRFI 1994 után]. A PGT-4 szeizmikus mélységszelvényen keresztekkel jelöltük az asztenoszféra magnetotellurikus mérésekkel meghatározott mélységét. Értelmezésünk szerint a medencerendszert az asztenoszféra magaslat felé irányuló mélytörés rendszer alakította ki

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— Eidgenössische Technische Hochschule.

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Nemzetközi együttműködésben végzett mélyreflexiós kutatás a “Magyar geotraverz” mentén

POSGAY K., TAKÁCS E., SZALAY I., BODOKY T., HEGEDŰS E., JÁNVÁRINÉ K. I., TÍMÁR Z., VARGA G. — BÉRCZI I., SZALAY Á., NAGY Z., PÁPA A. — HAJNAL Z., REILKOFF B. — MUELLER ST., ANSORGE J., DE IACO R. — ASUDEH I.

Magyar, kanadai és svájci együttműködésben DK Magyarországon kis-frekvenciás, reflexiós, szeizmikus litoszférakutatásokat végeztünk 1992-ben. A nemzetközi mérések jól illeszkedtek az ELGI negyed évszázados kisérletsorozatába, mellyel a szeizmikus reflexiós mérések mélységi behatolását kivánta kiterjeszteni a *felső köpeny* kutatására. A kisérletek célja olyan terepi és feldolgozási metodika kialakítása volt, mellyel a nyersanyagkutató szeizmikus méréseknél használt frekvenciatartománynál több oktávval kisebb frekvenciák is felhasználhatók. A nemzetközi mérés kulcsproblémája a refrakciós mérésekhez tervezett kanadai (PRS típusú) berendezések mélyreflexiós alkalmazása volt. A kisérlet sikerrel zárult. Az átviteli frekvenciatartományt sikerült *1–2 Hz* - ig csökkenteni és a teljes litoszféra szerkezetét megismerni.

A PGT-4 jelű szeizmikus szelvény az algyői kiemelt szerkezet oldaláról indult, a Hódmezővásárhely–Makói árkot, a Pusztaföldvár–Battonya-i medencealjzat felboltozódást és a Békési medencét harántolta (*1. ábra*).

A kanadai berendezéssel párhuzamosan (kisebb fedésszámmal) az előző mélyreflexiós kutatásoknál használt (MDS-18 típusú) felszerelést is üzemeltettük tájékoztató összehasonlítás, továbbá a neogén üledékek és a preneogén medencealjzat jobb felbontású vizsgálata végett. A méréseket kiegészítettük a szelvény végekre telepített, a mérés egész ideje alatt helyben maradó (svájci, magyar és kanadai) állomásokkal (*2. ábra*).

A terepi mérések megtervezésében és kivitelezésében a három ország kutatói együttműködtek. A feldolgozás és értelmezés feladatmegosztással folyik. Ebben a cikkben az ELGI-ben végzett feldolgozás első eredményeit ismertetjük.

A **neogén összlet** az MDS-18 berendezéssel felvett, kinagyított függőleges léptékű szelvényen (*3.* és *4. ábrák*) jól tanulmányozható. A közelitőleg 6 millió évnél fiatalabb rétegsor a szelvény teljes hosszában megtalálható. A rétegsor alján jelentős amplitúdóval és jellegzetes elvégződésekkel jelentkező, sárga színnel jelölt, reflektáló szintek delta üledékekkel azonosíthatók. Előzőleg a Pusztaföldvár–Battonyai hegyhát magasabb része a beltó szintje fölött volt. A neogén rétegsor alsóbb szintjei a hegyhát oldalában kiékelődnek.

A szeizmosztratigráfiai, szekvenciasztratigráfiai, magnetosztratigráfiai vizsgálatok és a radiometriai kormeghatározások eredménye szerint [VAKARCS et al. 1994] a sekély tenger a szarmata és pannon emeletek határán (11,5 Ma) izolálódott a világtengerektől és tóvá alakult. A szarmata végén és a pannon emelet elején a Békési medence és a Hódmezővásárhely–Makói árok elmélyülése gyorsabb volt mint az üledék felhalmozódása, viszonylag éhező medencék voltak [POGÁCSÁS et al. 1989].

A Békési medencében, a 70. szelvénykilométer táján a neogén üledékek mélyebb szintjébe történt *magmás benyomulásra* következtethetünk, amely megemelte a felette levő üledékeket (*5.* és *6. ábrák*). A magmás benyomulást *felső miocén (alsó pannon) bazalt*ként értelmeztük. Felette egy *lisztrikus vető* figyelhető meg, amelynek ÉK- i, azaz a medence felőli oldalán átforduló (roll-over) szerkezet látható. Valószinű, hogy a szerkezet kialakulása a magmatikus benyomulás és az üledékes rétegsor eltérő kompakciójával magyarázható. A magmatikus tevékenység a konszolidált kéreg teljes mélységében nyomozható (*1-4. mell.*).

Feltételezésünk szerint mindkét medence mély részén a bádeni rétegek alatt *alsó miocén* (esetleg paleogén) üledékek is keletkeztek. Ez a *szinrift formáció* enyhén tört szerkezetű és jelentős, kb. 1500 m vastagságú. Nagy amplitúdóval és kis frekvenciával jelentkezik. A 2. és 4. mellékleten és a 4. és 6. ábrán ezt a rétegsort zöld színnel jelöltük. A magnetotellurikus mérések szerint az összlet ellenállása több mint 200 Ωm [Varga és Nemesi 1994]. A szeizmikus és magnetotellurikus eredmények együttes értelmezése alapján *vastag pados mészkövet, vagy kvarcos kötésű homokkövet* tételezünk fel.

A Hódmezővásárhely-Makói árok az alsó miocén idején két (2. és 4. mell.) vagy három (*7. ábra*) részre választódott el. Az elválasztó gerinc(ek) magassága többszáz méterre becsülhető. Az árokrészek kialakításában a DNy-i oldalukon található mélytörészónák és az ezekhez csatlakozó kisebb törések játszhattak jelentős szerepet. A felső bádeni idején a tenger a gerinc(ek) fölé emelkedett és közös üledékgyűjtő alakult ki.

A Békési medencében a szinrift időszakban a medence belseje felé lejtő törések alakultak ki. A 85.–87. szelvénykilométer táján látható, sokszáz méter elvetési magasságú törészóna az alsó miocén rétegeket is elvetette. A jelentős elvetésre mind a szeizmikus képből, mind a magnetotellurikus mérésekkel meghatározott nagyellenállású réteg mélységváltozásából következtethetünk (2. és 4. melléklet).

A PGT-4 szelvényen, a **preneogén medencealjzatban**, 29–32, továbbá 57–60 szelvénykilométer között a környezetéből kiemelkedő, közel vízszintes **amplitúdó anomáliát** észleltünk. A *8.* és *9. ábrán* látható szelvényrészletet 2–40 Hz szűréssel készítettük.

Részletesebben az 57–60 szelvénykilométer között észlelt amplitúdó anomáliát vizsgáltuk meg. A kis-frekvenciás metodika használhatóságára következtettünk abból, hogy ugyanezen a szelvényszakaszon 10 Hz-es alulvágás esetén a kérdéses amplitúdó anomália már nem figyelhető meg (*10. ábra*), azaz csak *a litoszféra-asztenoszféra kutatáshoz kifejlesztett kisfrekvenciás metodikával határozható meg*. Értelmezéséhez longitudinális hullámsebesség, sűrűség és Poisson szám becslés történt [Takács 1996], különös figyelmet fordítva a reflexiós tényező előjelére. A kőzetfizikai paraméterek becslése a vizsgálati helyen mért szeizmikus csatorna, illetve az amplitudó-észlelési távolság (AVO) modellezésével történt (*11.* és *13. ábra*). A vizsgálatok alapján valószinű, hogy az anomális amplitúdójú reflexiót mezozoós karbonátos kőzetek törés- és repedésrendszerében lévő *széndioxid és víz*, vagy *szénhidrogén gáz és olaj*, vagy ezeknek más kombinációja okozhatta (*12. ábra*).

Az elképzelés kiegészítésére ismertetjük a PGT-1 és PGT-2 kereszteződésénél (1., *15.* és *16. ábrák*) észlelt amplitúdó anomália vizsgálatát, amelynél a szeizmikus modellvizsgálatnál akusztikus karottázs adatokból indulhattunk ki (*17., 18.* és *19. ábrák*) és az értelmezést területi magnetotellurikus eredmények is segítették (*14. ábra*). A szeizmikus modellvizsgálat és az ismertetett WEGA-D felismerő rendszerrel végzett vizsgálat azt mutatja, hogy az amplitúdó anomália *potenciális kőolaj és földgáz előfordulás*ként értelmezhető [Nagy 1992].

A **konszolidált litoszféra** szerkezetét tanulmányozva a nagy behatolású szelvényből az alpi orogén alatt kialakult takarórendszer bonyolultságára is következtethetünk. A Pusztaföldvár-Battonyai gerincen furásokból ismert és a szeizmikus szelvényen azonosított mezozoikumot nagy amplitúdójú, rétegzettségre utaló reflexiók jellemzik. Ezek a *Kodru takarók* mezozoikumához tartoznak [Györfi 1994].

Az alattuk látható képből töréses, gyűrődéses szerkezetre következtethetünk. A szeizmikus kép arra utal, hogy a Hódmezővásárhely-Makói árok és az Algyői medencealjzat magaslat között törés tételezhető fel, amelyik az Algyői szerkezet alatti, a Dorozsmai árok felé irányuló töréssel egyesülve a szelvény ÉK-i vége felé lejt (2. és 4. mell.). A vázolt zónától ÉK felé, a Hódmezővásárhely-Makói árok alól kiinduló további törések is feltételezhetők, azaz egy több km vastag, kis sziládságú zónára lehet következtetni, amely értelmezésünk szerint döntő szerepet játszhatott az árok kialakulásában. Ez a nyírási zóna — enyhébb dőléssel — az alsó litoszférában is nyomozható.

A 70. és a 80. szelvénykilométer között, 35 km alatt a reflexiós energia jelentősen lecsökken, a reflektáló felületek dőlése enyhül és 80-85. szelvénykilométertől kezdve uralkodóan közel vizszintes lesz (1-4 mell.). A jólvezető réteg a 70. szelvénykilométer után meredek emelkedővel 35 km fölé magaslik. A csökkent szeizmikus energiájú és jól vezető MT tartományt az *asztenoszféra felboltozódásaként* értelmezzük. (A magnetotellurikus adatokat 2D felépítés feltételezésével dolgoztuk fel. Elképzelhető, hogy a 2D feltételezéssel a valóságosnál kisebb mélységet határoztunk meg [ÁDÁM et al. 1993]). A Pannon geotraverzen a szeizmikus (PGT-1), a magnetotellurikus és a geotermikus eredmények integrált interpretációja alapján a Békési medence alatt az asztenoszféra megemelt helyzetére következtettünk [POSGAY et al. 1996]. A Magyar geotraverzen a mélyreflexiós (PGT-4) és a magnetotellurikus adatok szerint a litoszféra-asztenoszféra határ emelkedése a Békési medencén túl is valószínűnek látszik, azaz a Békési medence mély részéhez viszonyítva az asztenoszféra felboltozódása ÉK felé helyezkedik el és elképzelhető, hogy az Algyői szerkezet felől lejtő, töréses zóna ennek közelében végződik. A Makói árok alatt a kéreg-köpeny határ és a litoszféra-asztenoszféra határ is csak enyhe domborulatot képez (2. és 4. mell.).

Az eredmények értelmezéséhez vázolt **medencefejlődési modell**ünk szerint a szinrift fázisban a köpenylitoszférának a szelvényvég tájára eső része jobban megnyúlt mint a köpeny-litoszféra többi része. Ennek következménye volt, hogy az Algyő felől lejtő törészóna mentén litoszféraméretű megcsúszás következett be, létrehozva a Hódmezővásárhely-Makói árkot, a metamorf kőzetekből álló medencealjzatú, viszonylag vékony felső kéreggel jellemezhető Algyői magaslatot és valószinűleg a Dorozsmai árkot is. A köpenylitoszféra rendkivüli elvékonyodása a szelvény ÉK-i részén az asztenoszférának az átlagosnál nagyobb megemelkedéséhez is vezetett. A viszonylag magasabbra került asztenoszférarésznek az átlagosnál korábbi és gyorsabb kihűlése a *meggyengült (töréses) zóna közvetitésével* a Hódmezővásárhely-Makói árok (és a Dorozsmai árok) további besüllyedéséhez vezetett (*20. ábra*). Nézetünk szerint ezzel magyarázható, hogy a Hódmezővásárhely-Makói árokban anomális vastagságú üledék keletkezett annak ellenére, hogy az asztenoszféra a Kárpát medencére jellemző átlagos mélységben valószínűsithető. Az asztenoszférának a Kárpát medencében történt regionális összehúzódása hatásaként értelmezzük az Algyői medencealjzat domborulatnak és a Pusztaföldvár-Battonyai hegyhátnak 5-7 millió évvel ezelőtti megsüllyedését és elöntését (20c ábra).

A PGT-4 szelvényszakasz *átlagos megnyúlás*ára a *kéregre 1,5* és a *köpeny-litoszférára 2,5* értéket kaptunk, azaz egy *kb. 100 kilométeres kéregszakasz kb.150 km-re* történt megnyúlása volt (nagyjából) azonos egy lényegesen rövidebb (kb. 60 km-es) köpeny-litoszféra szakasz megnyúlásával. (Ezt alátámasztja például, hogy az algyői törészóna menti felső kéreg megcsúszásból kb. 15 km-es térmeghosszabbodásra következtethetünk.) A szelvény irányában egy — nagy vonalaiban szimmetrikus — medencesor ismert (*21. ábra*). A külső medencék félárokként fejlődtek ki és fő töréseik a Békési és a szomszédos Zarándi medence felé lejtenek [GYÖRFI 1994]. A medencesor és az azokat elválasztó hegyhátak Ny-ról K felé a következők: Dorozsmai árok, Algyői szerkezet, Hódmezővásárhely-Makói árok, Pusztaföldvár-Battonyai medencealjzat domborulat, Békési medence, Zarándi (Zarand) medence, Béli hegység (Codru-Moma), Belényesi (Beius) árok, Királyerdő (Paduera Craiului), Báródi (Vad-Borod) árok, Réz (Plopis) hegység. Feltételezhető, hogy a medencesor keletkezése a litoszférának a Békési és a Zarándi medence alatti felszakadásával kapcsolatos törésrendszerre vezethető vissza (*22. ábra*). Ezekben a medencékben és az alattuk elhelyezkedő litoszférarészben következtethetünk a legjelentősebb magmabenyomulásra is.

Tudomásunk szerint a Kárpát medencében végzett kisfrekvenciás reflexiós mérések az *elsők*, ahol az eredményekből a *teljes litoszféra* szerkezete vázolható [POSGAY et al. 1981, 1995., HAJNAL et al. 1996]. Érdekesnek látszott, hogy a Magyar geotraverzen kapott eredményeket összevessük olyan medencefejlődési modellel, amely a mérések értelmezését elősegítheti. A kapott eredmények emlékeztetnek WERNICKE [1981 és 1985] medence kialakulási modelljére. A felszíntől az alsó litoszféráig tartó nyírási zóna felszínközeli részén keletkezett a Hódmezővásárhely-Makói árok és feltételezésünk szerint a Dorozsmai árok. „Core Complex range"-ének helyén a PGT-4 szelvény elején is feldomborodik az alsó kéreg (a Dorozsmai árok és a Hódmezővásárhely-Makói árok között), és a litoszféra-asztenoszféra határnak a mélytörészóna mélyrésze (a szelvényben ÉK) felé történő emelkedése valószinűsíthető.

Eltérést jelent WERNICKE modelljéhez viszonyítva a Hódmezővásárhely-Makói árok nagy mélysége és annak magyarázata.

A mélylitoszférára vonatkozó új ismereteken kívül a medencealjzat és a fiatal üledékek mélységéből is érdekes szerkezetekre lehetett a mérési adatokból következtetni, amelyek a nyersanyagkutatás, a nagyszerkezet megismerése és módszertani szempontokból is figyelemre méltók lehetnek.

Új kutatási perspektivákat a kiemelt szerkezet lejtőin kialakult csapdák, illetve a lisztrikus vető oldalán létrejött átforduló (roll-over) szerkezetek jelentik.