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Seismic refraction investigations in Poland (1964–1978) and their use in continuing studies

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Seismic refraction investigations, performed in Poland between 1964 and 1978, are reviewed. Examples selected from the many seismic profiles, totalling approximately 15 000 km in length, are shown. The most useful profiles as regards geological interpretation are in the Precambrian Platform and along its southwestern edge. Both the top of the crystalline basement and a system of faults, downfaulting the basement towards the south-west, can be identified in that area. In the Carpathians and its foreland, the top of this basement may be identified together with the bases of thrust flysch nappes. In the Fore-Sudetic Monocline, the top of folded Carboniferous deposits can be determined. The most ambiguous results were obtained from the Palaeozoic Platform.

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INTRODUCTION

Seismic refraction investigations have been relatively unpopular in petroleum exploration across the world because this method yields information about single refracting boundaries, as opposed to the reflection seismic method which gives a wave image of the investigated depth interval. However, the advantage of refraction investigations is the acquisition of data on boundary velocities. In Poland this method was widely used, primarily in the period 1964–1978. The purpose of this paper is to review those early investigations and to attempt to evaluate their usefulness for today's geological interpretations. Despite certain differences in methodology, a comparison of those investigations with slightly later results of refraction and wide-angle reflection (DSS) seismic surveys is also given.

GENERAL INFORMATION

In 1952–1958, single refraction soundings along reflection profiles were performed in order to make easier correlations of reflecting horizons. Since 1961, continuous profiles have been run. The most intensive investigations were during 1964–1978. They were commissioned mainly by the Polish Geological Institute and Geophysical Exploration Company, and to a lesser extent by the Petroleum Mining Company.

In 1964, a project of regional reflection and refraction profiles, transecting major geological units in Poland from the SW towards the NE, was prepared, and work began. The first regional refraction profiles crossed the marginal zone of the Precambrian Platform and its contact with the Palaeozoic Platform. A number of seismic profiles were acquired in this zone in the following years, also extending the investigations into other areas. Regional refraction profiles of a total length of over 15 000 km were acquired during 1963–1978.

The refraction seismic method, as applied, allowed identification of one to several refracting boundaries, yielding simultaneously some information about wave velocities at these boundaries. With little borehole data available at that time, this method enabled a general depth determination to major geological boundaries.

The distribution of regional refraction profiles was uneven (Fig. 1). The density of the seismic profiling grid was dependent on geological tasks and objectives, having to do mainly with regional exploration, carried out in order to explore for oil and gas resources. Therefore, for example in northeastern Poland, seismic profiles are densely distributed on the submerged tectonic units of the Peribaltic and Podlasie depressions, filled

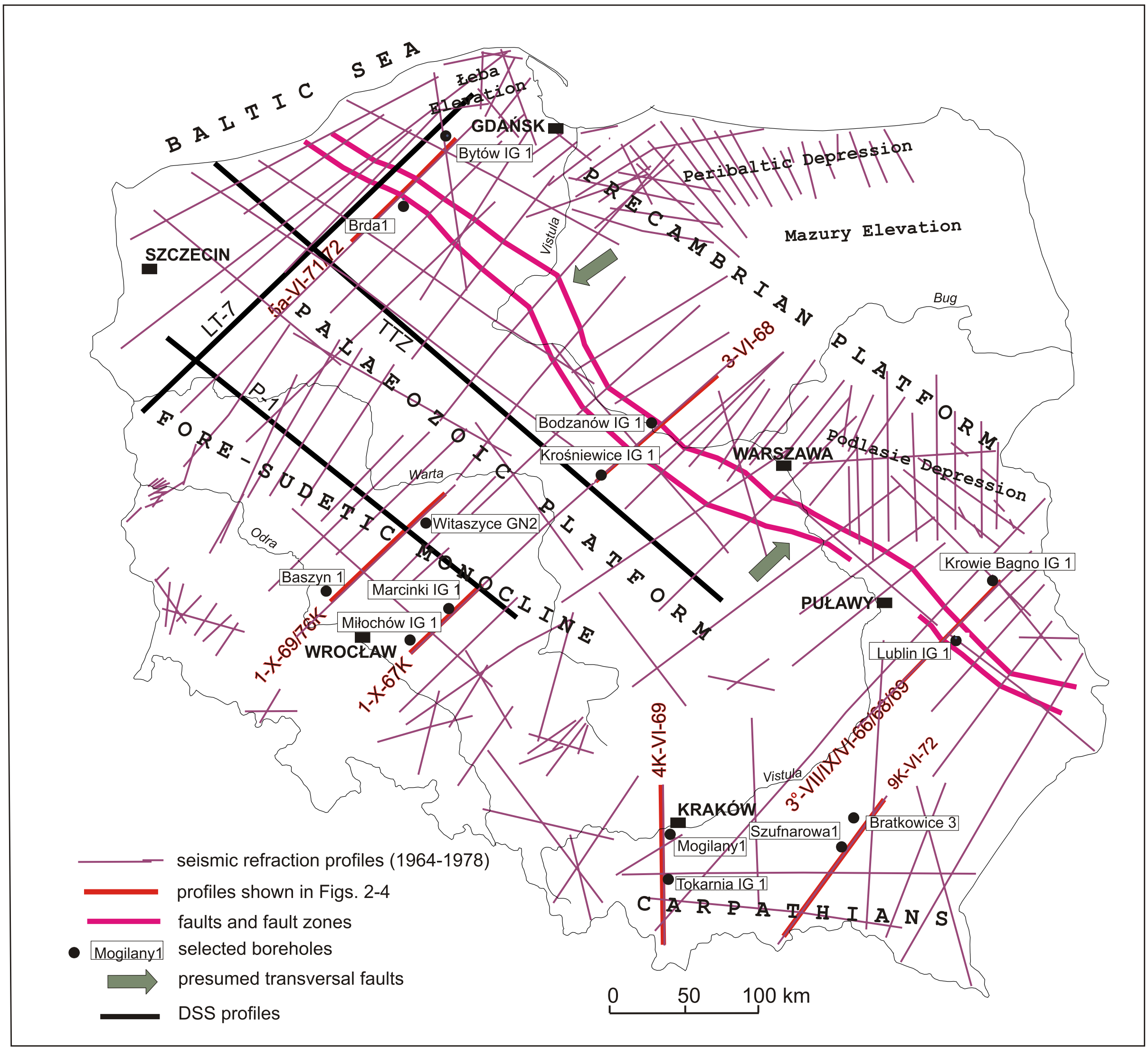

Fig. 1. Seismic refraction profiles in the territory of Poland

with Early Palaeozoic deposits, whereas they are absent on the Mazury Elevation where the crystalline basement is covered only by Mesozoic deposits.

The results of these seismic refraction investigations in Poland were never comprehensively overviewed. Published summaries (Skorupa, 1974; Młynarski, 1984), either did not concern all refraction surveys or concentrated only on a specified region.

Furthermore, during almost twenty years of investigation, technical surveys, recording and interpretation methods changed. Some profiles were realised across two and even three seasons. Sometimes, one profile was acquired over a few years by several seismic teams which used different surveying equipment. Such circumstances made it difficult to correlate the results of surveys. Initially, seismic teams used equipment with oscillographic recording on photographic paper. Later, magnetic tapes were commonly used to record analogue seismic signals. Data preparation and analysis were made manually, drawing travel-time curves that became the base for further interpretation. All such travel-time curves were plotted as a part of documentation for individual projects and were subsequently verified in summary interpretations. Thus, we can assume that refraction travel-time curves from the summary documentations are sufficient for re-analysis of the refraction data and for identifying refracting boundaries.

Such interpretations were performed in the years of 1977–1986 for individual geological units, and are given in several unpublished reports (Wojas and Hałoń, 1980 — western Pomerania; Wojas, 1979 — central Poland; Wojas *et al.*, 1984 — Warsaw and Lublin troughs; Patyk, 1979 — Carpathians and their foreland; Nowak *et al.*, 1986 — Fore-Sudetic Monocline). The results vary from region to region.

The present paper shows some examples of results obtained for various regions of Poland (Figs. 2–4), discussed in respect to their usefulness for elucidating problems of regional geology.

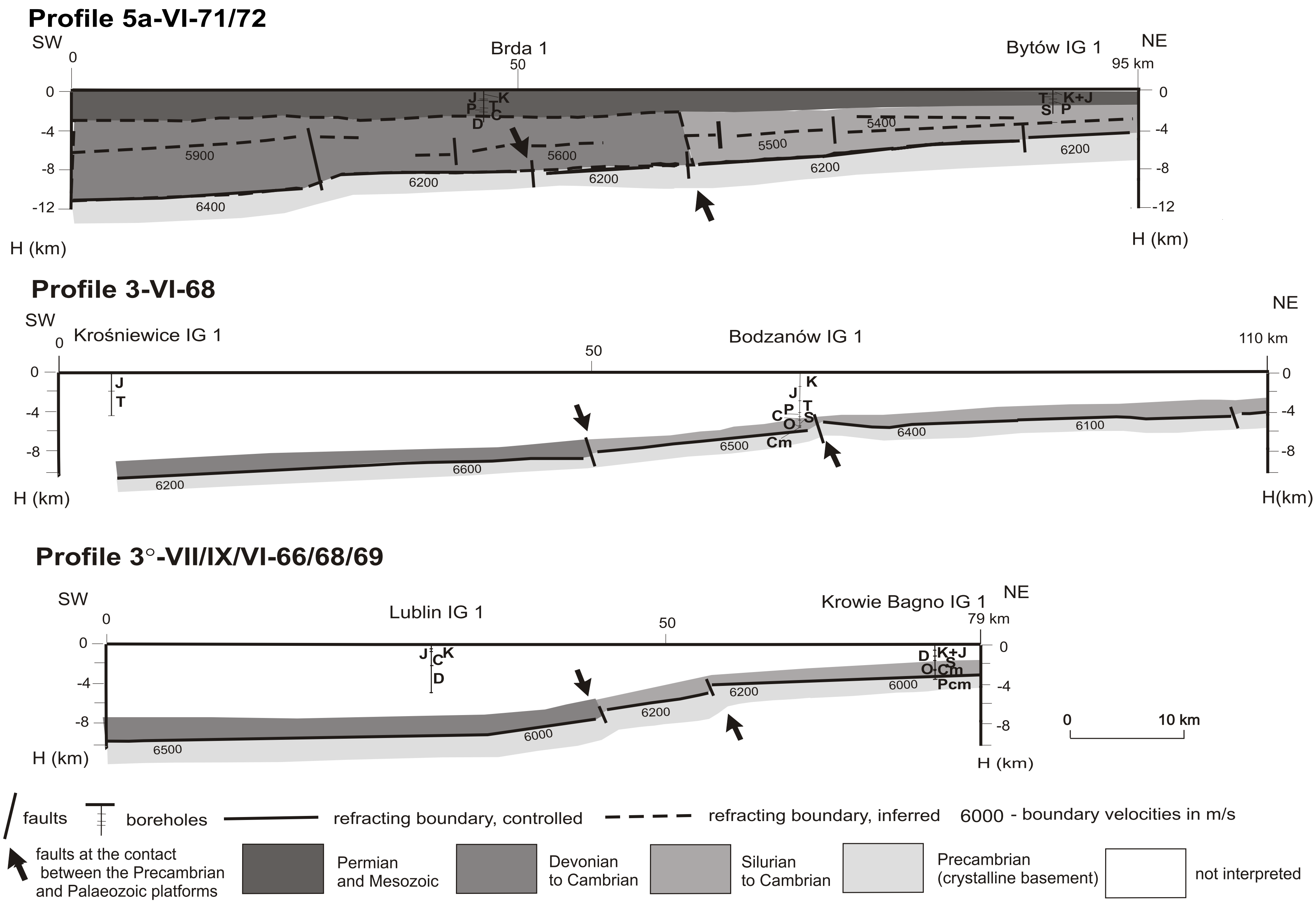

Fig. 2. Selected seismic refraction profiles across the contact between Precambrian and Palaeozoic platforms
K — Cretaceous, J — Jurassic, T — Triassic, P — Permian, C — Carboniferous, D — Devonian, S — Silurian, O — Ordovician, Cm — Cambrian, Pcm — Precambrian

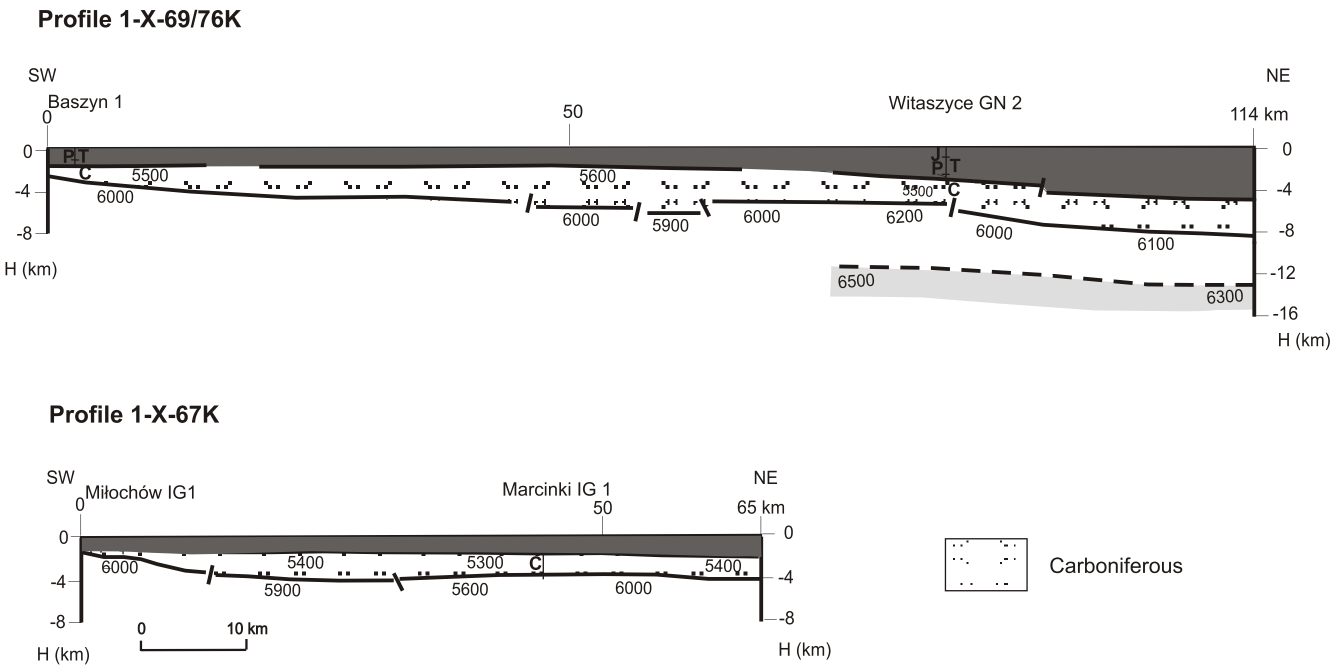

Fig. 3. Selected seismic refraction profiles in the Fore-Sudetic Monocline area

Explanations as in Fig. 2

PRECAMBRIAN PLATFORM

In this area, seismic refraction investigations show their greatest utility. The deepest recorded refracting boundary, with boundary velocities exceeding 6000 m/s, is undoubtedly associated with the top of the Precambrian crystalline basement (Fig. 2). It closely corresponds with results from the deepest boreholes in which the top was drilled at depths down to approximately 5000 m. Therefore, we can assume that the boundary reliably reflects the top of crystalline basement also at the marginal zones of the platform, where it descends to 8000–10 000 m. There is also a good correlation with the position of refracting horizons, showing velocities of 6000 m/s and more, recorded on DSS profiles (Guterch *et al*., 1986, 1994).

Shallower boundaries, with boundary velocities of approximately 5500 m/s, can also be observed on many profiles in this area (*cf*. Fig. 2 — northeastern part; profile 5a-VI-71/72). They lie within a thick Silurian succession; however, their exact geological nature is unknown. In the past, these boundaries were assigned to diabase intrusions, but boreholes have not confirmed this. The horizons are discontinuous, and so were interpreted to be a result of faults with small offsets.

CONTACT BETWEEN PRECAMBRIAN AND PALAEOZOIC PLATFORMS

This contact is distinct on the refraction profiles. Based on the interpretation of 23 profiles of a total length of 4000 km, it was possible — analysing travel-time curves — to identify two prominent fault zones on the deep refracting boundary: the northeastern and southwestern fault zones (Figs. 1 and 2). An exception is the lack of the southwestern fault zone on two neighbouring profiles in the Puławy region. At the structural step, located between these zones, boundary velocity values are identical to those recorded in the Precambrian Platform. At this step occur, beneath the Devonian or Permian, folded Older Palaeozoic deposits, as shown by boreholes from the northwestern sector of the contact. This led to the conclusion that these deposits are thrust over the edge of the Precambrian Platform in this area (Dadlez, 1984).

Correlation with other profiles has allowed a continuous interpolation of these two zones (Fig. 1). However, this can be a simplified interpretation because, when trends of the fault zones are analysed in detail, three sectors of confident correlation are observed (Fig. 1):

— northwestern sector, from the Baltic Sea to Vistula River;

— central sector, stretching along the Vistula River;

— southeastern sector (Lublin region).

We cannot preclude the occurrence of SW–NE-trending transverse strike-slip faults between these sectors (Fig. 1), as was postulated by Dadlez (1984). However, the lack of data from potentially constraining, NW–SE trending profiles does not allow the delineation of them, being based exclusively on refraction investigations.

PALAEOZOIC PLATFORM

In this area, refraction investigations have the least utility. The deepest recorded refraction wave has a boundary velocity over 6000 m/s (Fig. 2) and lies in the depth range 6–12 km.

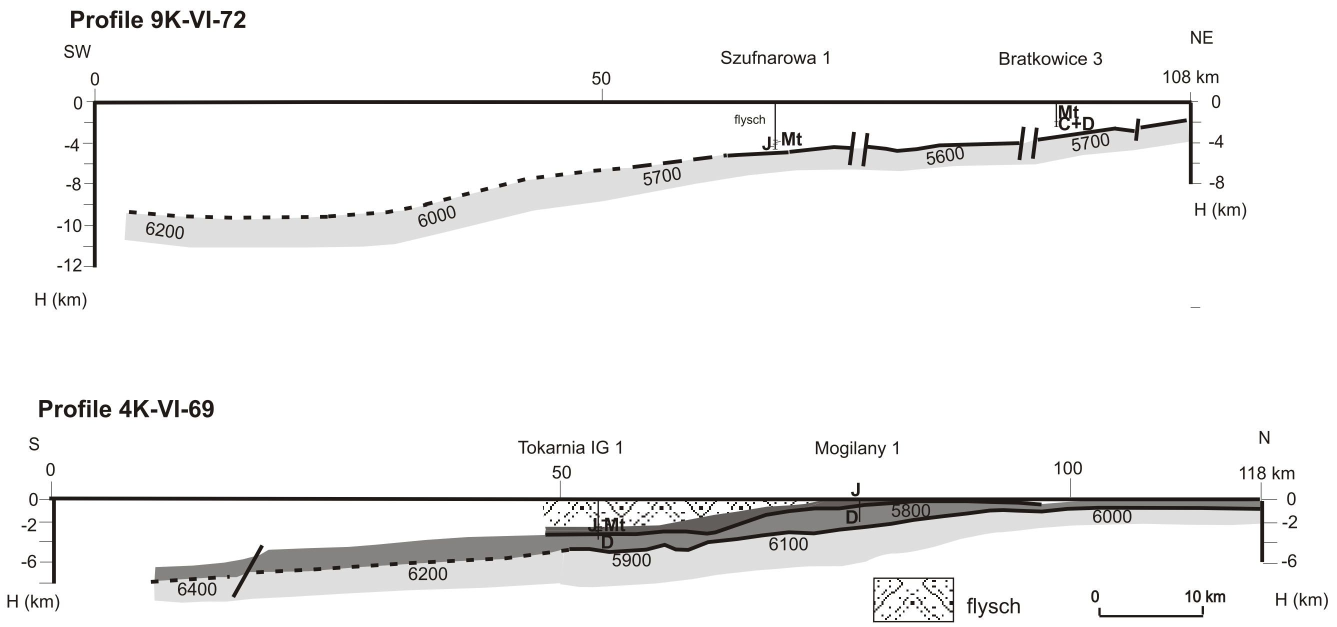

Fig. 4. Selected seismic refraction profiles in the Carpathian area

Mt — Miocene; other explanations as in Fig. 2

This boundary, however, is recorded discontinuously and with low confidence. It also occurs at different depths on neighbouring profiles. Therefore, it is impossible to map this boundary, the more so as it presumably represents different geological interfaces in different plans. In the Peribaltic area, the boundary can be identified with the top of weakly consolidated basement on DSS profiles, although basement velocities are lower, in the range 5700–5800 m/s (Guterch *et al*., 1994). Further towards central Poland, comparison with DSS profile TTZ (Grad *et al.*, 1999) reveals still greater discrepancies. Incidentally, the refraction profile grid is very sparse.

In addition to this deep horizon, we can also observe in this area refracting horizons with velocities ranging from 5600 to 5900 m/s (Fig. 2 — profile 5a-VI-71/72), corresponding to shallower geological formations of different ages.

FORE-SUDETIC MONOCLINE

Refraction investigations in the Fore-Sudetic Monocline were associated with prospects for Zechstein potash and copper ores, as well as with mapping of the crystalline basement top in order to prospect for oil and gas deposits. Two boundaries were identified in this area (Fig. 3): an upper one, with velocities between 5300 and 5600 m/s, separating the Permian and Mesozoic complex from underlying, strongly altered and deformed Carboniferous deposits, and a lower one, with velocities approximately 6000 m/s, originally interpreted as Lower Palaeozoic strata.

For depth interpretation, in most cases complex velocity analysis was conducted on the basis of data from mean velocity measurements in boreholes, available at that time. The measurements were performed in the Rotliegend (66 boreholes) and in Carboniferous (17 boreholes) sections. Velocities to the base of Zechstein were adopted from poorly constrained results of the reflection seismic surveys.

The refraction investigations revealed a complicated wave image for this area and several different interpretational versions were postulated. Skorupa (1974) was of the opinion that the recorded seismic phases represented diving waves and, therefore, he did not construct a map for this area but, rather, presented only individual profiles. Neglecting diving waves but taking into account inflections observed on the travel-time curves, we interpret several horizons at different depths instead of one refracting boundary of variable velocity. The first summary interpretation, by the Petroleum Mining Company in 1981, also included a multi-layer image, neglecting the possibility of the occurrence of diving waves.

In contrast, Nowak *et al.* (1986 — Seismic documentation of the Fore-Sudetic Monocline area) did take into account the possibility of such waves and therefore his interpretation shows fewer boundaries, but is more reliable. The image includes over 3000 km of refraction profiles from 23 source documentations. Despite their age, records are of good and very good quality. Good first arrivals are recorded up to 60–70 km or more away from the shotpoint. Reliability of the results depended mostly on observation schemes. The best results were obtained on profiles made in the 1970s, regarding both waves refracting at the top of Carboniferous and the wave with V_g ~ 6000 m/s, corresponding to deeper-seated deposits.

Three refraction boundaries can be distinguished beneath the Mesozoic on the basis of the interpretation cited above (Fig. 3):

1. A boundary correlated with the erosionally truncated top of folded Carboniferous strata, velocities 5200–5700 m/s. It seems that the boundary corresponds reasonably well to the boundary of velocities 5800–5900 m/s recorded on the DSS profile (Jensen *et al.*, 1999). The wave image indicates a lack of significant faulting along this horizon. This refraction record is a valuable addition to reflection seismic data, which have yielded satisfactory results down to the base of the Zechstein only, whereas the identified boundary approximately corresponds to the base of Permian.

2. A boundary which is conventionally correlated with Lower Palaeozoic deposits, with velocities 5800–5900 m/s (locally lower). This is the most complicated group of phases, not always detected as the first-arrival. In some cases it was the third phase arrival. The analysis of travel-time curves in the forward and reverse directions for this phase indicated that this is not a diving wave. Its geological nature is unclear. If it is really the top of the Lower Palaeozoic, it would represent the lower structural level, overthrust — according to thin-skinned tectonics — by Carboniferous strata.

3. The lowest boundary, detected partly as first-arrivals and partly as later ones, is characterised by velocities over 6000 m/s with extreme values of 6300–6500 m/s (Fig. 3 — profile 1-X-69/76K.). The geological nature of this boundary is unknown.

The two latter boundaries find no equivalent among the boundaries identified on the P1 DSS profile (Jensen *et al.*, 1999).

CARPATHIANS

The objectives of refraction seismic surveys in the Carpathians were to illuminate the basement of the Flysch Carpathians, thrust over its foredeep. The obtained results were unsatisfactory for this purpose; however, they are useful for regional interpretation of geophysical data.

A summary interpretation was performed for this area by Patyk (1977 — Seismic documentation of the Carpathians area). It includes interpretation of 15 seismic sections with re-interpreted travel-time curves from critically analysed input data. As compared with original studies, this re-interpretation showed a very rough image of seismic boundaries. It seems that such an approach, limiting the recording of refracting boundaries mainly to the northern sectors of profiles, was too cautious. Travel-time curves from the original documentation allow — perhaps with slightly lower confidence — identification of refraction boundaries also in southern sectors of some profiles. The analysis of basic materials (seismograms) shows that they are of variable quality, depending on both surface and subsurface conditions. It is also clear that seismic shooting performed from the north-southwards and from the east-westwards provided better quality results than shooting in the opposite direction.

A refraction profile from the eastern Carpathians with an unambiguously identified boundary of velocity from 5600 to 5700 m/s, shown in Figure 4 (9K-VI-72) serves as an example. The boundary is recorded by first arrivals in the offset interval 20 to 40 km. As on other profiles from the eastern Carpathians, the wave image of the southwestern sector of the profile is disturbed and complex, and there is the possibility of the occurrence of diving waves. Nevertheless, a refraction boundary of velocities 6000–6200 m/s, which descends towards the SW and reaches a depth of approximately 10 km at the end of the profile, can be identified here with lower confidence.

The most typical refraction profile of the western Carpathians is shown in Figure 4 (profile 4K-VI-69). A much better image of seismic boundaries, as compared with the eastern area, is observed here. Two boundaries can be identified: a shallower one, with velocities of 5800 m/s, and a deeper one, with velocities of 6000–6200 m/s. The shallower boundary is very distinctly projected on travel-time curves, in particular in the northern part of the profile. In the middle sector, the records are of slightly lower quality due to a poor shooting pattern, and travel-time curves from different shotpoints do not correlate well. Nevertheless, the interpretation is relatively simple. In the southern sector, the analysis and interpretation of travel-time curves allows only a hypothetical identification of this boundary, due mainly to the lack of records with distinct first arrivals.

The shallower boundary, tied to borehole data, corresponds to the base of thrust flysch nappes, and simultaneously to the top of basement of various ages. The deeper boundary, in the northern sectors of both these profiles, used to be associated with the top of Precambrian basement. It is probable that, in the southern sectors, the boundary represents the same surface; however, this problem, due to the lack of drilling control, remains an open question.

CONCLUSIONS

1. Travel-time curves, included within summary seismic documentations, are a basis for re-interpretation of old refraction data. Their analysis, with the use of new velocity data which have recently been obtained, allows inference of a high quality depth image that can be used for geological exploration in Poland. Using computer techniques, this can be achieved at relatively low cost. Such data taken together can be a valuable addition and supplement in elaborating the large DSS seismic experiments: POLONAISE ’97 and CELEBRATION 2000.

2. In areas where refraction boundaries are well tied to geological data (Precambrian Platform and Carpathian Foreland), reliable information about the morphology of the top of Precambrian basement is inferred. In the Carpathians, the base of thrust flysch nappes can also be identified.

3. The analysis of fault zones enables determination of the contact between the Precambrian and Palaeozoic platforms.

4. An interesting image of the morphology of some refraction boundaries in the Fore-Sudetic Monocline requires further investigation.

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