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A deep palaeovalley in the floor of Polish Carpathian Foredeep Basin near Pilzno and its control on Badenian (Middle Miocene) evaporite facies

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The Pogórska Wola palaeovalley of combined tectonic and erosional origin dissects the Mesozoic floor of the Carpathian Foredeep Basin to a depth exceeding 1200 m. It formed during Paleogene times presumably due to fluvial and submarine erosion, concentrated along a local pre-Late Badenian graben system. All members of the foredeep's Badenian-Sarmatian sedimentary fill attain distinctly greater values inside the palaeovalley than on top of elevated plateaux on palaeovalley shoulders. The fill comprises the Early to Late Badenian sub-evaporite Skawina Formation, the laterally equivalent Late Badenian evaporite Krzyżanowice and Wieliczka formations and the supra-evaporite Late Badenian to Early Sarmatian Machów Formation. Over the plateaux and in the highest palaeovalley segment, the evaporites are developed in the sulphate facies Krzyżanowice Formation, whereas in the lower palaeovalley segments chloride-sulphate facies evaporites of the Wieliczka Formation occur. The rock salt-bearing rocks are involved in thrusting and folding at the Carpathian orogenic front, which helps to assess the lateral extent of the Wieliczka Formation in seismic records. The deep palaeotopographic position of the evaporites inside the palaeovalley, combined with their lithological and sedimentary features, point to their formation via subaqueous gravity flow-driven redeposition of originally shallow-water evaporites, preferentially halite-bearing, presumably combined with precipitation from sulphate and chloride brines at the palaeovalley floor. Both the redeposited sediments and the brines must have come from the adjacent plateaux and from a thrust-sheet top basin, approaching from the south on top of the Cretaceous-Paleogene Carpathian flysch thrust wedge.

Key words: Carpathian Foredeep, reflection seismics, deep-water evaporites, Badenian salinity crisis, Paratethys, Cenozoic.

INTRODUCTION

The Middle Miocene, Late Badenian, evaporites of the Carpathian Foredeep Basin have been for decades a subject of discussion, concerning aspects such as the conditions of their deposition in the Paratethys (e.g., Garlicki, 1968, 1979; Kolasa and Ślączka, 1985; Bukowski, 1994, 2011; Peryt, 2006) and the nature of tectonic deformation they underwent at the Carpathian orogenic front (e.g., Połtowicz, 1974, 1997, 2004; Tarka et al.,1988; Tarka, 1992; Jones, 1997; Krzywiec et al., 2004, 2012, 2014; Głuszyński, 2014; Głuszyński and Aleksandrowski, 2014, 2015). Here, we aim to illustrate and explain the occurrence of the fore-Carpathian evaporites at strongly varied palaeobathymetric positions in the foreland basin, using a case study from the vicinities of Pilzno (Fig. 1), where the PGNiG S.A. (Polish Oil and Gas Company) have completed two high-resolution 3D seismic projects in the transition zone between the foreland basin and the Carpathian orogenic wedge. Analysis and interpretation of seismic and borehole data enabled us to recognize, in some detail, the basin floor palaeotopography and the 3D geometry of the Carpathian orogenic front, the latter significantly affected by mechanical properties of the rock salt contained in one of the evaporite facies. Based on these results, we discuss the influence that the local dramatic morphology of the basin floor, itself partly controlled by structural features of its Mesozoic bedrock, must have exerted on the deposition of the evaporites occupying the lower part of the basin-fill. Although the dependence of the evaporite facies on their palaeotopographic position and the role of palaeovalleys in the Carpathian Foredeep sedimentation have been already widely discussed at the basin scale (e.g., Garlicki, 1979; Bukowski, 2011), our contribution consists in delivering a case study that shows these problems at a relatively detailed scale. Moreover, since the origin of the fore- and sub-Carpathian palaeovalleys and the mode(s) of saline sedimentation in the Carpathian Foredeep are still far from being fully understood, we also briefly discuss these questions in the context of the research results of other authors. Central to our interpretation of evaporite facies differentiation and distribution are processes of evaporite redeposition. These are well-known from various sedimentary basins worldwide (e.g., Schreiber et al., 1976; Schlager and Bolz, 1977; Sellwood and Netherwood, 1984; Peryt et al., 1993; Manzi et al., 2005), including also the Carpathian Foredeep Basin (e.g., Kolasa and Ślączka, 1985;

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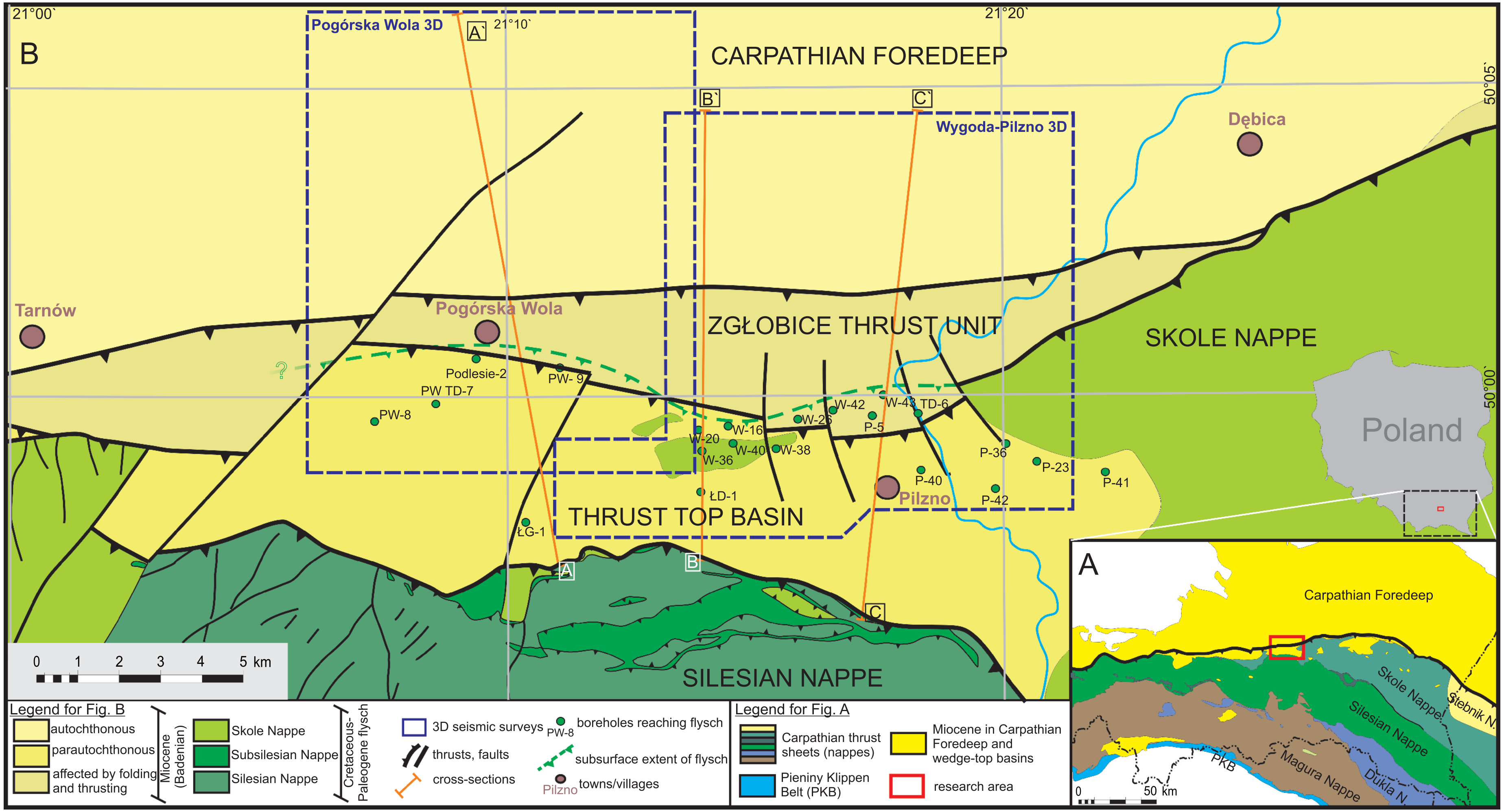

Fig. 1. Tectonic setting (A) and geological map (B) of the study area (within the boundaries of the 3D seismic surveys) simplified from Jasionowicz and Kuciński (1965a, b) Żytko et al. (1989), Boratyn and Brud (1996), Brud (1999) and Marciniec and Zimnal (2009a, b)

Peryt and Kasprzyk, 1992; Bukowski, 1994, 1997; Peryt and Kovalevich, 1997; Ślączka and Kolasa, 1997; Kasprzyk and Ortí, 1998; Peryt et al., 1998; Połtowicz, 1999; Peryt, 2000, 2013; Cendón et al., 2004; Hnylko, 2014). At the same time, however, these processes are an object of ongoing discussion and controversy. We hope to advance the debate with our contribution, in outlining a case study of a deep, structurally controlled palaeovalley that strongly influenced the pattern of evaporite deposition.

GEOLOGICAL SETTING

The area of our study is located in south-east Poland, between the town of Pilzno and village of Pogórska Wola, ca. 5 to 25 km east of Tarnów (Fig. 1), at the orographic and tectonic front of the northern Carpathians.

STRUCTURE AND STRATIGRAPHY

Three major tectonic units occur in the study area (Książkiewicz, 1974; Połtowicz, 1974; Boratyn and Brud, 1996; Brud, 1999; Marciniec and Zimnal, 2009a, b). The Outer Carpathian fold-and-thrust belt (1) is located in the south and east and is composed mainly of deep-water siliciclastic turbidites (the Carpathian flysch) of Cretaceous to Paleogene age, tectonised in Miocene times and represented by a stack of the major Skole, Silesian and Sub-Silesian thrust sheets (nappes), at the frontal part of the Carpathian orogenic wedge. To the north it adjoins the Carpathian foreland (foredeep) basin (2), formed during the Miocene due to lithospheric flexure in front of an advancing orogenic wedge (e.g., Oszczypko, 1997, 1998; Krzywiec, 1997, 2001; Oszczypko et al., 2006). The Miocene fill of the foreland basin comprises Badenian–Sarmatian (Middle Miocene) siliciclastic strata with an important lowermost Upper Badenian evaporite unit near to the base of the succession (see e.g., Oszczypko et al., 2006; Peryt, 2006; Bukowski, 2011, for details and references). The Miocene strata are essentially undeformed over most of the basin; however, to the south, they become affected by folding and thrusting in front of the Skole frontal thrust, thus being included in the Outer Carpathian fold-and-thrust belt as its marginal Zgłobice fold-thrust unit (Połtowicz, 1974, 1991; Kotlarczyk, 1985). Both the Outer Carpathian fold-thrust belt and the Carpathian foreland basin are underlain by Permo-Mesozoic strata (3), representing a slightly deformed sedimentary cover of the West European Paleozoic Platform of Variscan and Caledonian basement consolidation ("epi-Variscan platform"), that extends far to the north and north-west (e.g., Oberc and Pożaryski, 1977; Khain, 1977; Ziegler, 1990; Jarosiński et al., 2009).

Studies on the Badenian sedimentary fill of the Carpathian Foredeep Basin date back to the 19th century (see Oszczypko et al., 2006 and references therein). According to the stratigraphic subdivision of Alexandrowicz et al. (1982), the Badenian succession of the study area, from base to top (Fig. 2), comprises:

– the siliciclastic Skawina Formation,
– the laterally equivalent evaporite Wieliczka and Krzyżanowice formations,
– the topmost and thickest, siliciclastic Machów Formation.

The Skawina Formation is composed of shallow to deeper marine, partly turbiditic, conglomerates, sandstones and claystones. The overlying Wieliczka Formation is formed of rock salt with intercalations of anhydrite, gypsum and siliciclastic deposits (claystones, mudstones), whereas its lateral equivalent Krzyżanowice Formation (sulphate facies) consists of gypsum and anhydrite, intercalated with mudstones and claystones. The topmost and thickest Machów Formation comprises mudstones, sandstones, claystones and conglomerates, mostly of turbiditic and deltaic to lagoonal origin (e.g., Piwocki et al., 1996; Aleksandrowski et al., 1996; Porębski, 1999; Aleksandrowski and Mastalerz, 2000; Oszczypko et al., 2006; Lis and Wysocka, 2012).

The contact of the Outer Carpathian fold-and-thrust belt with its foreland basin is structurally complex with the geometry changing along strike (Połtowicz, 1974, 2004; Sieniawska and Aleksandrowski, 2008; Głuszyński and Aleksandrowski, 2014; Krzywiec et al., 2014; Głuszyński, 2014). Near Pogórska Wola, stacked tectonic slices of the Skole thrust sheet constitute a tectonic wedge that splits the Middle Miocene rock-salt bearing evaporite succession into two packages (Fig. 3). A result of the Badenian and Sarmatian wedge tectonics (cf. e.g., Banks and Warburton, 1986; McKay et al., 1996; Krzywiec and Aleksandrowski, 2004) at the front of the Skole thrust sheet are folding and thrusting phenomena, including major backthrusts and triangle zones, that affect the southern margin of the foredeep Miocene strata.

BASIN FLOOR TOPOGRAPHY AND EVAPORITES IN DEEP PALAEOVALLEYS

The floor of the Carpathian foreland basin near Pilzno is an erosional surface partly following the top of and partly deeply dissecting flat-lying Cretaceous and Jurassic strata of the basin's basement (Figs. 4–6). The latter is transected with NW–SE and NE–SW trending faults (Oszczypko et al., 1989; Moryc, 1996) and contains a system of erosional troughs, in the Carpathian Foredeep referred to as palaeovalleys (Jucha, 1974; Nowotarski and Gara, 1985; Krzywiec, 1997, 2001; Połtowicz, 1998, 1999; Karnkowski and Ozimkowski, 2001; Krzywiec et al., 2004; Oszczypko et al., 2006). In the study area this system of troughs, composed of the merging Żukowice-Wygoda (Karnkowski, 1989) and Jaśniny palaeovalleys (Połtowicz, 1998; Bukowski, 2011) is represented by the prominent, southerly widening and deepening palaeovalley of Pogórska Wola that cuts several hundred metres down into the basin's Mesozoic basement (Figs. 4–6). Połtowicz (1999) described the presence of Miocene evaporites from this palaeovalley and interpreted them as olistoliths mobilised by mid-Badenian erosion of shallow parts of the palaeovalley and its surroundings and redeposited into deeper locations. At the same time, Karnkowski and Ozimkowski (2001) expressed the opinion that the Miocene sedimentary fill of the Pogórska Wola palaeovalley contains no evaporites, which was considered by them as typical of the fore-Carpathian palaeovalleys. The alleged absence of evaporites from the palaeovalleys' sedimentary fill was explained by these authors as due to the considerable depths of the erosional troughs, which must have hampered chemical deposition. Other authors, however, on the basis of borehole and seismic data, expressed quite different opinions. For example, according to Krzywiec et al. (2008), the seismic record suggests the probable presence of evaporites inside deep palaeovalleys incised into the so-called Rzeszów island, an area otherwise devoid of such deposits, believed by some authors as due to postdepositional erosion (Komorowska-Błaszczyńska, 1965; Oszczypko et al., 2006; but see Krzywiec et al., 2008 for a different opinion). In particular, Bukowski (2011) maintained that the chloride facies deposits in the Carpathian Foredeep must have formed in the originally deepest, southern part of the basin, including palaeovalley floors, such as that of Pogórska Wola, whereas in the shallower areas to the north, the sulphate evaporites originated.

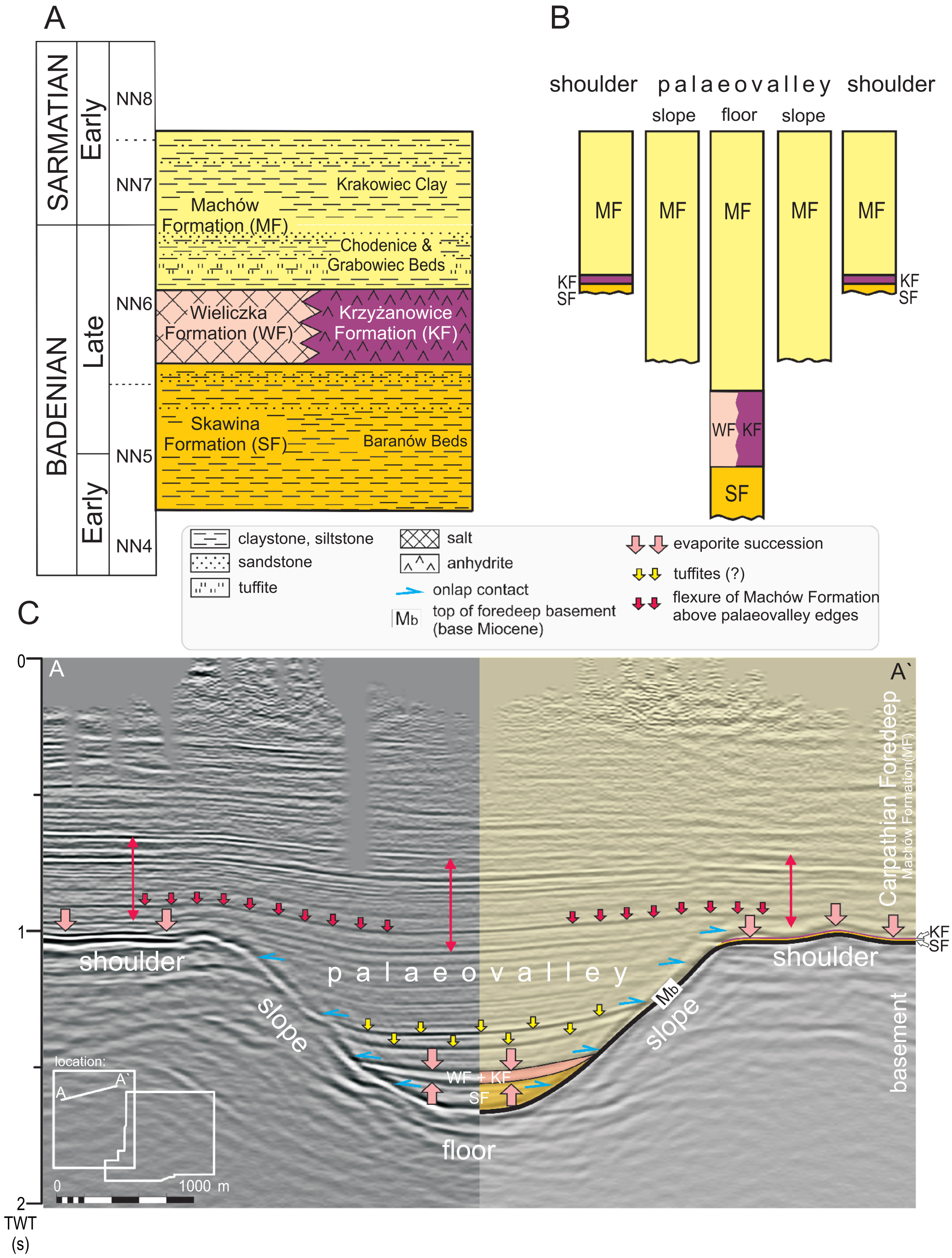

Fig. 2. Stratigraphy of the Miocene deposits in the Carpathian Foredeep near to Pilzno (A) and its variations at different palaeotopographic positions in the Pogórska Wola palaeovalley (B) shown on a seismic section transverse to the palaeovalley axis (C)

DATA AND METHODS

Time-migrated seismic data from two 3D surveys of PGNiG S.A. were used for the analysis: “Wygoda-Pilzno 3D”, carried out in the year 2000, and reprocessed and depth converted in 2007, and “Pogórska Wola 3D” of 1994. Our structural interpretation of the 3D seismic data concerned the sedimentary fill of the Carpathian Foredeep, north of the Carpathian flysch thrust front. Its results were integrated with those of several 2D seismic sections extending farther south, over the Carpathian flysch thrust sheets, and of a study of ca. 150 borehole profiles (containing data from mud logs, boreholes and, infrequently, borehole geophysics). The interpretation and integration of geological and geophysical data were performed using the petroleum industry-oriented software *Petrel* (TMSchlumberger). Our analysis made use of the capabilities of the software to handle 3D data in order to create seismic sections in any orientation, including horizontal time-slice maps. It was aided, too, by using seismic attributes available in the software.

RESULTS

Our structural interpretation resulted in detailed recognition of the top surface of the Carpathian Foredeep Mesozoic sub-

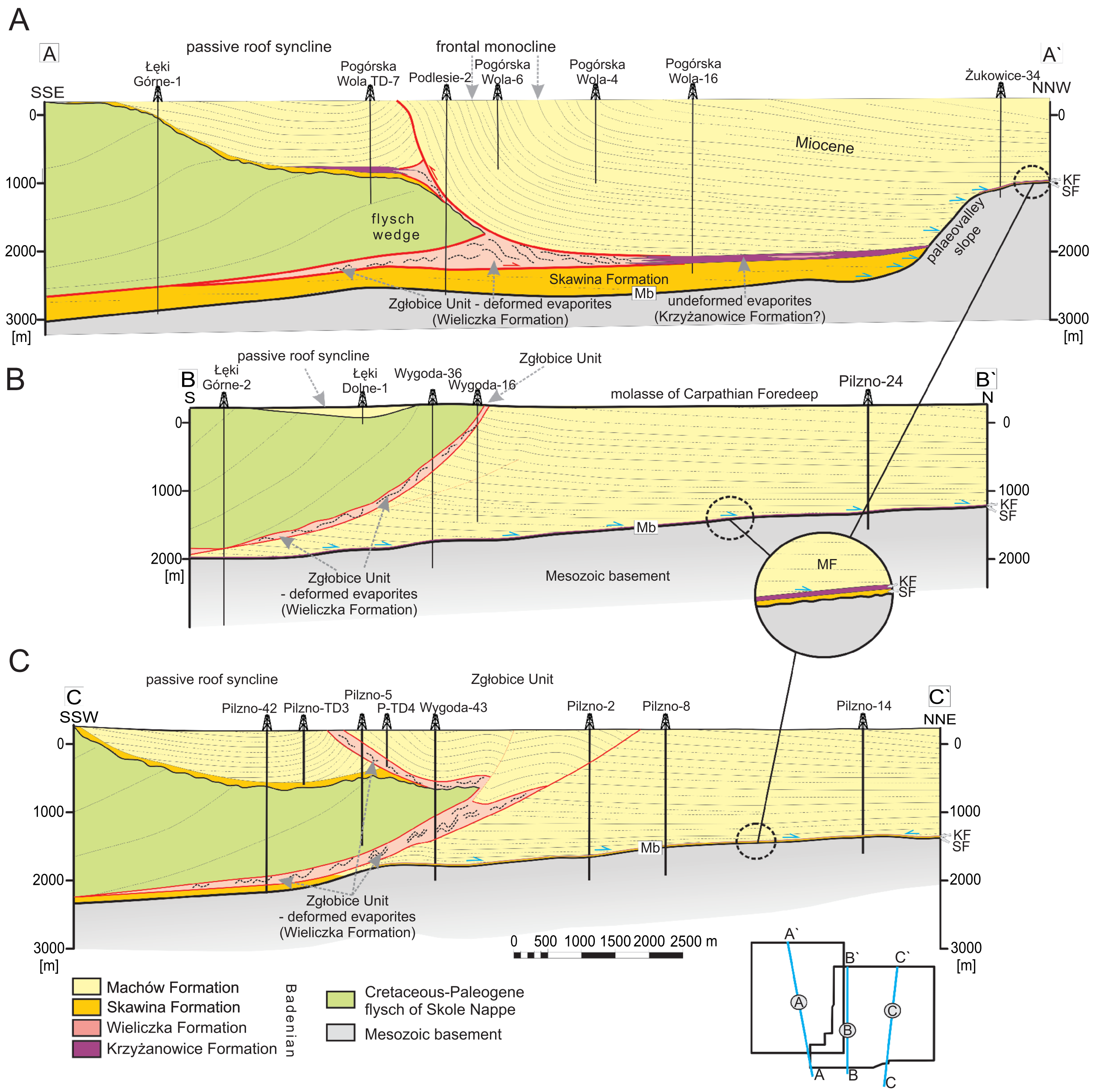

Fig. 3. Geological cross-sections showing along-strike changing wedge structure of the Carpathian orogenic front along the axis of the Pogórska Wola palaeovalley (location respective to the 3D seismic survey boundaries shown in inset below and in Fig. 1)

The evaporite succession is split, tectonically thickened and deformed in front of the flysch Skole Nappe; for other explanations see Figure 2

Our structural interpretation resulted in detailed recognition of the top surface of the Carpathian Foredeep Mesozoic substrate between Pilzno and Pogórska Wola. The palaeotopography of the Pogórska Wola palaeovalley and of its high-standing, uneroded flanks (shoulders; below also referred to as plateaux) was studied. The seismic data, locally complemented with archival borehole information on the lithology and stratigraphy, made it possible to trace several lithostratigraphic horizons within the Middle Miocene fill of the foredeep, and in its Mesozoic basement, and, thus, to recognize the basement faults and to understand the 3D geometry of the Carpathian front at its transition to the foreland basin, which will be discussed in detail in separate publications.

FLOOR OF THE FOREDEEP

As revealed by the 3D seismic data studied, the erosional top of the Mesozoic succession, defining the foredeep basin floor, is morphologically highly diverse. The western part of the area is dominated by the Pogórska Wola palaeovalley of south-easterly to southerly plunging axis. It cuts across the Creta-

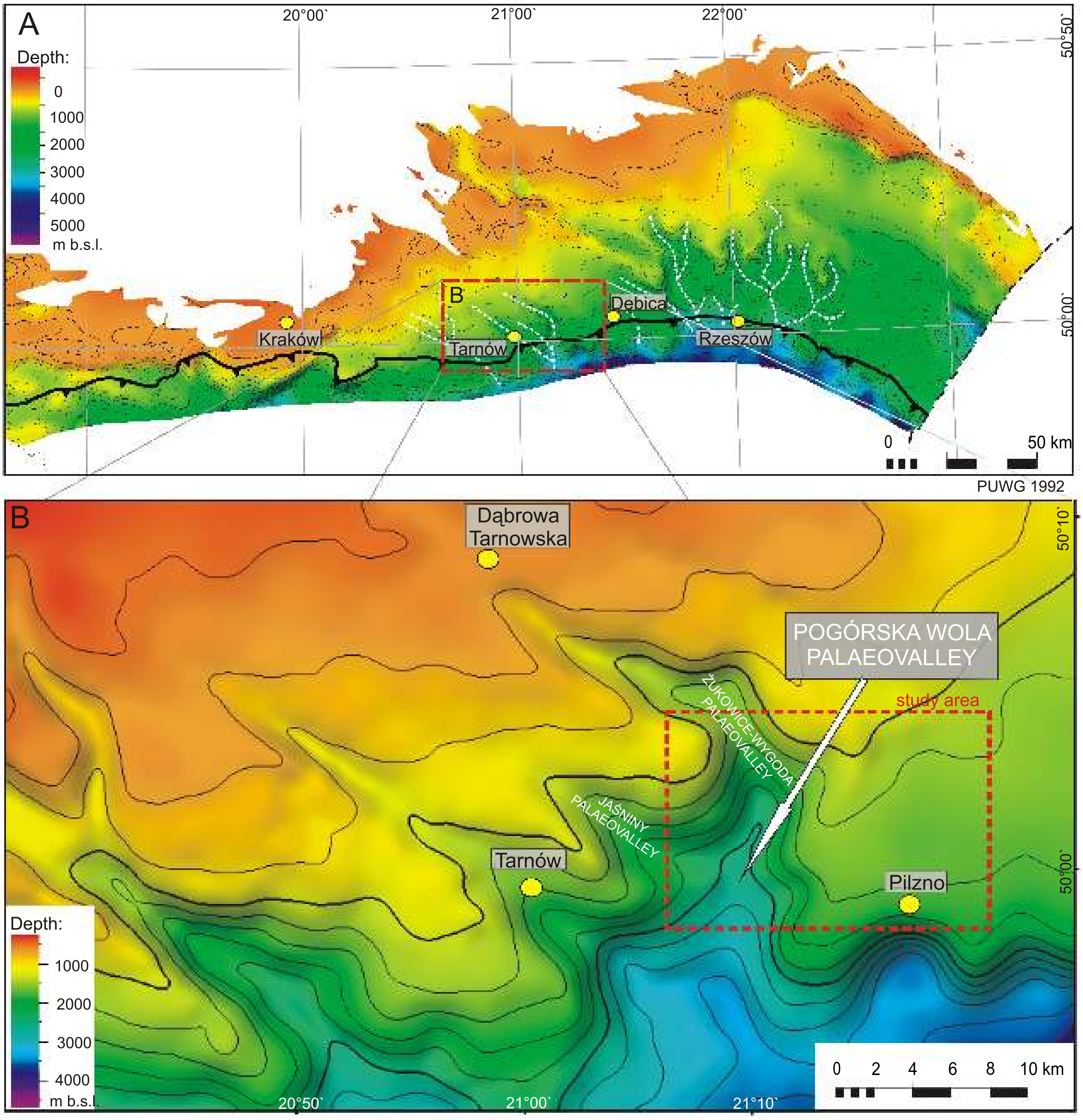

Fig. 4. Basement top surface morphology of the Carpathian Foredeep Basin (A) and around the Pogórska Wola palaeovalley (B); based on Nowotarski and Gara (1985) and Górecki et al. (2012)

sional top of the Jurassic has been reached at 2609 m b.s.l. in the Podlesie-2 borehole (the only borehole that has reached the Mesozoic in the axial part of the palaeovalley) and at 1051 m b.s.l. in the Żukowice-34 borehole (located on the most elevated fragment of the foredeep floor on a palaeovalley shoulder). This amounts to 1558 m of elevation difference (Fig. 5).

In its northern segment, the NW–SE trending palaeovalley is relatively narrow (ca. 3400 m in width) and cuts ca. 1200 m deep into the Mesozoic basement. To the south, its trend changes to that of NNE–SSW, and its width considerably increases. Ultimately, at the southern limit of the study area, the palaeovalley attains a width >8 km and cuts into the (slightly southerly inclined) Mesozoic substrate by ca. 750 m (Figs. 5 and 6). The palaeovalley edges are dog-leg shaped in map view, whereas in cross-section the palaeovalley is V-shaped in the north, with its profile gradually becoming more gentle and open to the south (Fig. 5).

In the eastern part of the area, near Pilzno, the erosion has only slightly affected the Mesozoic basement, except for its southern extremity (Fig. 5). The top Mesozoic surface is at a much higher position than the palaeovalley floor and defines a plateau, inclined slightly southwards to southeastwards. At the south, mostly outside the map area of Figure 5, the wide erosional depression of Pilzno extends (Fig. 5), from which the Cretaceous strata were removed prior to the Late Badenian. The latter depression and the Pogórska Wola palaeovalley are separated by a flat-topped ridge south of Łęki Dolne, which continues far to the south, beyond the area of study (Fig. 5). In the

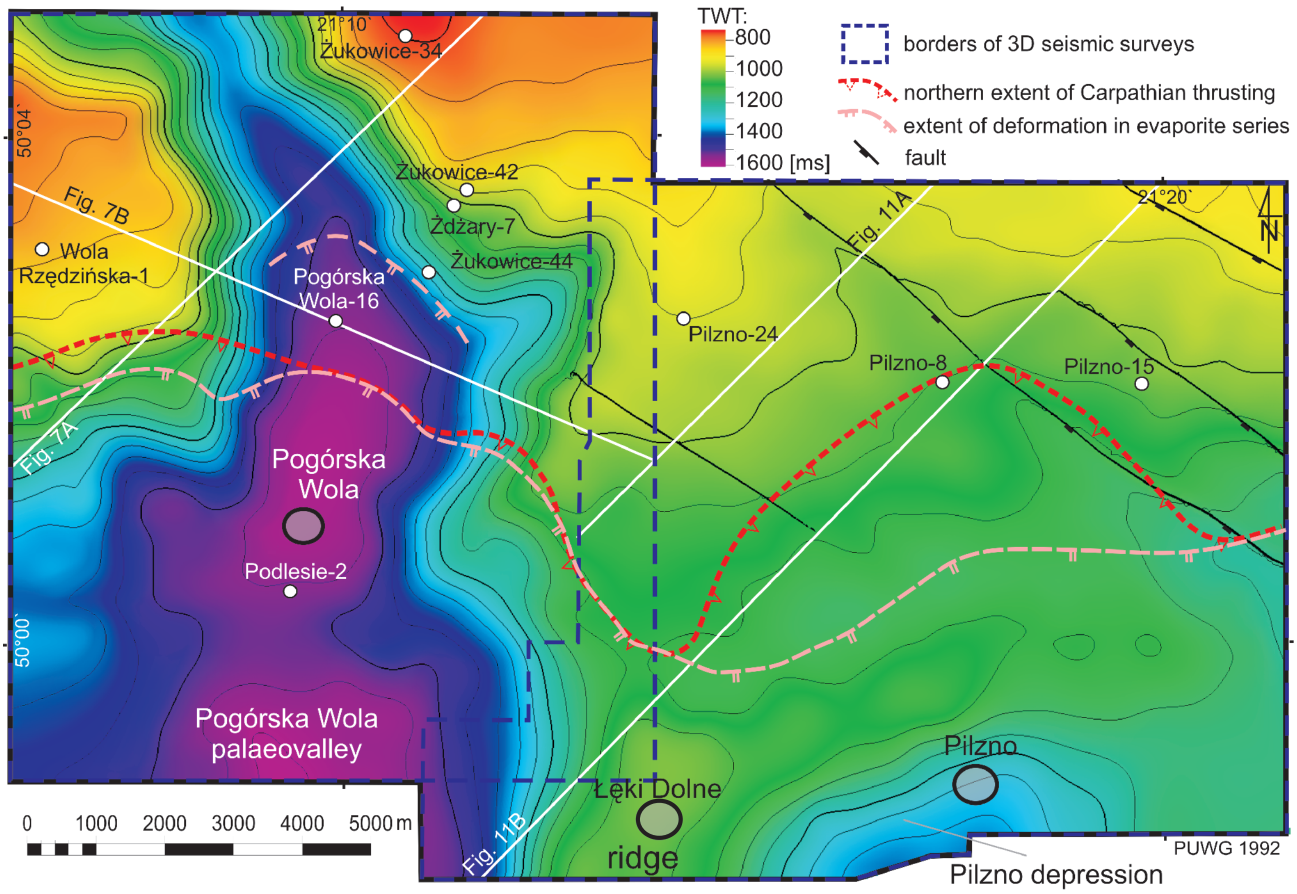

Fig. 5. Time structure map of the Carpathian Foredeep basement top surface near Pilzno based on structural interpretation of 3D seismic data and location of boreholes referred to in the text

Cretaceous strata were removed prior to the Late Badenian. The latter depression and the Pogórska Wola palaeovalley are separated by a flat-topped ridge south of Łęki Dolne, which continues far to the south, beyond the area of study (Fig. 5). In the northeastern part of the area, the top Mesozoic surface shows gentle wavy morphology, presumably in part due to displacements on NW–SE faults, which collectively have an effect of stepwise lowering of this surface towards the south-west.

FAULTING IN THE MESOZOIC BASEMENT AND ITS CONTROL ON THE BASIN FLOOR TOPOGRAPHY

In the western part of the study area, around the Pogórska Wola palaeovalley, two high-angle fault sets of NW–SE and NE–SW trends, cutting the Cretaceous-Jurassic basement, were interpreted from seismic profiles and time-slice maps, using amplitude and variance seismic attributes (Figs. 6–10). As a rule, the displacements on the faults do not continue from the Mesozoic basement up into the Miocene strata (Figs. 7 and 8), which constrains the upper age limit for the fault activity and shows that the Badenian-Sarmatian sedimentation in the study area was, in general, not influenced by fault-block activity of the basement.

The NW–SE and NE–SW trends are mimicked by rectilinear edges of the Pogórska Wola palaeovalley (Figs. 5 and 6). On seismic profiles running across the NW–SE and NE–SW fault zones, steep structural discontinuities are visible along the palaeovalley edges (fault zones F4 to F6 and F7 to F9 in Figs. 9D and 10). The faults throw the Jurassic strata much in accordance with the palaeovalley profile shape (Figs. 7 and 9), implying that the palaeovalley developed in a tectonic graben system, modified by pre-Late Badenian erosion along mechanically weak fault-related fracture zones in the Mesozoic basement.

The NW–SE fault zones are composed of clusters of reverse faults (labelled F4 and F6 in Figs. 8 and 9), which, as shown by their geometry, likely represent positive flower structures related to a pre-Late Badenian (pre-Miocene? possibly end Cretaceous?) strike-slip component of motion.

In the eastern part of the area, the seismics has recorded mainly faults of one system, of NW–SE trend. They are well-represented on seismic sections running NE–SW and on seismic depth-slices (seismic maps showing horizontal intersection planes at a given depth level; Figs. 11 and 12). Those faults are mostly normal, with the major ones (F1 to F3) having their SW sides downthrown. They are accompanied by lower-order antithetic or synthetic faults (Figs. 11 and 12) with displacements at the limit of seismic resolution. Their interpretation was facilitated by using seismic attribute analysis (Fig. 12).

Since the Miocene strata in the Carpathian Foredeep Basin near Pilzno are not or little affected by activity of the basement faults, the relief of the top Mesozoic erosional surface must have already been mostly finished (i.e. in its present-day shape) and highly varied during Late Badenian times. On the other hand, the earlier, pre-mid Badenian erosional incision into the Mesozoic bedrock that produced the Pogórska Wola palaeovalley, was presumably partly coeval with the fault activity. The incision pattern, represented by the Pogórska Wola palaeovalley polygonal edges, clearly mimics that defined by fault traces exposed on the Mesozoic top surface (Figs. 5 and 6),

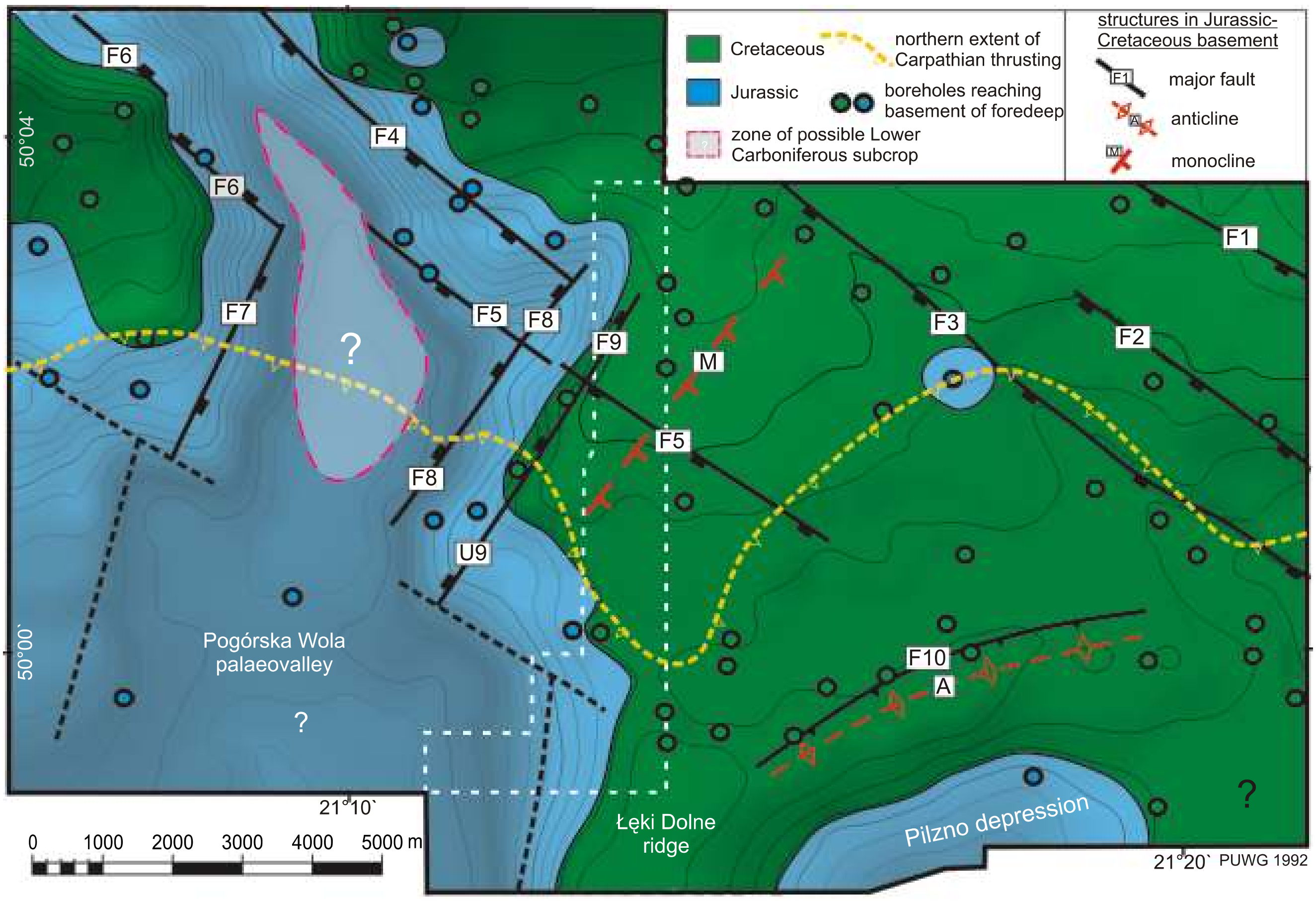

Fig. 6. Geological subcrop map of the Carpathian Foredeep basement top surface near Pilzno based on borehole data, shown on the background of a seismic time structural map

The Cretaceous has been eroded in the Pogórska Wola palaeovalley and Pilzno depression

FACIES, PALAEOTOPOGRAPHIC POSITION AND LITHOLOGY OF THE EVAPORITES

The lower part of the foredeep basin's Miocene fill in the study area has been reached by >70 boreholes during the last six decades (Fig. 13). The boreholes encountered either the Krzyżanowice Formation (sulphate facies) or mixed, sulphate-chloride facies of the Wieliczka Formation or, in places, did not record the evaporite succession in the stratigraphic profiles penetrated.

The present-day and original distributions of the evaporite facies in the study area, as reconstructed by us from borehole and seismic data, are shown in Figure 13. On the elevated plateaux of the northern part of the area, mostly north of the Carpathian orogenic front, the evaporites are currently represented by autochthonous Krzyżanowice Formation sulphates (anhydrite), except for several boreholes situated on the plateaux, but already south of the orogenic front, in which chloride-sulphate facies evaporites of the Wieliczka Formation were drilled in allochthonous position along the sole thrust of the Skole Nappe. The latter situation is common south of the Carpathian frontal thrust over the palaeobathymetric lows inside the Pogórska Wola palaeovalley and in the Pilzno depression, where deformed, tectonically thickened Wieliczka Formation evaporites also frequently accompany major backthrusts of the Zgłobice thrust unit, or represent a piggy-back sedimentary succession settled on top of the Skole Nappe (Figs. 3, 13 and 14). In some boreholes halite-bearing evaporites are tectonically duplicated or even triplicated. However, apart from the most common allochthonous position and tectonically deformed characteristics of the Wieliczka Formation, in the southern part of the study area, there are also some evaporite strata of the Wieliczka Formation, particularly the lowermost ones, that probably occur in autochthonous situation.

As the mechanically weak halite-bearing horizons significantly facilitated the thrusting, the northern extent of the Wieliczka Formation has controlled that of the Carpathian orogenic front as well as the tectonic involvement of the Miocene strata in the Zgłobice thrust unit. Therefore the extent of intense deformation in the evaporite succession reflected on seismic time slices from inside the palaeovalley (Fig. 14), was used by us in some problematic situations to infer the presence of halite-bearing evaporites and to differentiate the lateral extent of the Wieliczka vs. Krzyżanowice formations (Fig. 13).

On the steep slopes of the northern part of the palaeovalley, near the villages of Żdżary and Żukowice, no evaporite deposits were penetrated. This happened in e.g., the Żdżary-7 borehole (Figs. 13 and 14), located in the middle of the palaeovalley slope, where the Machów Formation rests directly on top of Jurassic strata. On the uppermost part of the slope and on the palaeovalley shoulders, on top of the plateaux, the evaporites of the Krzyżanowice Formation show insignificant thickness, usually <10 m, though sporadically >20 m. This is exemplified in the Żukowice-42 borehole (Fig. 15), where a 9 m thick evaporite

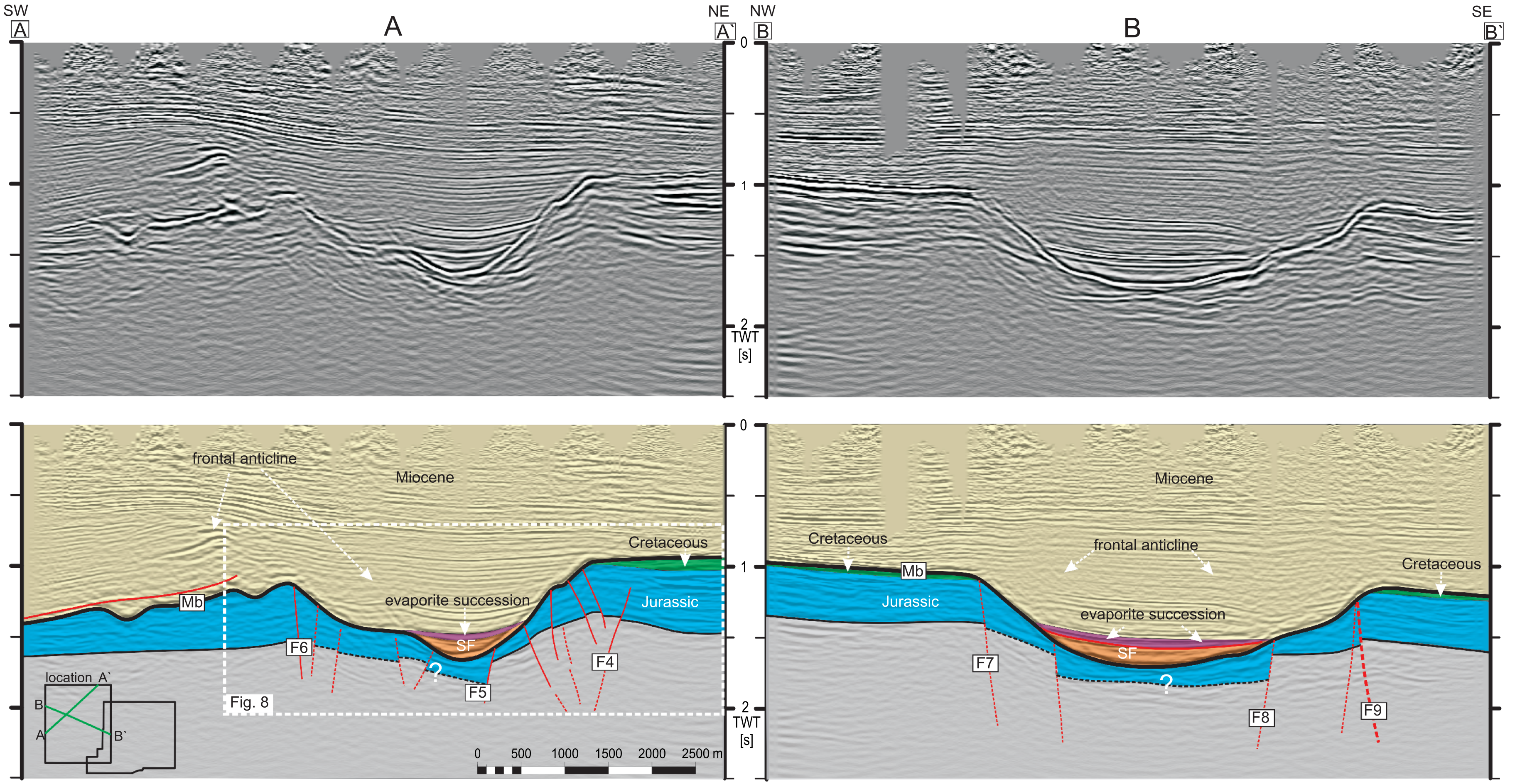

Fig. 7. Faults in the Mesozoic basement seen on seismic sections A and B

Thrust-related frontal anticlines in the Miocene fill are independent of faults in the foredeep basement

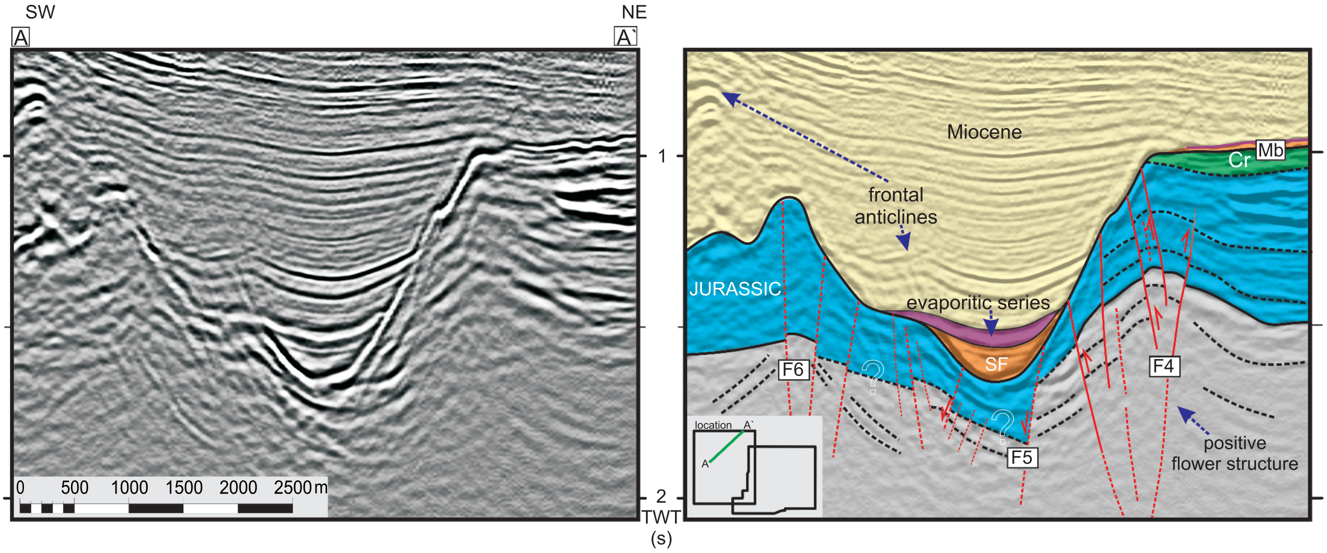

Fig. 8. Detail of seismic profile from Figure 7A, vertically exaggerated to show the possible positive flower structure (F4) in the Mesozoic basement

succession of light grey anhydrite with clayey intercalations had been drilled (but not cored), underlain by only 1 m of sub-evaporite deposits before the Jurassic substratum was reached. A similar development of the evaporites was observed in the Wola Rzędzińska-1, Żukowice-34 and Pilzno-8, -15 and 24 boreholes (Fig. 15 and Appendix 1*).

Inside the palaeovalley, still within the extent of the zone of orogenic deformation, but near to its northern boundary, the Pogórska Wola-16 borehole reached the subevaporite succession (Figs. 15–17). In this borehole the succession is up to 118 m thick and, according to a PGNiG S.A. archival borehole description (Appendix 1), is represented by "greyish, parallel or wavy, laminated anhydrite with intercalations of grey claystone and mudstone, occasionally containing fragments of Jurassic limestone" with no halite. Since, however, only few, selected core intervals have been extracted from this borehole, it is still possible that the sulphates are accompanied there by (insignificant) chloride interlayers. The evaporites in this borehole are underlain by the sub-evaporite Skawina Formation, at least 120 m thick (not drilled through) of claystones and siltstones. No rock salt intercalations were mentioned, either, in an archival documentation of the Żukowice-44 borehole, where no coring in the evaporite succession was made.

In the southern part of the area, in the deepest segment of the palaeovalley affected by the orogenic deformation, thick or very thick chloride-sulphate evaporite accumulations are documented in several boreholes (Figs. 15 and 16). An example is the Podlesie-2 borehole with a 330 m thick evaporite succession of anhydrite and halite with clayey intercalations (Figs. 15–17). Below it, the Skawina Formation occurs, represented by claystones and siltstones, also of abnormal thickness (360 m). Evaporite rocks within the palaeovalley often show blocky, disrupted characteristics, defining chaotic fabrics typical of submarine slumping, debris flow or olistostrome-type deposits (e.g., Bukowski, 1994, 2011; Połtowicz, 1999). An example of evaporite development from inside the palaeovalley may be "white, crystalline rock salt, in layers 30 to 220 cm thick, folded together with up to several centimetre thick light colour sandstone layers; dark grey salt, regularly laminated with clayey, sandy and anhydritic material, locally small-size anhydrite debris and dark grey shale with anhydrite and halite laminae" (PGNiG S.A. archival core description from the Jaśniny-7 borehole, 1982). The available information on the characteristics of evaporite rock drilled inside the Pogórska Wola palaeovalley is synoptically presented in Appendix 1. This information comes directly from archival drilling borehole descriptions. As mentioned earlier, the much increased total thickness of the Wieliczka Formation observed in the palaeovalley is partly due to post-depositional tectonic deformation: folding and thrusting in front of the Carpathian nappe stack, including involvement in wedge tectonics phenomena (Krzywiec et al., 2014; Głuszyński, 2014), which makes the restoration of the original position of the rock salt deposits difficult, though not impossible.

The evaporite succession in the palaeovalley is covered by clastic deposits of the 1000 to 2000 m thick Machów Formation, which onlap the palaeovalley slopes and, at higher levels, spread laterally across the adjacent plateaux. The flexure of intra-Machów Formation seismic reflectors across the palaeovalley edges and their downwarping above the palaeovalley axis (Fig. 2C) are due to late differential compaction that has affected the post-evaporite deposits, the latter being much thicker above the palaeovalley than over its surroundings.

DISCUSSION

TIMING AND ORIGIN OF THE PALAEOVALLEY

The Pogórska Wola palaeovalley is one of a system of more than twenty erosional troughs plunging below the Outer Carpathian fold-thrust belt that are deeply incised into the Mesozoic, Paleozoic and, locally, older bedrock of the Carpathian northern foreland in a zone extending from Austria and the

* Supplementary data associated with this article can be found, in the online version, at doi: 10.7306/gq.1297

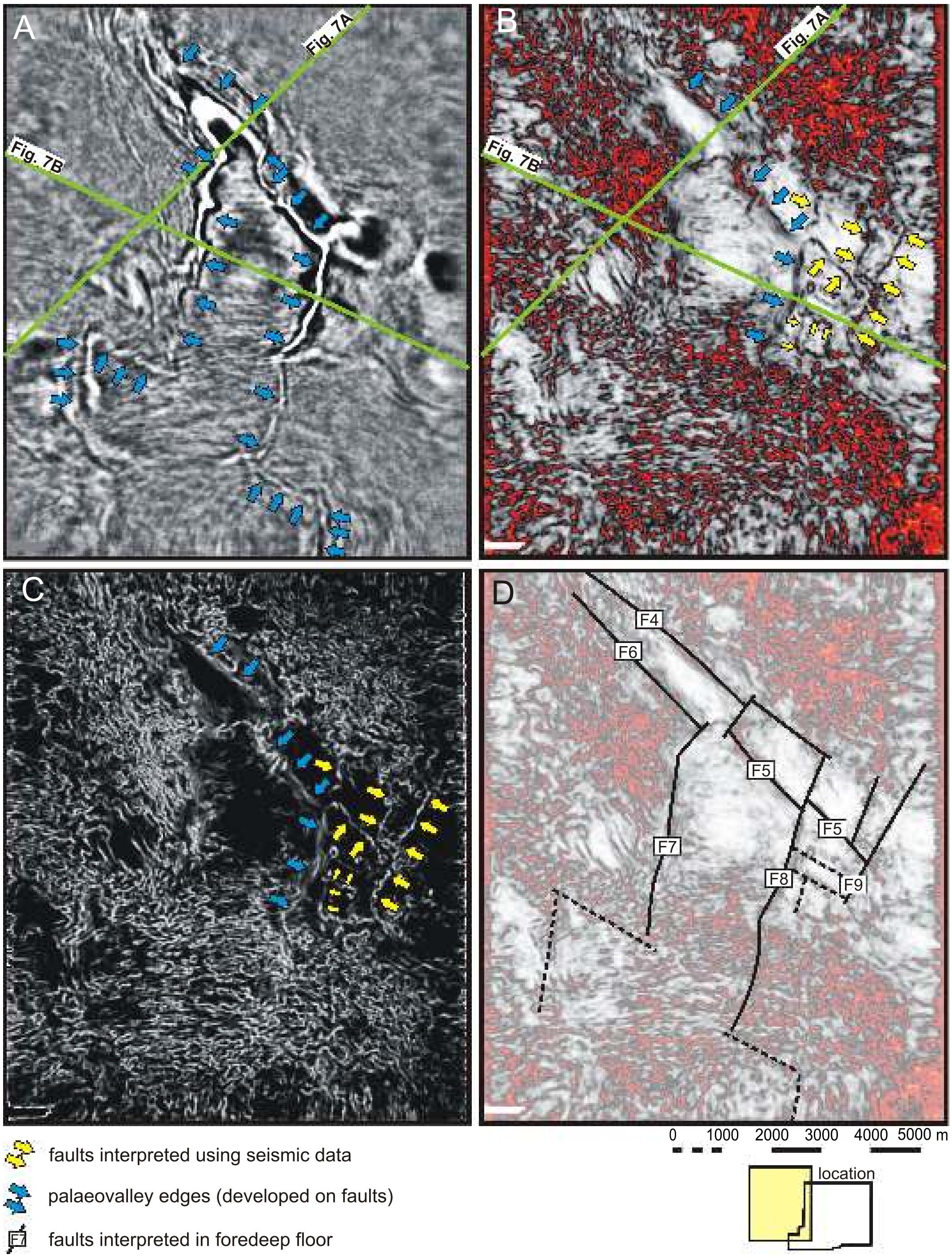

Fig. 9. Time slices at 1.63 second TWT from a 3D seismic survey made in amplitude version (A) and in variance (B), and amplitude contrast attribute (C) versions; such time slices have been used for interpreting faults in the Jurassic-Cretaceous basement of the basin; the interpreted faults are shown in (D) on the background of time slice B

Czech Republic in the west, through Poland, to Ukraine in the east. In Poland the palaeovalleys are predominantly oriented NW–SE to N–S west of Rzeszów, and N–S to NE–SW further to the east (e.g., Stahl, 1932a, b; Jucha, 1974, 1985; Oszczypko and Tomaś, 1976; Nowotarski and Gara, 1985; Oszczypko and Ślączka, 1985; Karnkowski, 1989; Połtowicz, 1998; Jura, 2001; Oszczypko et al., 2006; Baran and Jawor, 2009). Their sedimentary fill is still not sufficiently known (Krzywiec, 2010). In the cases where their axial zones have been drilled, the palaeovalleys are filled with thick Badenian (in places older) to Sarmatian clastic molasse deposits with an evaporitic unit in their lower parts (e.g., Karnkowski, 1989; Moryc, 1995, 1996; Połtowicz, 1998; Krzywiec, 2010; Bukowski, 2011).

In most general terms, the origin of the palaeovalleys in Poland has been explained either by Paleogene fluvial erosion of the Carpathian foreland (e.g., Jucha, 1974; Oszczypko and

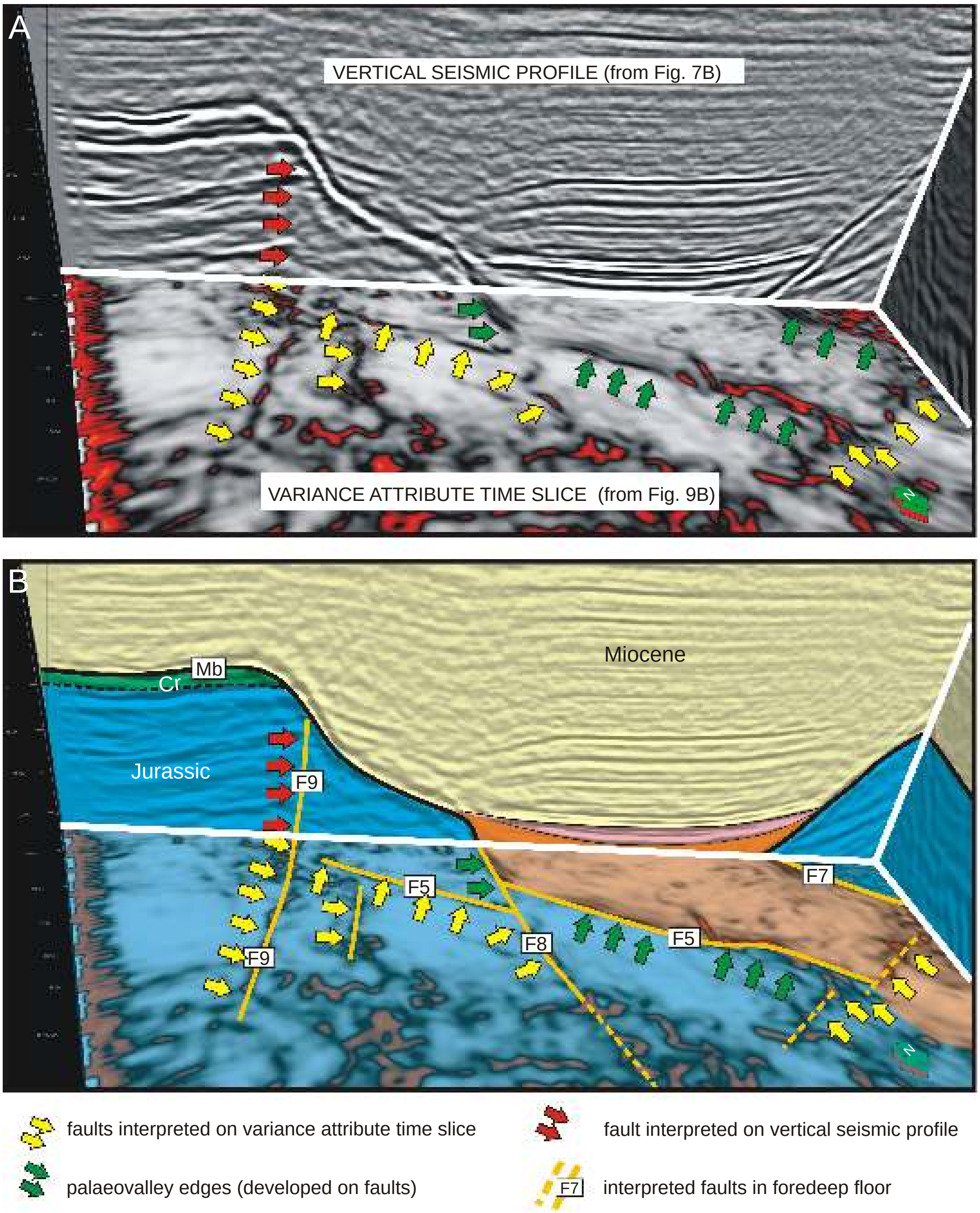

Fig. 10. 3D diagram (A – partly interpreted, B – interpreted) combining vertical seismic sections with a horizontal time slice map (made using variance attribute)

View looking south-west; a section from Figure 7B is used, but in a view from the other side

Tomaś, 1976; Karnkowski, 1989; Połtowicz, 1998), by some authors believed to have continued in submarine conditions (e.g., Karnkowski, 1989; Połtowicz, 1998) following the fore-Carpathian subsidence that commenced in the Early Miocene. An alternative idea, now mostly abandoned, consisted in considering these linear depocentres in the floor of the Carpathian Foredeep as tectonic grabens (e.g., Oszczypko and Ślączka, 1985), an idea still, in part, timely, however, in interpreting the erosional troughs as structurally controlled (Krzywiec, 1997, 2001; Krzywiec et al., 2004).

In more detailed approach, an explanation for the origin of these erosional troughs in the Polish and Moravian segments of the Carpathian Foredeep is usually made in two ways. The geological interrelationships in erosional troughs in southern Moravia some 300 km WSW, and in a few such troughs near Sędziszów Małopolski and Rzeszów approximately 50–60 km east of the study area (Fig. 18) are taken as evidence for intense Early Paleogene fluvial incision (Picha et al., 2006; Krzywiec, 2010) affecting areas significantly uplifted during the end-Cretaceous “Laramide” compressional event (e.g., Ziegler

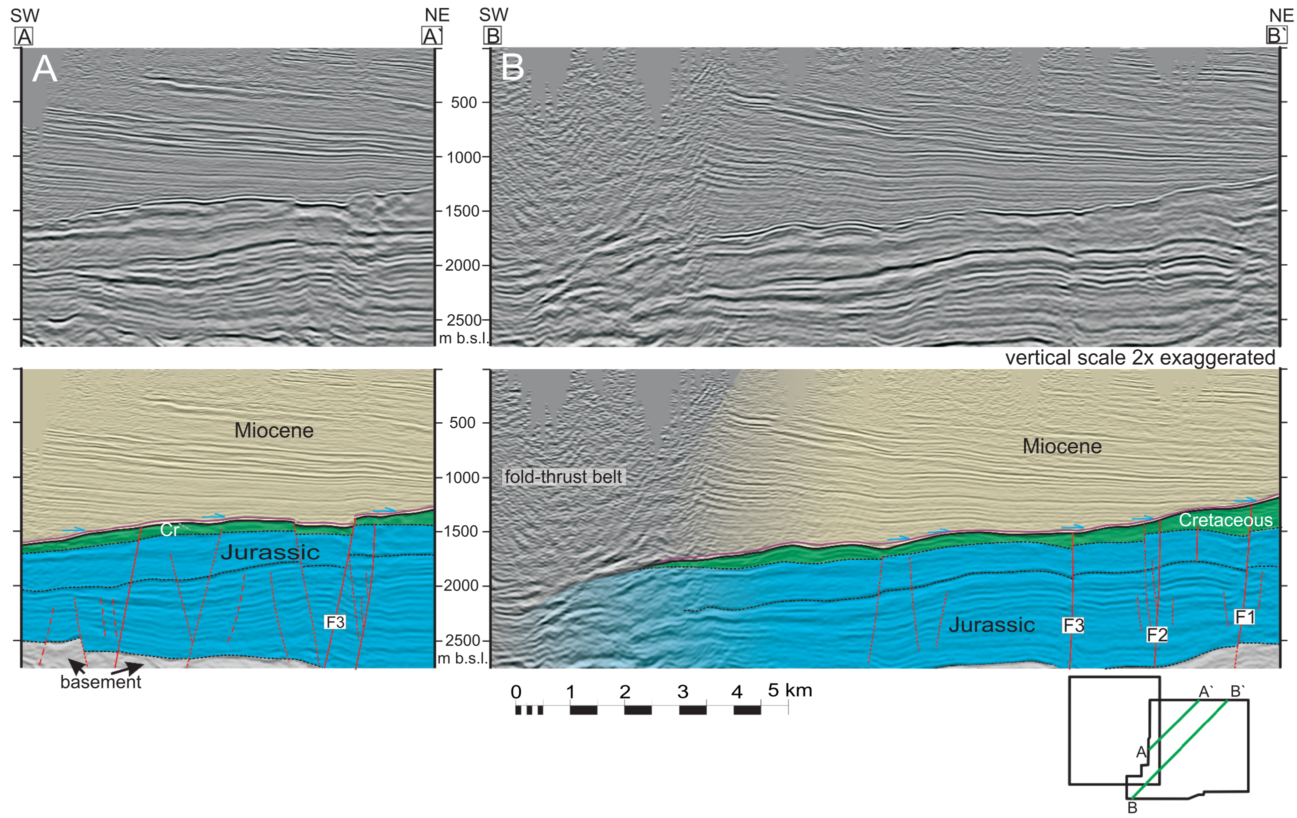

Fig. 11. Seismic sections A and B (depth domain) showing faults in the Mesozoic basement of the eastern part of the study area

The faults do not continue upwards into the Miocene strata

and Dèzes, 2007; Kley and Voigt, 2008; Scheck-Wenderoth et al., 2008), such as the peri-Carpathian parts of the Mid-Polish Swell and the peripheries of the Bohemian Massif that were drained to the Carpathian flysch basin. The basis for such an interpretation, assuming deep erosion immediately after the end-Cretaceous uplift, is supplied by the two major, 1.5 km deep, tectonically controlled erosional southern Moravian troughs of Vranovice and Nesvačilka (Fig. 18), plunging below the Carpathian frontal thrust (Picha, 1979; Picha et al., 2006) and filled with Paleogene clastic deposits, ranging in age from the Early Paleocene to the Early Oligocene (Jiřiček, 1994). The Paleogene sedimentation is believed to have occurred there directly after a period of fluvial erosion and subsequent subsidence. A similar situation is interpreted in a few palaeovalleys around Rzeszów that are filled with pre-Badenian, probably Paleogene, continental deposits (Moryc, 1995; see also discussion by Krzywiec, 2010, contradicted by Jarosiński et al., 2010). Analogous situations in a number of major Paleogene-filled palaeovalleys are reported by Shpak et al. (1999) from the Ukrainian Carpathian Foredeep.

An alternative view (Jarosiński et al., 2009, 2010), considers the fluvial incision of the Mesozoic and older strata of the Polish Carpathian foreland to have occurred rather later, during Late Oligocene to Early Miocene times and to have affected the uplifted fore-Carpathian peripheral bulge that formed in front of the approaching Carpathian flysch fold-and-thrust wedge in its early, "Savian", stage of advancement. The incision is believed to have shortly or directly preceded the deposition of the Badenian-Sarmatian fill of the palaeovalleys. Similar opinions were earlier expressed by Połtowicz (1999), who opposed the Paleogene age assessment by Moryc (1995) for the fill of the palaeovalleys near Rzeszów and Sędziszów. Moreover, the Early Paleocene to Early Oligocene age determination of Jiřiček (1994) for the sedimentary fill of the Moravian palaeovalleys is at odds with earlier determinations by other authors, several of which point to its Late Eocene to Early Oligocene age (Picha et al., 2006 and references therein).

Taking into account all the available data from the environs of Pilzno, both the above approaches to date the development of the deep erosional troughs at the Carpathian foreland can be successfully applied to the Pogórska Wola palaeovalley. A combination of both approaches can also be theoretically considered, assuming a complex evolution of Carpathian palaeovalley systems with alternating periods of erosion and deposition, influenced by successively changing scenarios, including mutually dependent episodes of recurrent thrusting and tectonic extension, subsidence and uplift events, of eustatic and changing topography-controlled sea level variations, additionally affected by climatic changes. Such an approach, although far from being recognized in detail, may nevertheless be quite appropriate in the case of the fore-Carpathian palaeovalleys, including that of Pogórska Wola, taking into account the complex evolution of the Moravian palaeovalleys. The already mentioned major NW–SE trending (orogen-transverse) Vranovice and Nesvačilka Paleogene erosional troughs in Moravia are superimposed at right angles by a younger, SW–NE (orogen-parallel) Iváň canyon (Dellmour and Harzhauser, 2012; Fig. 18), incised to a depth of 600 m into Karpatian (Lower Miocene) clastic deposits of the Carpathian Foredeep fill and unconformably filled with Upper Karpatian (uppermost Burdigalian) strata.

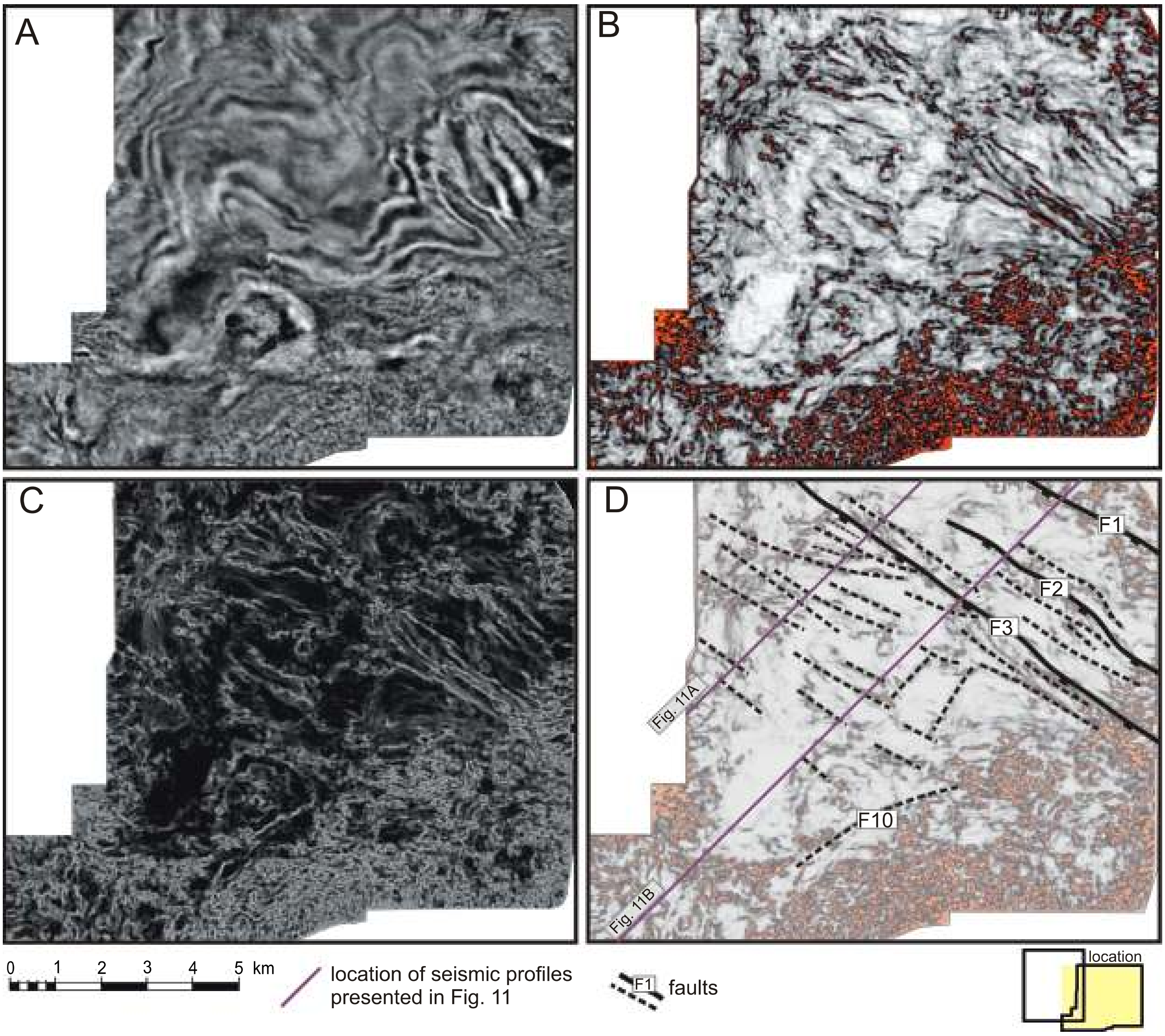

Fig. 12. Seismic depth slices at 2304 m TVDSS (=True Vertical Depth Sub Sea) showing faults in the Mesozoic basement of the foredeep basin in the eastern part of the study area

Depth slices made in amplitude version (A) and in variance (B) and amplitude contrast (C) attribute versions; the interpreted faults are shown in (D) on the background of the depth slice from (B)

Farther to the north this palaeovalley cuts even deeper, into the Eggenburgian of the foredeep fill and into the Jurassic basement (Jiřiček and Seifert, 1990; Jiřiček, 1995). The timing of its stage of major erosion is there established at 16.5 Ma (Late Karpatian) and followed by another erosional event affecting the palaeovalley fill and bracketed between 16.3 Ma (Late Karpatian) and 15.1 Ma (Early Badenian). The main erosion is attributed there to an isostatic rebound of the orogenic foreland, following thrust emplacement of the adjacent Carpathian orogenic front at 17–18 Ma (Dellmour and Harzhauser, 2012).

A separate question can be posed as to the proportion of the palaeovalleys' history that took place in subaerial *versus* submarine conditions. In general, as regards the palaeovalleys in Poland, no attempts have been made to ascribe their origin fully to marine processes, in contrast to some hypotheses put forward to explain the scenario of the Messinian salinity crisis (cf. e.g., Roveri et al., 2014; Lugli et al., 2015). This attitude seems to be correct, taking into account the important contrasts between the geological settings of the Mediterranean and the Carpathian Foredeep: a deep marine basin, partly underlain by oceanic crust and containing no areas expected to be much uplifted prior to and during the saline deposition in the former case, compared with an orogenic foredeep basin resting entirely on continental crust and undergoing more or less substantiated and significant vertical motions due to the continental-scale end-Cretaceous compressional event, to flexural bending of the Carpathian foreland loaded with the orogenic wedge and to an expected subsequent isostatic rebound in the latter case.

In the Mediterranean, the origin of both currently exposed and buried submarine canyons related to the Messinian salinity crisis is generally explained in two ways. The classical model (Hsü et al., 1973) of "shallow-water deep-basin" (SWDB) assumes a radical sea level fall by ca. 1.5 km due to evaporation in an isolated marine basin, leading to subaerial exposure of the basin slopes and shelves and to localised deep fluvial incision. Alternative models of "deep-water deep-basin" (DWDB; Schmalz, 1969, 1991; De Benedetti, 1982; Dietz and Woodhouse, 1988) do not require sea level fall and assume a submerged position of eroded basin slopes during persistent sea level highstand conditions, while referring to such mechanisms

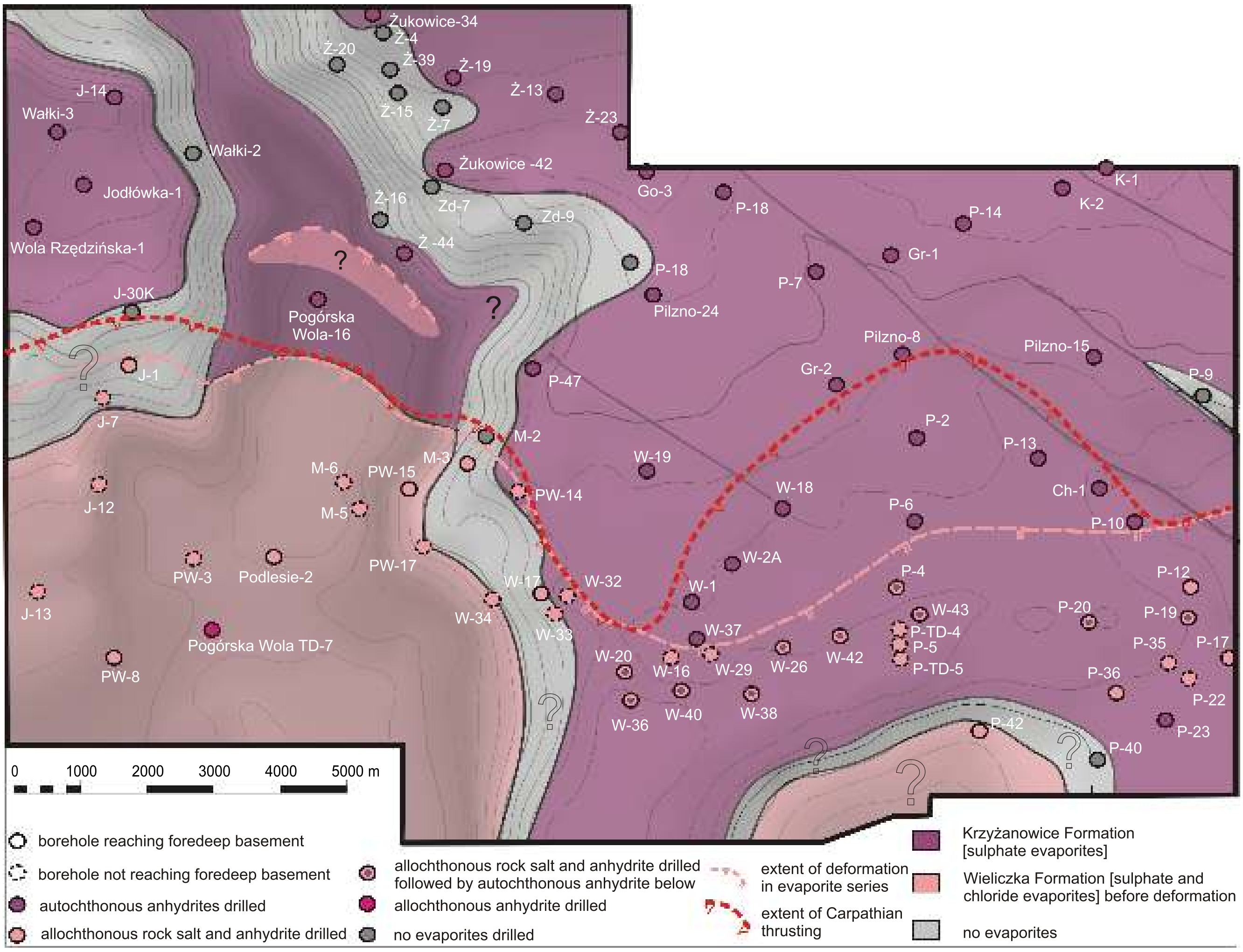

Fig. 13. Evaporite facies distribution in the Carpathian Foredeep near Pilzno, based on borehole and seismic data

The extent of the halite-bearing facies has been partly determined as equivalent to the seismically recorded extent of tectonic compressional deformation; Go – Golemki, Gr – Grabiec, K – Karolówka, M – Machowa, J – Jaśniny, P – Pilzno, PW – Pogórska Wola, W – Wygoda, Ż – Żukowice, Żd – Żdżary

of subaqueous erosion, canyon incision and sediment transport in canyons, as turbidity currents, storms, hyperpycnal flows from river floods, marine saline underflows and dense shelf water cascading (Lugli et al., 2013; Roveri et al., 2014 and references therein).

Both the above Mediterranean models obviously can be of some applicability in explaining the origin of the peri-Carpathian palaeovalleys, however, distinguishing features resulting from each of them, and, thus the contribution of each mode of erosion, is not a trivial task, and, hence, again, the opinions of some geologists engaged in investigations of the Carpathian foreland (Picha, 1979; Karnkowski, 1989; Połtowicz, 1998; Krzywiec, 2001; Picha et al., 2006) assuming – in general terms only – a transition from subaerial into subaqueous erosion during the palaeovalleys' evolution should be regarded as justified and reasonable.

PROBABLE MODES OF DEPOSITION

In considering the course and conditions of the Late Badenian evaporite deposition in the environs of Pilzno we basically accept the model presented by Bukowski (2011). The evaporites were deposited both on the floor of the Pogórska Wola palaeovalley and – up to 1300 m higher – on the adjacent high-standing plateaux. At the onset of deposition the palaeovalley floor became covered with a succession several tens of metres (in the Pogórska Wola-16 borehole) to at least 350 m thick (in the Podlesie 2 borehole) of sub-evaporite claystones and mudstones of the Skawina Formation (Figs. 15 and 19), partly representing fine-grained turbidites. During the subsequent evaporite sedimentation, the initial large elevation differences of the basin floor were thus already slightly subdued, because of the Skawina Formation partly filling the palaeovalley. However, even assuming an eventual considerable compaction of the sub-evaporite strata, the relief of the basin floor still remained prominent, with elevation differences of 600 to 900 m (Fig. 19). The sediments did not settle permanently on steep palaeovalley slopes. Even if transient deposition on these slopes had locally occurred, the resultant sediments must have been soon washed away and finally redeposited on the palaeovalley floor.

Two contrasting groups of scenarios of deep evaporite deposition on the Pogórska Wola palaeovalley bottom can theoreti-

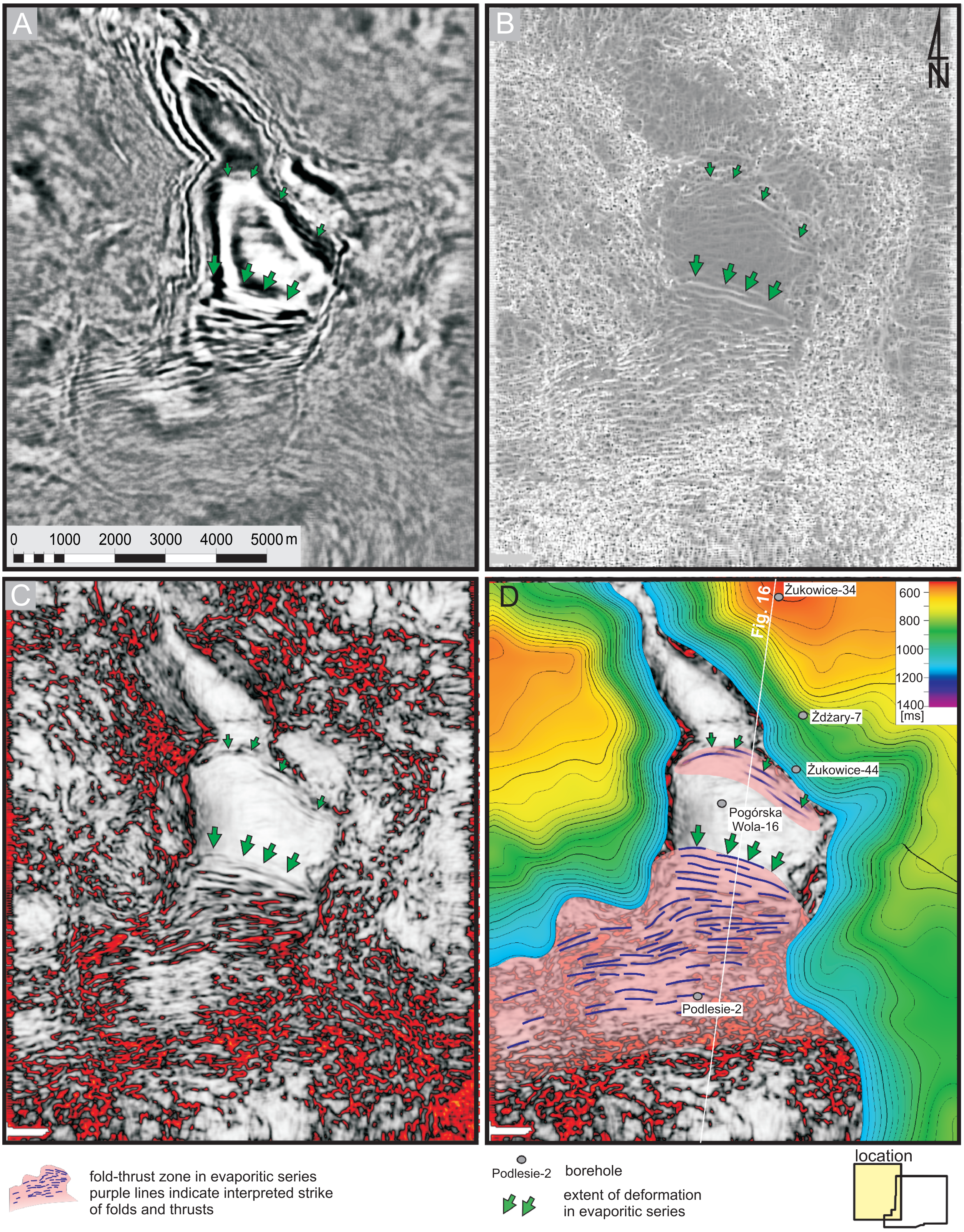

Fig. 14. Interpretation of the extent of tectonic compressional deformation using time slice maps derived from 3D seismics

Time slice at 1.52 second TWT in amplitude version (A), and in 3D curvature (B), and variance contrast (C) attribute versions; the interpreted extent of compressionally deformed (i.e. inferred to be halite-bearing) evaporites is shown in D, using the time slice from C imposed on the time structure map of foredeep basement top surface (Fig. 4); the lateral extent of fold-thrust type deformation in the lower evaporite package and in the triangle zone of the upper package was determined using seismic attributes analysis; the fold-thrust type deformation in the evaporite succession is laterally confined to the palaeovalley interior; the structures are generally transverse to the palaeovalley slopes, showing some drag at the contact

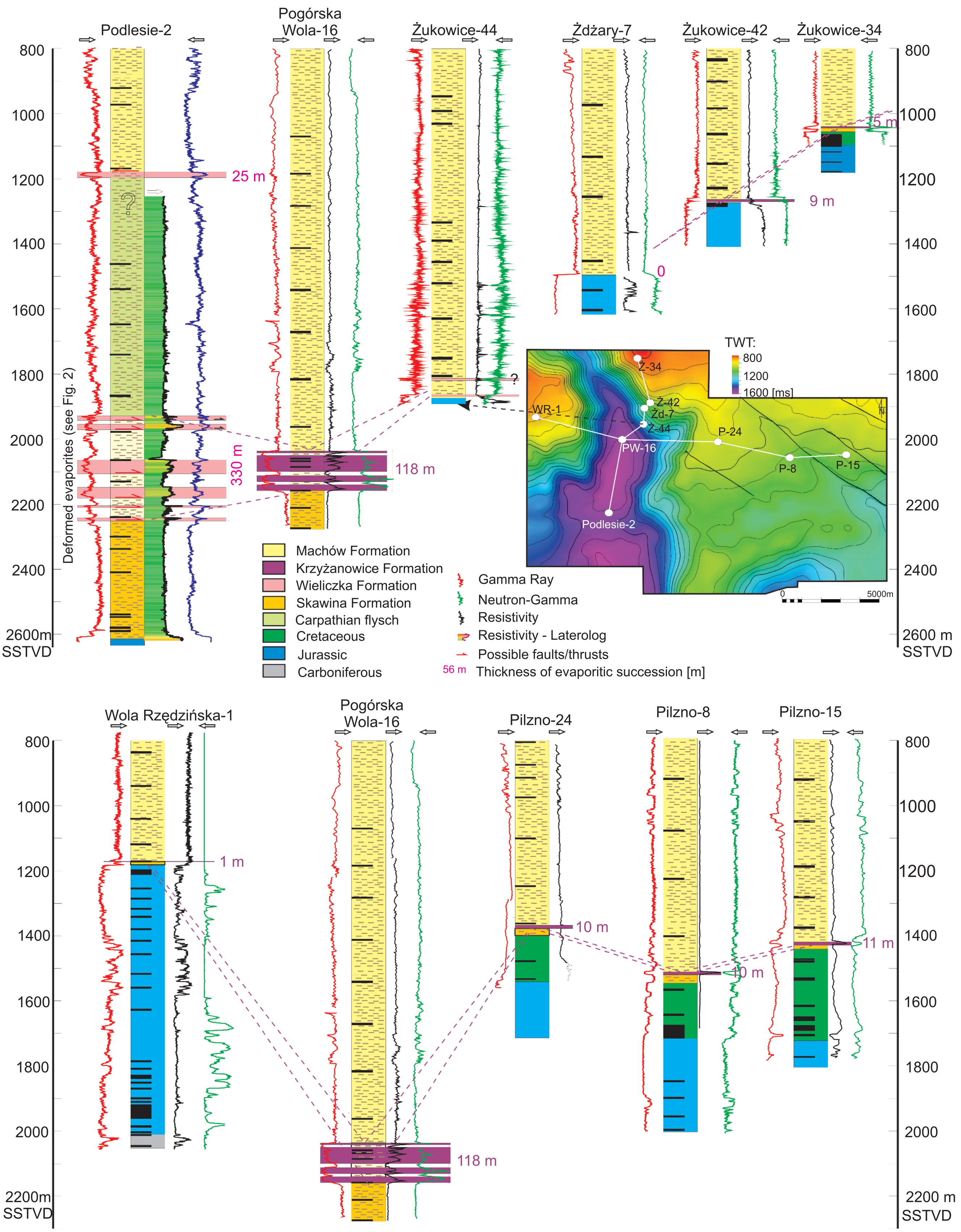

Fig. 15. Selected borehole profiles used in this study

The boreholes Podlesie-2 and Pogórska Wola-16 are located in the axial part of the palaeovalley; the Podlesie-2 borehole shows the evaporite succession tectonically thickened (up to 330 m), whereas Pogórska Wola is outside the zone of deformation; the Żdżary-7 borehole with no evaporites is on the palaeovalley slope; the boreholes Żukowice-34 and 42 with a much reduced evaporite succession (5 and 9 m, respectively), are located on palaeovalley shoulders

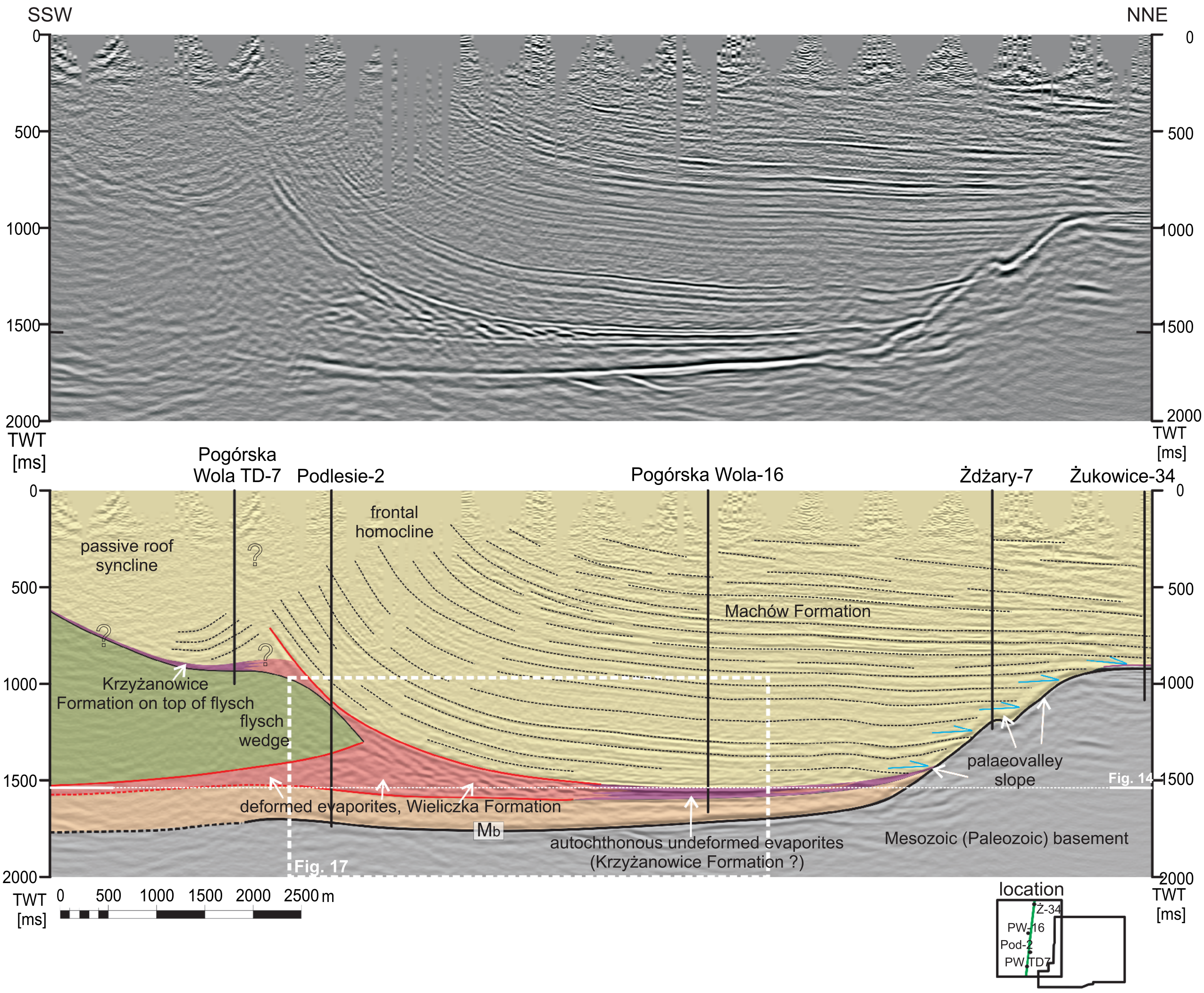

Fig. 16. Seismic section in time domain, across the axial part of the palaeovalley

The Miocene fill deposits onlap the palaeovalley slope; evaporites are tectonically deformed in front of and below the Skole Nappe flysch wedge

cally be considered, reminiscent of the already reviewed Mediterranean SWDB and DWDB models: (1) shallow-water deposition in the case of a several hundred metres sea level drop and (2) deep-water deposition at depths in the range of 600–900 m. The shallow-water hypothesis seems to be improbable, though not impossible in the case of an isolated basin, because of the required extreme value of sea level drop, at odds with the eustatic curve (cf. Haq et al., 1988), apparently in absence of tectonic block differential displacements during the evaporite sedimentation and at later times, as can be inferred from our studies of the seismic data. Moreover, if even such a significant sea level fall actually took place, the thin evaporite succession and the underlying Skawina Formation sediments, deposited on top of the high plateaux, would have been likely mostly eroded and removed, which apparently has not occurred. Only the deep-water scenarios of evaporite deposition (cf. e.g., Roveri et al., 2014; Lugli et al., 2015) in the palaeovalley seem thus to be acceptable in our case, in line with the sea level drop not exceeding 100 m in the Carpathian Foredeep during the Badenian salinity crisis assessed by other authors from regionally more comprehensive studies (Oszczypko, 1998; Bąbel, 2004; Peryt, 2006; Bukowski, 2011). The deep-water scenarios are, moreover, capable of combining simultaneous shallow-water evaporite deposition on the plateaux and sedimentation in deep-water conditions on the palaeovalley floor.

Considering in general terms the Miocene evaporite deposition in the vicinity of Pilzno, it can be assumed that the sulphate and chloride brines were presumably concentrated due to sea water evaporation on flat or gently undulating shoals at the top of the plateaux extending beyond the palaeovalley to the north, east and west. Precipitation of calcium sulphate and, probably also, halite took place on the plateaux when the brines became saturated. Important volumes of the brines may have been transported down the palaeovalley slopes (Bukowski, 2011).

The sodium chloride brines, being heavier than those of calcium sulphate, may have easily flowed down the slopes of the palaeovalley, possibly achieving saturation on the palaeovalley bottom. This may have given rise to a deep-water precipitation of halite, as indicated by some (though few) core descriptions (Appendix 1), recording regular halite layers that may have resulted from precipitation. The available historical core material is, unfortunately, very sparse and, thus, of limited applicability in attempts to decisively constrain this, otherwise probable, hypothesis.

Apart from the possibility of deep-water precipitation of halite, another mechanism of halite and anhydrite accumulation

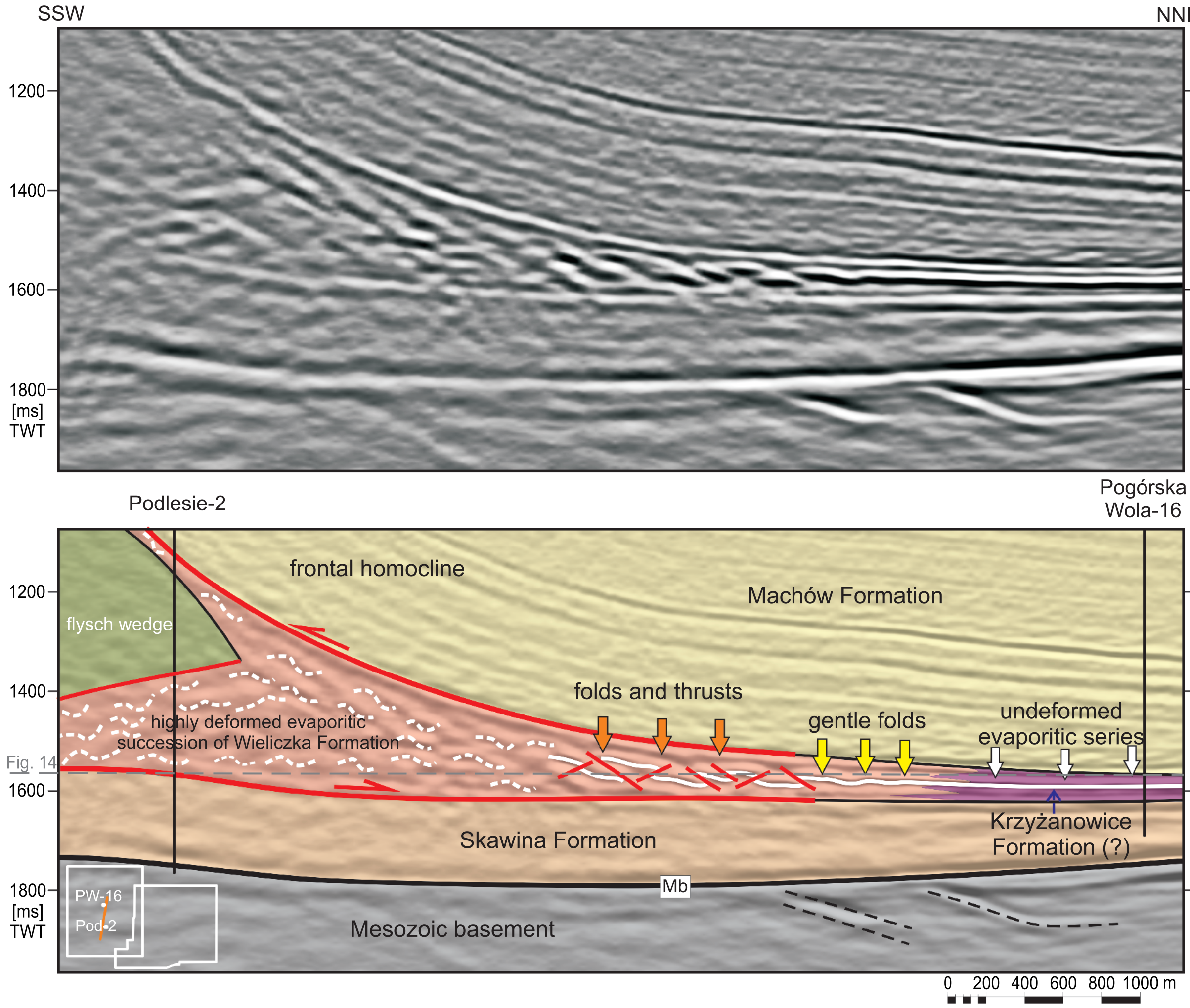

Fig. 17. Detail of seismic section from Figure 16 showing thickened and deformed evaporites in the palaeovalley

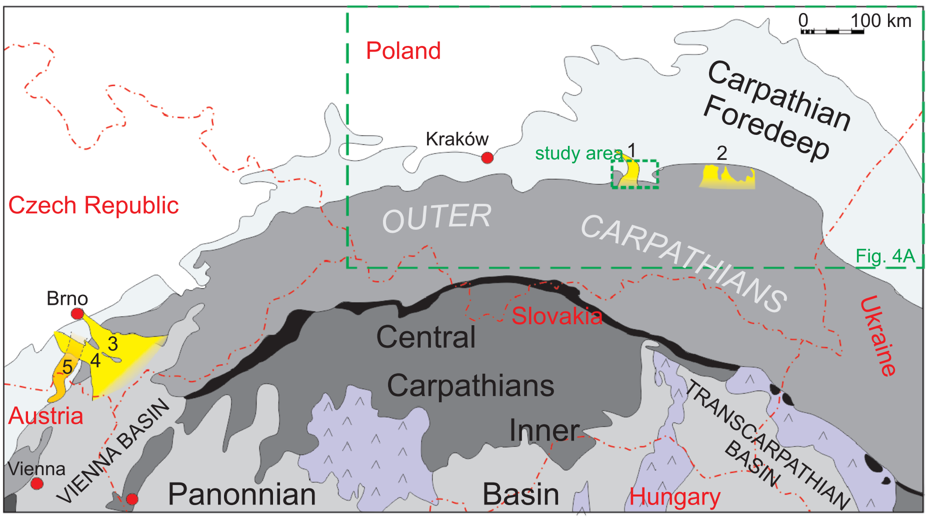

Fig. 18. Location of selected palaeovalleys discussed in the text
(base map after Kováč et al., 1998)

Palaeovalleys discussed: 1 – Pogórska Wola, 2 – Rzeszów-Sędziszów, 3 – Nesvačilka, 4 – Vranovice, 5 – Iváň

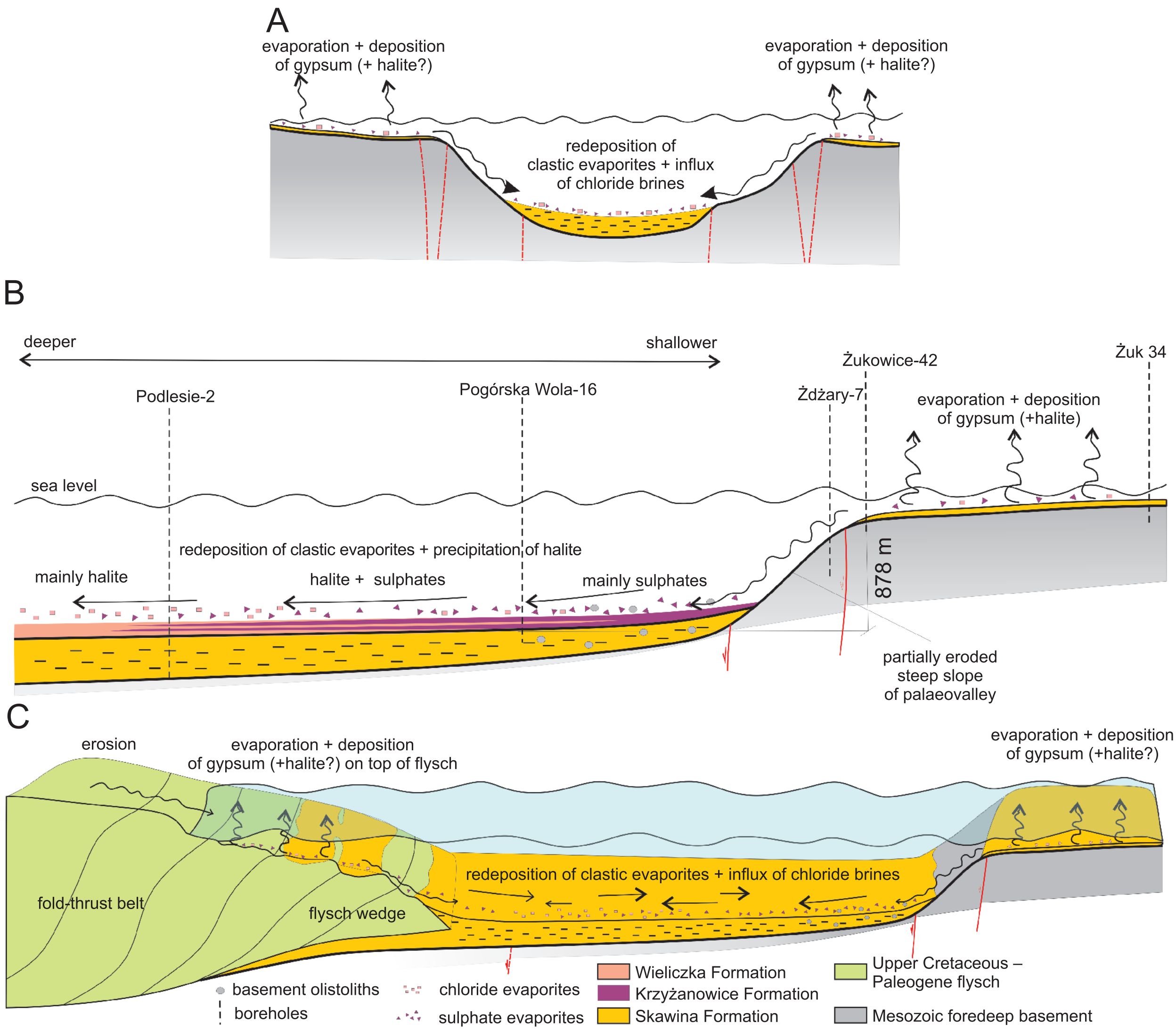

Fig. 19. Reconstruction of the Pogórska Wola valley during the evaporite deposition on a transverse (A) and longitudinal (B) cross-section and on a synoptic, generalized, block diagram showing basin-scale interrelationships (C)

attempts to decisively constrain this, otherwise probable, hypothesis.

Apart from the possibility of deep-water precipitation of halite, another mechanism of halite and anhydrite accumulation on the palaeovalley floor must have certainly operated. This was redeposition of evaporitic sediment that had originally precipitated in shallow-water conditions on the plateaux. These probably not-yet-fully lithified evaporites were subsequently likely mechanically mobilized by sea currents, wind waves and/or earthquakes that must have been frequent in front of the advancing orogenic wedge (Peryt and Kasprzyk, 1992). The slightly less dense chloride-facies deposits (in contrast to heavier chloride brines), that, moreover, had most probably originally settled on top of earlier precipitated anhydrites (G. Czapowski, pers. comm., 2015), were likely more mobile than the latter and more easily removed from their original place of settlement (Cendón et al., 2004; Bukowski, 2011). The residue remaining on the plateaux comprised mostly sulphate minerals. The mobilized material of chlorides and sulphates was subsequently transported to the depressed locations in the basin, notably to the palaeovalley bottom. The transport was in the form of gravity flows of suspended material, carrying crystal fragments and debris of evaporite sediments, together with the accompanying mud, sand and clay (cf. Kolasa and Ślączka, 1985; Bukowski, 1994; Ślączka and Kolasa, 1997; Peryt, 2000; Cendón et al., 2004). The heavier sulphate crystals were the first to settle from suspension in the upper parts of the palaeovalley, whereas the lighter chloride crystals must have been preferentially transported farther south, down the the palaeovalley axis (Fig. 19) and deposited in its deeper parts (density differentiation typical of gravity flow deposits – e.g., Middleton and Hampton, 1973; Weimer and Link, 1991).

The redeposition of evaporites in the palaeovalley is corroborated by the presence of Jurassic rock fragments, apparently coming from the palaeovalley slopes, documented in the evaporite succession in the Pogórska Wola-16 borehole (see Appendix 1). The rapid transport made it possible for the chloride crystals to avoid dissolution by undersaturated sea water on their way down the palaeovalley axis, whereas at their final destination, the sea water may have been saturated with respect to sodium chloride.

The above explained hypothetical deposition mechanism for the Pilzno evaporites explains the fact that in the shallower, northern part of the palaeovalley it is mostly sulphate facies evaporites that are preserved (in the Pogórska Wola-16 and Żukowice-44 boreholes), whereas the southern, more distal part of the valley is more abundant in chlorides.

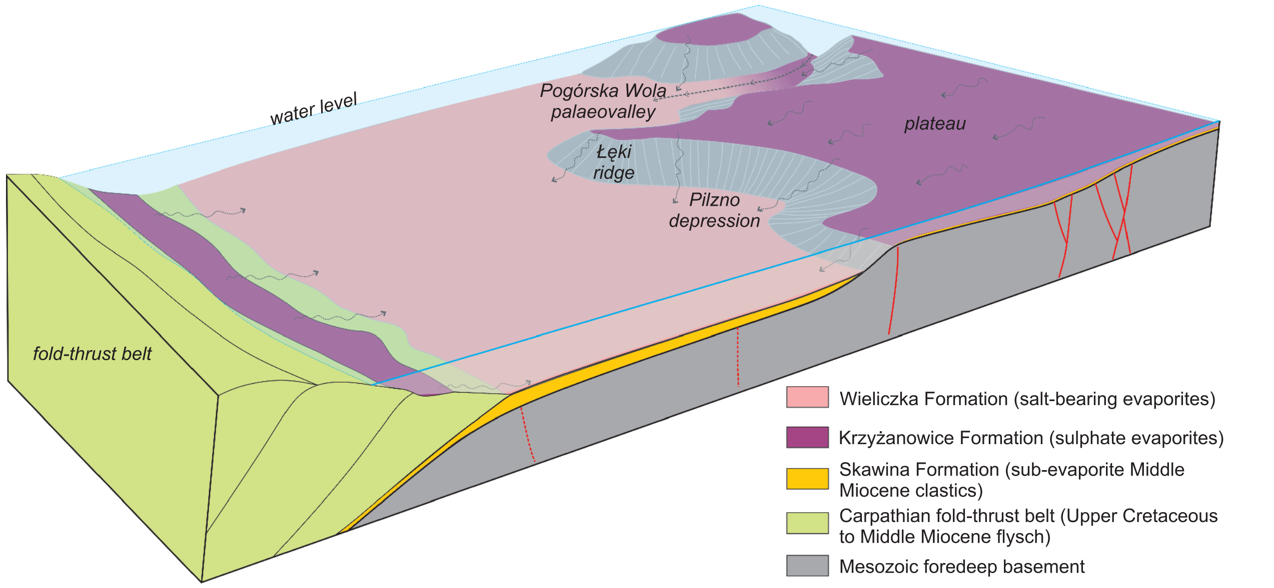

Fig. 20. Scheme of evaporite facies distribution during deposition near to Pilzno

Such a distribution later controlled the thrusting at the Carpathian orogenic front and resulted in variations in its structural geometry

In the area studied, the redeposition probably occurred in several pulses, synchronous with clayey-muddy sediment supply to the basin from the advancing and concurrently eroded Carpathian flysch wedge (Figs. 19C and 20), resulting in coexistence of halite, anhydrite, clayey and clayey-marly material in the evaporites on the palaeovalley floor. A synchronous supply of brines to the palaeovalley from the shallow-water plateaux in the north, and of the eroded clayey material derived from the Carpathians in the south, produced salty-clayey (*zuber*) deposits and anhydrite-clay laminites (Appendix 1). Neither the evaporite facies deposits nor the sub-evaporite Skawina Formation sediments were preserved on the steep palaeovalley slopes, as known from the Żdżary-7 borehole and from the seismic data. The lack of the evaporite horizon also on top of the palaeovalley shoulders near Żdżary and Żukowice, can, similarly, be explained by erosion that must have been particularly active near to the upper edges of the palaeovalley slopes. Worth mentioning here is the radical idea of Połtowicz (1999), who assumed that the origin of halite inside the Pogórska Wola palaeovalley is solely due to its redeposition and that no precipitation took place at depth on the palaeovalley floor.

CONCLUSIONS

Intense pre-Late Badenian (end Cretaceous and/or Oligocene–Early Miocene?) erosion, localized in a shallow graben and along pre-existing faults and fracture zones, produced the prominent, Pogórska Wola, palaeovalley, deeply cut (up to 1300 m) into the Cretaceous–Jurassic floor of the Carpathian Foredeep Basin near Pilzno, SE Poland. The palaeovalley strongly affected the pattern of Middle Miocene sedimentation of the basin fill, resulting in much increased thicknesses (independently of tectonic deformation) of the Badenian sub-evaporite, evaporite and supra-evaporite beds inside it, when compared to those on the adjacent plateaux.

We infer that the evaporite deposits, currently constituting the lower part of the Pogórska Wola palaeovalley fill, were redeposited in deep-water conditions (600–900 m) after removal from the nearby shallow-water plateaux in a scenario earlier suggested for the erosional troughs in the Carpathian Foredeep. Originally, the sulphate and chloride brines became concentrated and saturated on the relatively flat or undulating tops of the shallow-water plateaux and on top of the Carpathian flysch in a thrust-top situation SW of the study area. The brines, in particular the heavier chloride-rich brine, were partly transported downslope into the palaeovalley bottom. From the brines remaining *in situ*, evaporites formed on the plateaux due to precipitation of sulphates and chlorides. Subsequently, the newly formed evaporites, particularly chlorides, became mobilised and eroded by endogenic, most probably earthquake-driven, and supergene factors, such as e.g., sea currents or wind waves, and transported to lower locations in the basin, in particular to the palaeovalley floor, where they became redeposited. In this way, the significant, elevation-sensitive lateral facies differentiation of the evaporites in the vicinities of Pilzno and Pogórska Wola, is explained by depletion of the more elevated areas, where the original evaporite precipitation occurred, in the less dense halite material, which was most easily transported downslope and down the palaeovalley axis before it became redeposited. The heavier sulphate crystals, even if mobilized and eroded, settled sooner and partly avoided such distant transport, thus contributing to the facies differentiation. Independently, the palaeotopography of the Miocene foredeep floor and the related evaporite facies distribution exerted a paramount influence on the thrust geometry at the Carpathian orogenic front, which will be addressed in a separate paper.

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