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Anomalous dips of some Upper Carboniferous strata in the Mšeno-Roudnice Basin based on borehole data and reflection seismic measurements

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Abstract. Sediments of the Central Bohemian Carboniferous basins have long been considered as typical platform deposits with subhorizontal dips of strata and a predominance of normal faulting. Nevertheless, seismic measurements in the Mšeno-Roudnice Basin (MRB) have revealed that some Upper Carboniferous sediments dip at angles of 20° or more (Kadlečík et al. 1985, 1990). These strata are overlain by subhorizontally deposited Upper Carboniferous sediments. This situation was also confirmed by samples from several boreholes (Bosák 1989, Bosák in Žbánek et al. 1990). The dips were, however, explained by deltaic deposition in a lacustrine environment (Bosák 1991).
As suggested by the revision of seismic sections from the MRB area performed during the past few years at the Faculty of Science of Charles University in Prague, the above mentioned dips of strata can be explained otherwise. Upper Carboniferous rocks usually dip at the same angle from the base of the Carboniferous up to a certain stratigraphic level (commonly to the lower part of the Hředle Member), while the overlying Upper Carboniferous sediments are subhorizontal. The length of the inclined structures often exceeds 1 km, and the respective dips of strata are generally observed even at intersecting seismic profiles.
A zone with the occurrence of mutually non-interlocking structures resembling monoclinal folds lies between Mělník and Benátky nad Jizerou, in an area about 20 km long and 3 km wide. This zone may represent the westernmost extension of folds documented in some Sudetic Permo-Carboniferous basins, e.g. in the southern part of the neighbouring Mnichovo Hradiště Basin, east of the MRB.

Key words: Mšeno-Roudnice Basin, Stephanian B/C, seismic structural investigation, fold-like structure

Introduction

Central Bohemian and Western Bohemian Upper Carboniferous basins of the Bohemian Massif have been traditionally considered as examples of typical platform-type sedimentation (e.g., Mísař et al. 1983), with their fill being generally deformed only by normal faults. This aspect is understood as one of the differences between the Carboniferous fill of these basins and the Permo-Carboniferous fill of some Sudetic basins with more intensive folding. The present contribution deals with the setting in the SE part of the Mšeno-Roudnice Basin (MRB) where the situation does not fit the general assumption, as shown by seismic reflection measurements and some borehole data. Although the MRB is part of the Central Bohemian Upper Carboniferous basins, the prominent dips of Carboniferous units are visible on seismic sections, and were also confirmed by several boreholes. The structures of the dipping strata have the character of monoclinal folds, and their existence is linked with the unconformable deposition of strata. Such features are best visible in rocks of the Slaný Formation near the SE margin of the MRB. The deposition of the Slaný Formation has been hitherto believed to have been uninterrupted, but the new data suggest that this may have not been the case in all Central Bohemian basins.

Brief geological description of the Mšeno-Roudnice Basin

The MRB is the easternmost of all Central Bohemian Upper Carboniferous basins. It borders the Kladno–Rakovník Basin in the west. The Mnichovo Hradiště Basin in the east is already ranked among the Sudetic Permo-Carboniferous basins. Sediment deposition in the MRB started in a small area in its SW part in the Radnice Member (Table 1) in the Bolsovian (= Westphalian C). A marked extension in depo-

Table 1. Lithostratigraphic subdivision of Carboniferous rocks of the Central and Western Bohemian basins

Age		Formation	Member		Horizon	Group of Seams, Seams
Stephanian	C	Líně			Stránka	
					Klobuky	Klobuky
					Zdětín	Zdětín
	hiatus					
	B	Slaný	Otruby	Kamenný Most		
				Kounov		Kounov
				Ledce		
			Malesice	Hředle		
				Mšec		
			Jelenice			Mělník
	Barruelian	Týnec				
	Cantabrian	Kladno	Nýřany			Nevřeň
						Chotíkov
Westphalian	D					Nýřany
	hiatus				Komberk= Mirošov	Touškov
	Bolsovian		Radnice			Lubná
					Whetstone	Radnice
						Plzeň

sition occurred after the hiatus in the Nýřany Member (Westphalian D to Cantabrian), when the deposits of this unit progressively spread over almost the entire basin. The deposition of sediments in the MRB continued, with a number of diastems and a prominent hiatus between Stephanian B and C, probably until the Autunian. Nevertheless, the youngest preserved deposits of the Líně Formation date only to Stephanian C (Kadlečík et al. 1985, 1990).

The basin floor is formed by Upper Proterozoic rocks, and the Carboniferous rocks are overlain by horizontally deposited sediments of the Bohemian Cretaceous Basin. Tectonic deformations of the Upper Carboniferous deposits are partly synsedimentary, and partly postsedimentary. Some faults are undoubtedly post-Cretaceous in age.

In view of the theses to be discussed later, it is necessary to mention the lower and middle parts of the Slaný Formation (Stephanian B). The Jelenice Member at the base of this unit is formed by cyclically arranged psammites and aleuropelites with coal seams up to 4.5 m thick. This is overlain by laminated claystones of the Mšec Member 10–30 m thick. Further up, the Hředle Member, locally as much as 160 m thick, is represented by two lithologically contrasting complexes: the lower part is dominated by siltstones up to 100 m thick, while the upper part is formed by alternating sandy siltstones and fine-grained sandstones with fusitized plant detritus up to 90 m thick (called "žíhance" in Czech, which means "streaks").

Seismic reflection measurements in the Mšeno-Roudnice Basin

Seismic reflection measurements were carried out in the SE part of the MRB during the years 1979–1981, within a campaign of geological investigations aimed at the coal distribution and geological setting of this basin (Žbánek et al. 1990). Field measurements were performed by the company Geofyzika Brno, n.p. Altogether 257 km of seismic profiles were measured (Fig. 1) using a vibrating energy source, and the common-midpoint (CMP) method with a six-fold stack. After digital processing, the results of the measurements were presented in the form of depth sections and maps inferred from these sections (Kadlečík et al. 1985, 1990). The quality of the acquired data was generally good, with the negative influence of the irregular relief locally encountered only in the northern part of the area studied.

The results provided information on the geological setting of the studied area, such as the thickness of Carboniferous sediments, their tectonic deformation, the courses of prominent physical and geologically significant boundaries (e.g., Carboniferous/Cretaceous boundary), and the course of the highly-reflective Jelenice Member. In addition, data on the internal structure of the Upper Carboniferous formations were collected. These also related to the problem of the contrasting dips of the strata and unconformities in some Upper Carboniferous units: the seismic measurements revealed segments up to 2 km long, with dips of Carboniferous strata locally reaching 20° or more (Kadlečík et al. 1985, 1990), overlain by subhorizontally deposited Upper Carboniferous clastics.

These prominent angular unconformities immediately attracted the attention of geologists. Some structural elements of this type were reflected in the map of the Slaný Formation base by Kadlečík et al. (1990). This map, however, combines the effects of many factors, which makes the determination of the course and the extent of the inclined structures very difficult. Geophysically indicated dips were confirmed by several boreholes (Bosák 1989, Bosák in Žbánek et al. 1990). They were partly interpreted as a result of irregular deposition of rock material in the Carboniferous continental basins, and partly as manifestations of subaquatic parts of lacustrine deltas (Bosák 1991).

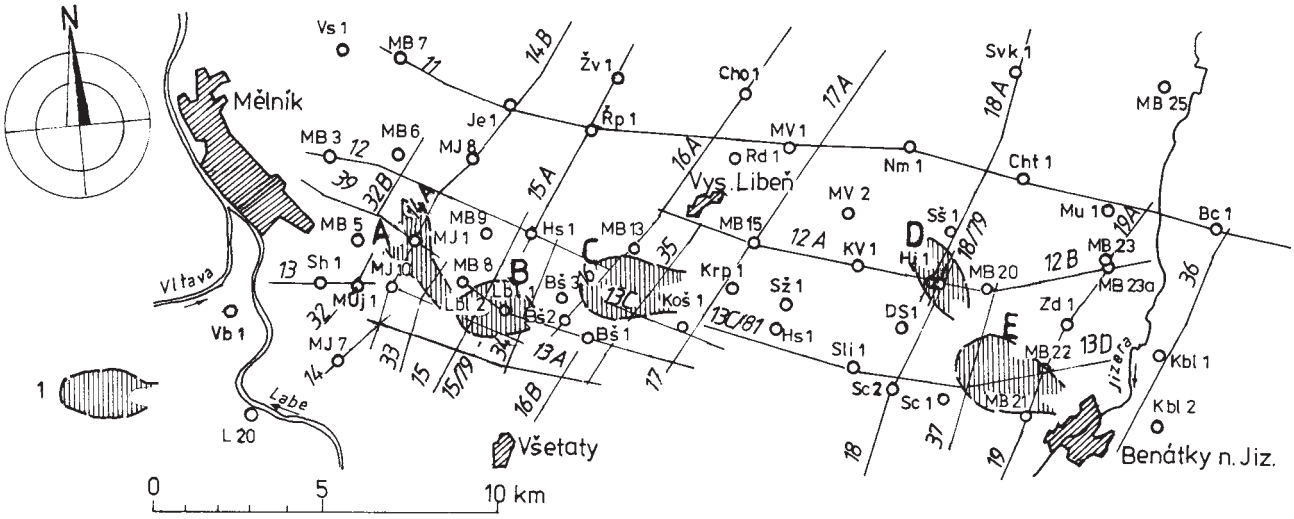

Figure 1. Locations of boreholes, seismic profiles, and areas with anomalous dips of strata in the SE part of the Mšeno-Roudnice Basin.
1. location of the fold-type structure.

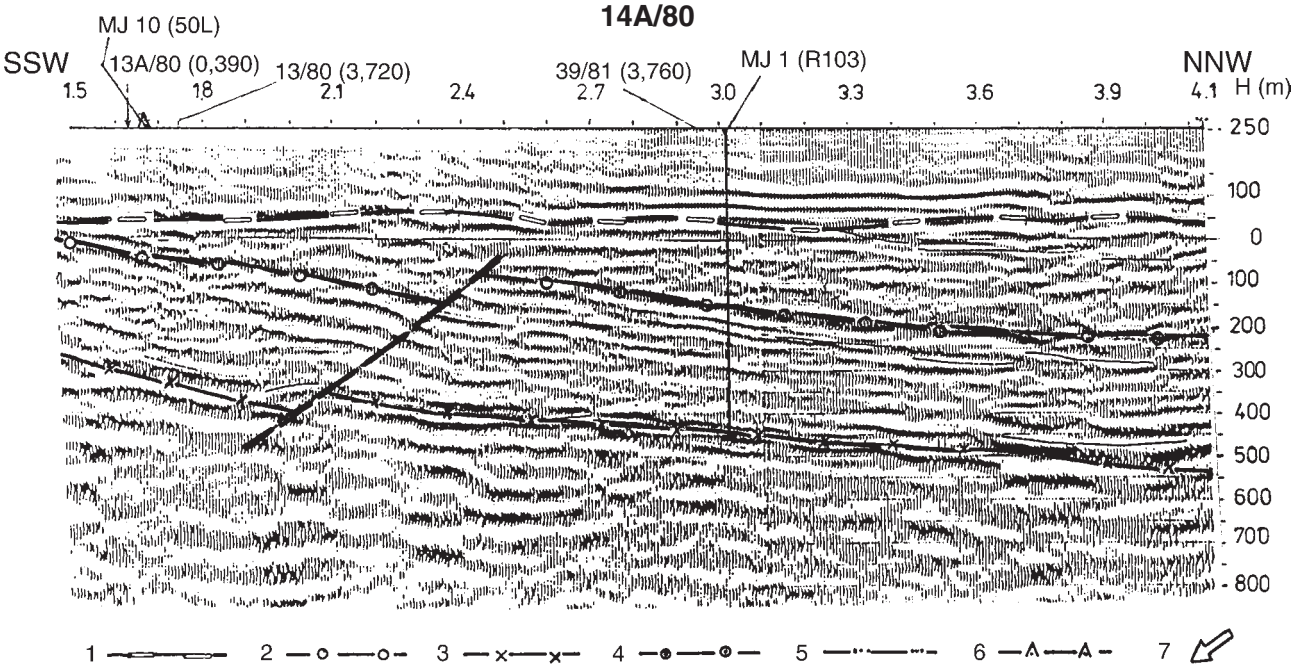

Figure 2. Structure A: depth-converted seismic section – profile 14A/80.
MJ-1 – designation of borehole, R – borehole to the right of the profile, L – borehole to the left of the profile.
1 – Cretaceous/Carboniferous boundary, 2 – top of the Jelenice Member of the Slaný Formation (reference level), 3 – base of the Carboniferous, 4 – alternative base boundary of the Carboniferous, 5 – top of the subsided block, 6 – Stephanian B/C boundary, 7 – reflections revealing the structure resemble a dejection cone of a river delta. Legend refers also to Figs 3–9.

Unconformities caused by the formation of uplift and subsidence zones

Based on the revision of seismic sections performed at the Faculty of Science of Charles University in Prague, the above conclusions are justifiable to some degree only. The dips found in boreholes have the character of the local bedding, but their validity is areally restricted. Inclined structures often exceeding 1 km in length, usually visible on several neighbouring seismic profiles, can instead be considered a result of movements giving rise to structures resembling monoclinal folds. The magnitude of subsidence locally exceeds 150 m. Subsidence affected Carboniferous rocks from their base up to a certain stratigraphic level corresponding to the formation time of the given structure. Above this level, sediments of younger strata are deposited unconformably – usually subhorizontally. Angular unconformities are visible in the lower part of the Líně Formation (Stephanian C) but also in the Hředle Member of the Slaný Formation (Stephanian B). The presence of this phenomenon in the Líně Formation has been pointed out by Skopec et al. (2003). The present contribution is focused on similar structures formed during the deposition of the Hředle Member sediments.

Unconformable sediment deposition in the Hředle Member of the Slaný Formation is indicated in its lower part. Anomalous dips of strata are mostly visible 40–60 m above the top of the Jelenice Member of the Slaný Formation. On the southern edge of the MRB, however, the traceability of these phenomena is limited by the pre-Cretaceous erosion of the Slaný Formation. Erosion of upper portions of the Slaný Formation, i.e. the absence of subhorizontal sediments of the upper part of the Hředle Member does not permit the unequivocal determination of the structure's age by the dips of the Jelenice Member and its footwall. The structure may be younger than the above mentioned age, generally of the pre-Cretaceous age.

The origin of subsidence structures was followed by the filling of the space above the subsided areas by subhorizontally deposited sediments, with occasional signs of erosion visible in the uppermost parts of the structures. In boreholes, the presence of these structures is manifested by reduced thicknesses of the lower part of the Hředle Member.

Brief description of fold-type structures in the Mšeno-Roudnice Basin associated with the Hředle Member

Altogether five structures were identified in the seismic reflection sections from the MRB (Fig. 1). Their origins undoubtedly coincide in time with the deposition of the lower part of the Hředle Member. For easier correlation of the time of the angular unconformity formation, the top of the Jelenice Member was designated as the reference level. This level is highly visible in the majority of seismic sections due to corresponding strong reflection.

Structure A lies ca 5 km ESE of Mělník, near the village of Mělnická Vrutice. It is visible on profiles 14A/80 and 33/81. The section of profile 14A (Fig. 2) shows unconformable surfaces between km 2.20–3.80, where a gradual dip of the Carboniferous strata towards NNE oc-

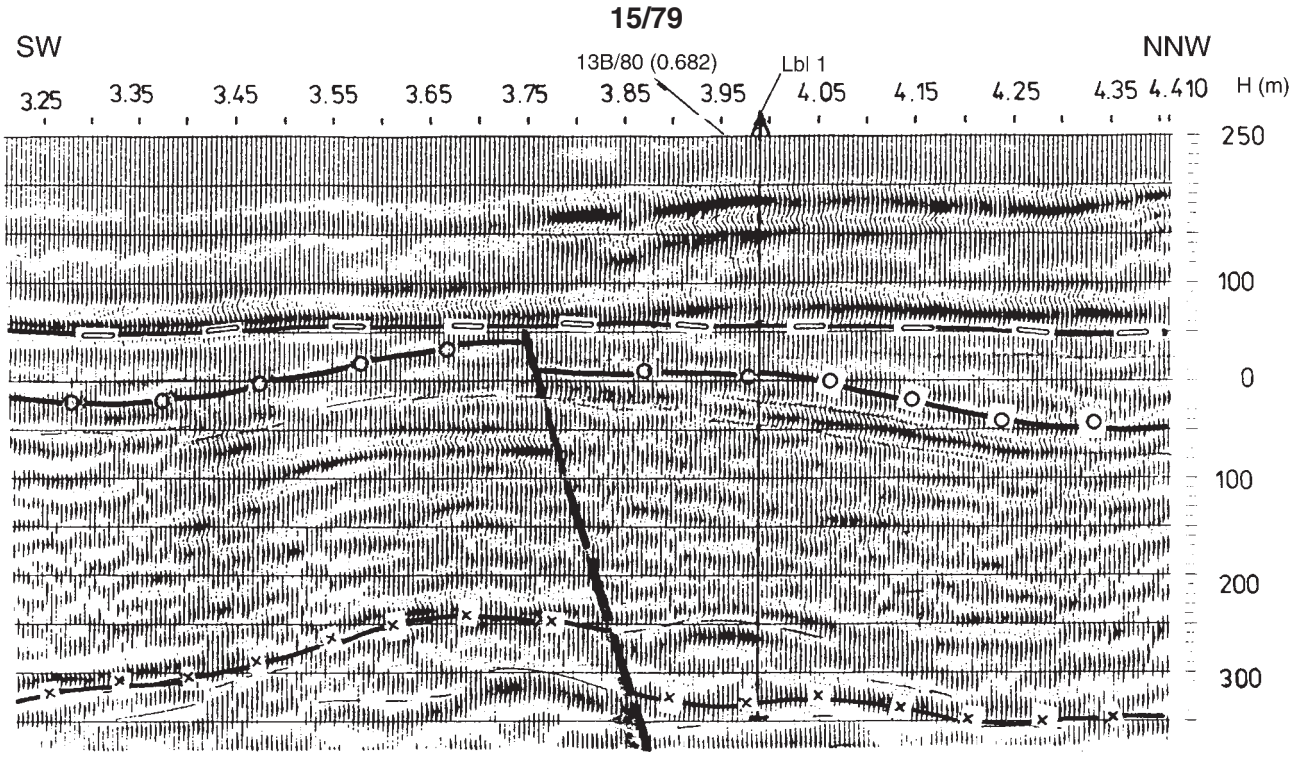

Figure 3. Structure B: depth-converted seismic section – profile 15/79. For explanations see Fig. 2.

curs from their base (Westphalian D) up to the lower part of the Hředle Member, ca 40 m above the reference level. The overall subsidence magnitude is about 120 m. On the neighbouring profile 33/81, the position of the unconformity is the same but the altitude difference is only 50 m. The thickness of the lower, finer-grained part of the Hředle Member of the Slaný Formation is reduced to 40 m in borehole MJ-1 (Jelenice), lying on profile 14A/80, while strong reduction by pre-Cretaceous erosion in borehole MJ-10 (Vavřineč), farther south, precludes the acquisition of additional data for a correlation.

Structure B lies to the ESE of structure A, about 3 km N of the Všetaty town. It is visible on sections of profiles 15/79 and 12A, 13B and 15A/80 as a subsidence of the NNW block by 70 m. The angular unconformity is clearly visible only on the section of profile 15/79 (Fig. 3), ca 40–50 m above the reference level. On other sections, the erosion of the Slaný Formation is so deep that only inclined strata below the base of the Hředle Member are preserved. The section in Fig. 3 also shows that the strata dip towards NNE between km 3.75 and 4.30, they dip towards SSW between km 3.70 and 3.25, again with the subsidence magnitude of ca 70 m. This structure is reminiscent of a flat anticline. Certain shift in the quality of material can be stated between results of experimental measurements of 1979 in comparison with results of following measurements of 1980.

Only a minor part of the Hředle Member is preserved in the vicinity of structure B, though a reduction of the lower part of the Hředle Member was observed in boreholes Lbl-2 (Liblice) and MB-8 (Liblice, lying between structures A and B), similar to that in borehole MJ-1.

Structure C was identified NE of Byšice. It is visible on sections of profiles 16/80 and 13A, and 35/81. This structure is strongly deformed by normal faults. On a section along profile 35/81 (Fig. 4), the conformable dip of the rocks of the Týnec and Slaný formations can be observed between km 2.6 and 4.0, 60 m towards NNE. An angular unconformity is visible 40–50 m above the reference level, but lies somewhat deeper in the apical part of the structure. Sediments deposited as alluvial fans, formed by filling the space above the subsided block, are visible between km 3.3 and 3.6 and in the vicinity of km 3.9 on the section. A section along the profile 16/80 (Fig. 5) documents that the structures formed during the deposition of the Hředle Member are not as simple as suggested by the previous examples. While dips to the N to NNE have been observed in these structures up to this point, Fig. 5 shows opposite dips of strata, i.e. towards the SSW, with a tectonically deformed subsiding area. The total subsidence reaches about 180 m. Various dips of strata – angular unconformity – are observed about 40 m above the reference level. On the transverse profile 13C/81, where this unconformity lies 50–60 m above the reference level, the WNW block has subsided by 80 m.

Structure C resembles a flat syncline with its axis oriented approximately WSW–ENE, apparently as a continuation of structure B (profile 15/79 between km 3.70–2.85), though their interconnection cannot be confirmed by the intermediately situated profile 34/81. In addition, the interval of profile 15/79 between km 2.85 and 3.25 is also characterized by the low dip angles of the Carboniferous/Cretaceous boundary, and therefore cannot be grouped within the described set of structures. Thicknesses of aleuropelites

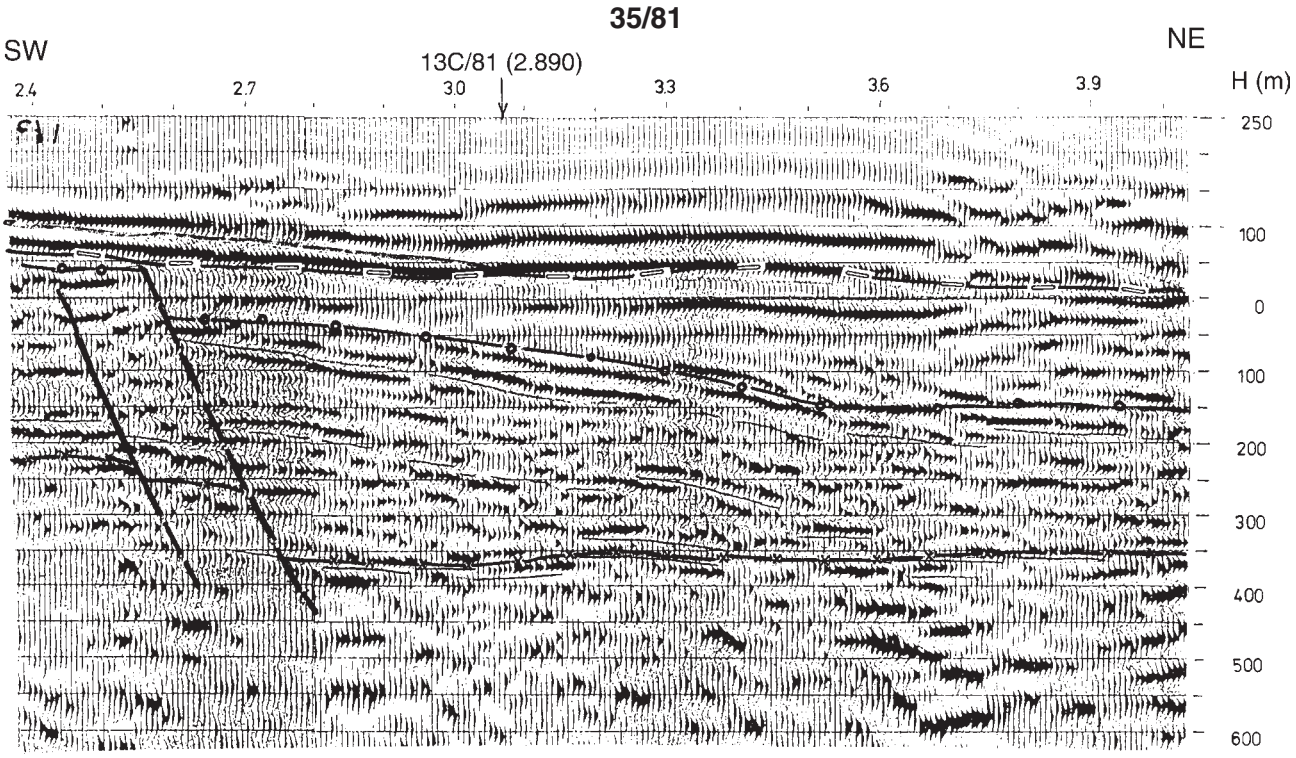

Figure 4. Structure C: depth-converted seismic section – profile 35/81. For explanations see Fig. 2.

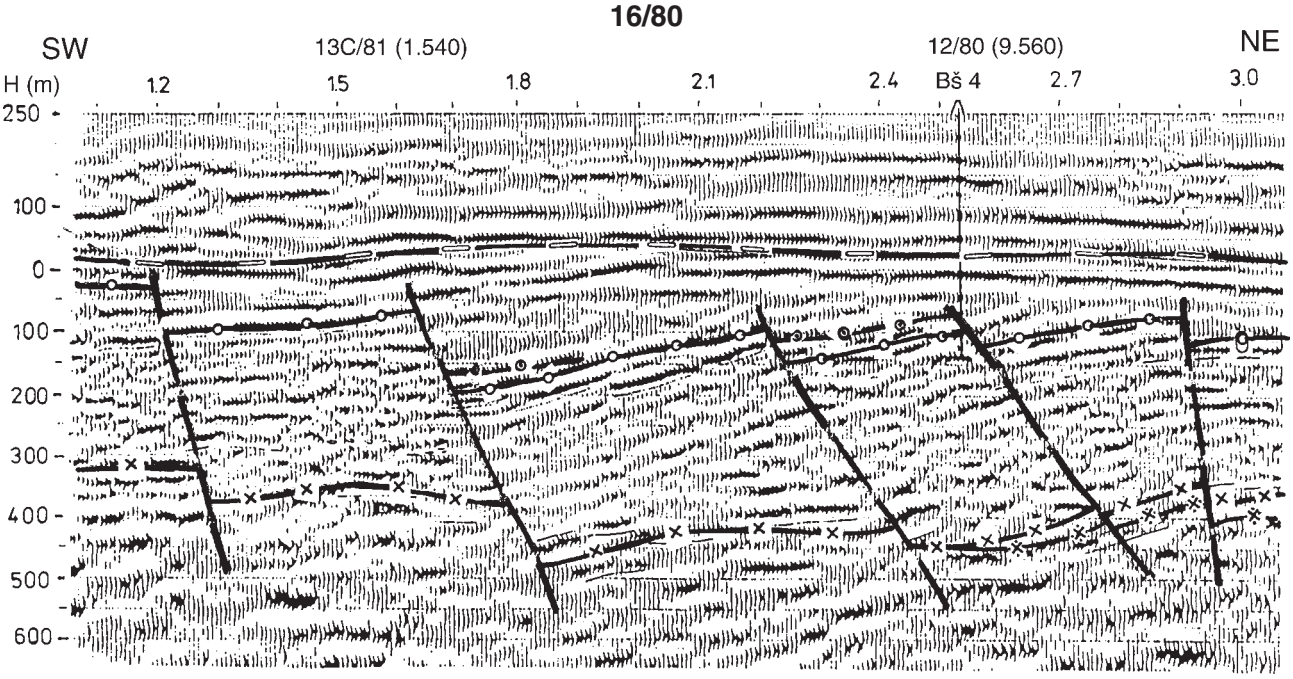

Figure 5. Structure C: depth-converted seismic section – profile 16/80. For explanations see Fig. 2.

in the lower part of the Hředle Member are reduced to a mere 3 m in borehole Bš-4 (Byšice) in the area of structure C. The borehole is, however, transected by a fault that also reduces the thickness of the Jelenice Member. In borehole Krp-1 (Krpy), the so-called streaks immediately overlie the Mšec Member (38 m above the reference level). In other boreholes in the area, the thickness of the Hředle Member is either strongly reduced (boreholes Sž-1 Stříž kovice and Bš-3 Byšice) or no sediments of this member have been preserved (borehole Koš-1 Košátky).

Structure D was identified in the three nearby, practically parallel profiles 18/79, 18/80, and 18A/80 near borehole Hi-1 (Hřivno), and on transverse profile 12A/80. A subsidence of strata by ca 130 m towards the NE and a difference in the dip of strata by ca 40 m above the reference level is clearly visible on the N end of profile 18/80. An an-

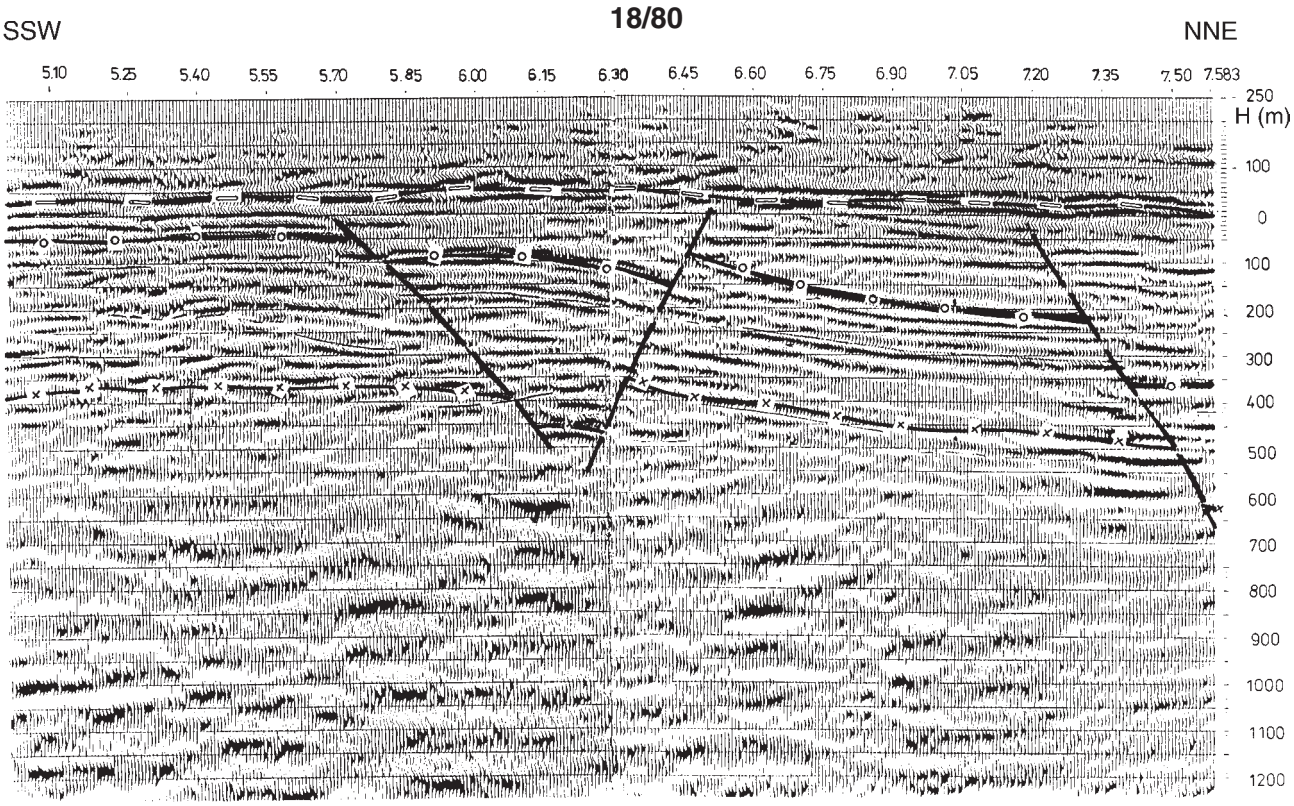

Figure 6. Structure D: depth-converted seismic section – profile 18/80. For explanations see Fig. 2.

gular unconformity is apparent from km 6.15 onwards. It then slightly diminishes and, from km 7.0 onwards, even the upper part of the Hředle Member tends to show a dip similar to that of its lower part and its footwall (Fig. 6). This can be most readily explained by local reactivation of movements after the deposition of the Slaný Formation. In addition, the effects of gradual filling of the depositional basin from the NE, i.e. towards the slope, are visible in the interval between km 6.5 and 6.9.

The above mentioned dip of strata is also traceable on the section of profile 18/79 (Fig. 7) that runs across borehole Hi-1. The neighboring section of profile 18A/80 revealed only the NW margin of the subsidence zone. The transverse profile 12A/80 shows the inclined deposits of the Týnec Formation and the base of the Slaný Formation towards the east by about 60 m. A different dip of strata is visible some 50 m above the reference level. Structure D thus generally has the character of a monoclinal fold dipping to the NE, with its amplitude increasing towards the ESE.

In the immediate hanging wall of the Mšec Member, sediments of the Hředle Member were encountered in the 110 m thick sandy development of its upper part in borehole Hi-1. Conversely, the thickness of the aleuropelite complex of the Hředle Member is reduced in the nearby borehole KV-1 (Kropáčova Vrutice).

Structure E is not as well documented as the preceding ones. It lies 1–2 km NW of Benátky nad Jizerou. Profile 19/80 clearly shows a locally inclined flexure of strata (Fig. 8), with a subsidence of ca 170 m between km 1.8 and km 3.3. The subsided block lies to the NNE. An angular unconformity is clearly visible 30–40 m above the reference level. Even here one can observe indications of the filling of the subsided zone towards the elevated area. The entire studied area has been deformed by faulting. Profile 37/81, however, shows only an indication of such a setting, with an unconformity at the same level but with a total subsidence of only 40 m. The transverse profile 13D/80 has a similar character. A subsidence of 50 m towards the NNE is manifested between km 1.05 and 1.65, with the unconformity lying ca 50 m above the reference level. The direction of structure E cannot be reliably determined, and its interconnection with structure D is merely hypothetical.

A structure found in the lower part of the Líně Formation on profile 14B/80 is shown in Fig. 9 for comparison. Within this structure, strata dip towards the NNE between the villages of Jenichov and Velký Újezd S of Mšeno (Skopec et al. 2003). The structure can probably be characterised as a subsidence of the SW block along a fault marked on the section. The SW margin of the block resembles the above described structures formed during the Slaný Formation deposition. In the present case, however, the angular unconformity developed only after the ca 200 m thick deposition of the Líně Formation sediments.

All of the structures presented here appear to be anomalous as sudden dips of certain parts of the Carboniferous strata over a limited distance, while subhorizontal strata are present over a vast majority of the area.

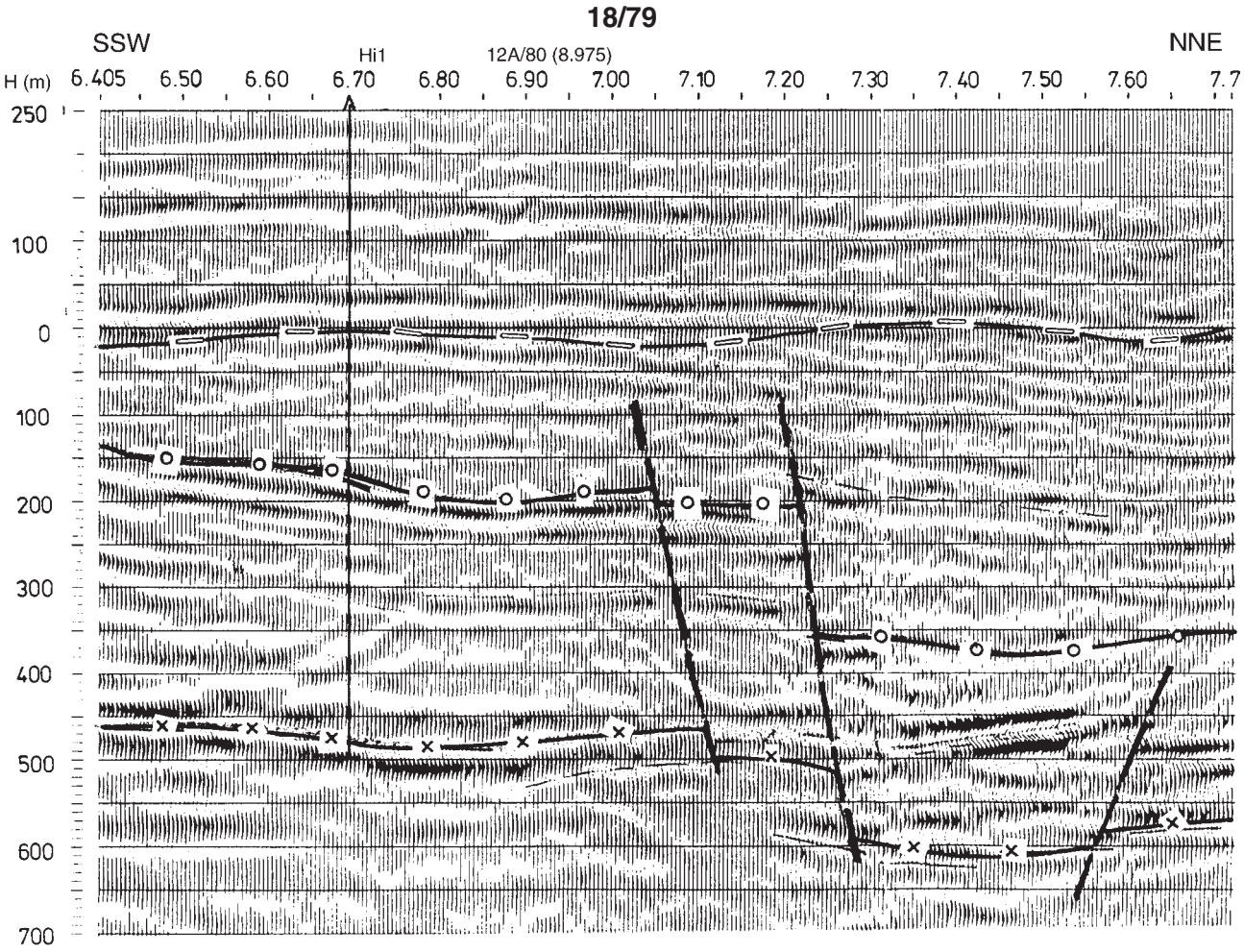

Figure 7. Structure D: depth-converted seismic section – profile 18/79. For explanations see Fig. 2.

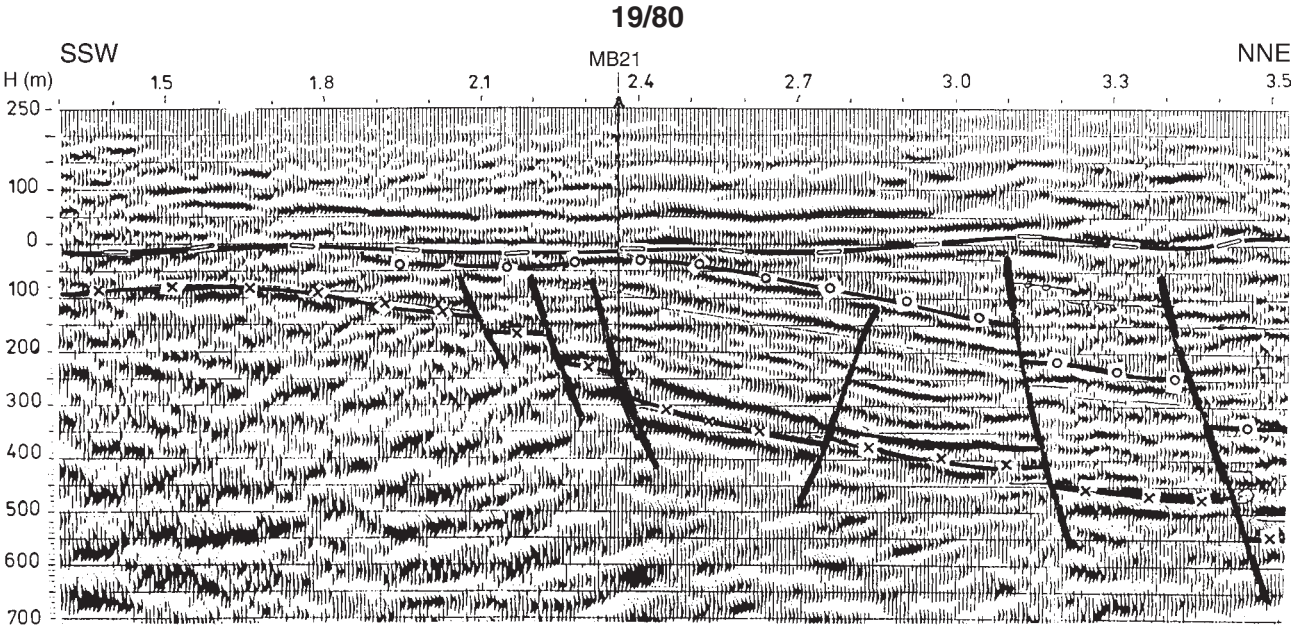

Figure 8. Structure E: depth-converted seismic section – profile 19/80. For explanations see Fig. 2.

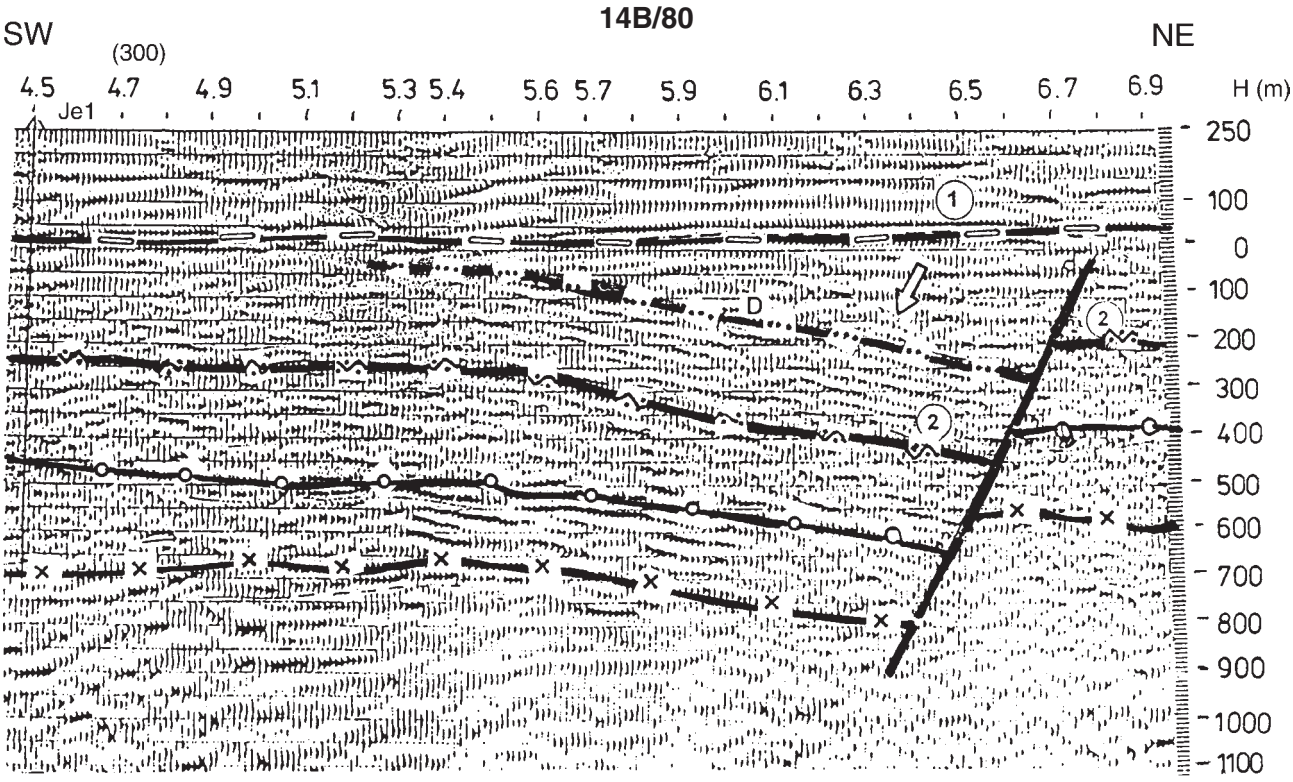

Figure 9. Depth-converted seismic section – profile 14B/80. Area originated after the deposition of the 200 m thick Stephanian C sequence (Líně Formation). For explanations see Fig. 2.

Conclusions

The study of depth-converted seismic reflection sections from the SE part of the MRB revealed a zone ca 20 km long and ca 3 km wide between Mělník and Benátky nad Jizerou towns, with occurrences of structures resembling flat monoclinal folds. As indicated by the different dips of strata on seismic sections, their formation coincides in time with the deposition of the lower part of the Hředle Member. This is manifested by reduction in the thickness of sediments in this part of the Slaný Formation in several boreholes. Five sites where these structures are present were identified but their interconnection across the length of the entire zone is not supported by the seismic data. This zone may represent the westernmost extension of folds known from the Sudetic Permo-Carboniferous basins. No structures of this type have yet been reported from other Central and Western Bohemian basins.

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