PS Carpathian Foredeep Basin (Miocene, Poland and Ukraine): Significance of Evaporite Deposition*

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Abstract

The Carpathian Foredeep – the largest foredeep basin in Europe - developed during the early and middle Miocene as a peripheral flexural foreland basin in front of the advancing Carpathian front. There were three periods of intense foreland subsidence: during the early Miocene, early Badenian, and late Badenian to Sarmatian times. The Carpathian Foredeep basin is subdivided into two parts: inner and outer. The inner foredeep is located at the front and beneath the Carpathian Overthrust and is characterized by strongly folded Eggenburgian-Badenian strata. In the Ukraine, evaporites (halite and potash) are important constituent of the sedimentary column. The outer foredeep is filled by generally undisturbed, flat lying Middle Miocene marine deposits a few hundred meters to 5 km thick. Evaporites (initiated to form 13.81 Ma) are prime marker beds and are included into two formations: Wieliczka Formation, 30–100 m thick, composed of chlorides with siliciclastic intercalations accompanied by tuffites and bentonites and occurring close to the Carpathian orogen, and Krzyzanowice Formation, 10-55 m thick gypsum and anhydrite. Study of foraminifers occurring in marls underlying the Badenian gypsum strongly suggests oxygenation and productivity changes in the Carpathian Foredeep Basin prior to the Badenian salinity crisis. In turn, the composition of benthic foraminifer assemblages and their C isotopic values indicate nutrient-rich waters and mesotrophic to eutrotrophic environments in surface waters, and low oxygenation at the sea floor, during deposition of marly deposits related to the transgression that stopped the basinwide evaporite deposition. There occur benthic and planktonic foraminifera in the marly intercalation sandwiched in Badenian gypsum originated in environment of an evaporitic shoal (<1 m deep) what indicates a major short-lived (few thousand years) seawater flooding event (with seawater rise >50 m) in the previously isolated Carpathian Foredeep. A distinctive decreasing trend of 87Sr/86Sr ratios from western Ukraine to southern Poland as observed in the gypsum is due to a consistent direction of a brine inflow during gypsum crystallization (typical cyclonic circulation controlled by the Coriolis effect). Paleogeographical gradient and rapid, well-documented environmental changes controlled by eustatic and tectonic changes cause that in particular the northern part of the Carpathian Foredeep is regarded as a model example of dynamic stratigraphy.

Carpathian Foredeep Basin (Miocene, Poland and Ukraine): Significance of Evaporite Deposition

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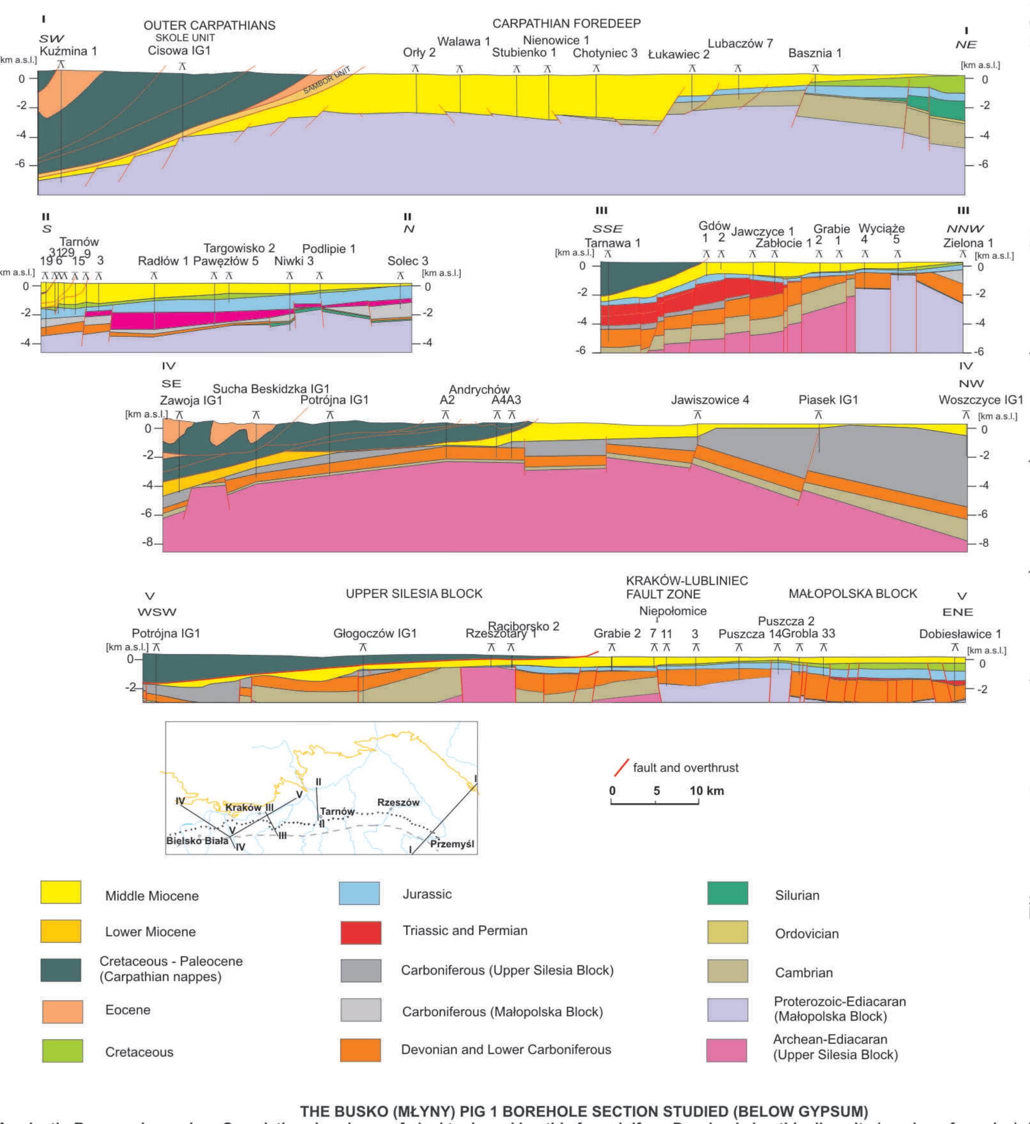
The Carpathian Foredeep – the largest foredeep basin in Europe - developed during the early and Middle Miocene as a peripheral flexural foreland basin in front of the advancing Carpathian front. There were three periods of intense foreland subsidence: during the early Miocene, early Badenian, and late Badenian to Sarmatian times. The Carpathian Foredeep Basin is subdivided into two parts: inner and outer. The inner foredeep is located at the front and beneath the Carpathian Overthrust and is characterized by strongly folded Eggenburgian-Badenian strata. In the outer foredeep, the Middle Miocene is the most important constituent of the sedimentary column. The outer foredeep is filled by generally undisturbed, flat lying Middle Miocene deposits. Evaporites (initiated to form 13.81 Ma) are prime marker beds and are included into two formations: Wieliczka Formation, 30–100 m thick, composed of chlorides with siliciclastic intercalations tuffites and bentonites and occurring close to the Carpathian orogen, and Krzyżanowice Formation, 10-55 m thick gypsum and anhydrite. Study of foraminifers occurring in marls underlying the Badenian gypsum strongly suggests oxygenation and productivity changes in the Carpathian Foredeep Basin prior to the Badenian salinity crisis. The benthic foraminiferal assemblages and stable isotopic values indicate nutrient-rich waters and mesotrophic to eutrotrophic environments in surface waters, and low oxygenation at the sea floor, during deposition of marly deposits before the transgression that stopped the basinwide evaporite deposition. The occurrence of benthic and planktonic foraminifers in the marly intercalation between the evaporitic shoal (<1 m deep) what indicates a major short-lived (few thousand years) sea-level rise (>50 m) in the previously isolated Carpathian Foredeep. A distinctive decreasing trend of $^{87}Sr/^{86}Sr$ ratios from western Ukraine to southern Poland recorded in the gypsum is due to a consistent direction of a brine inflow during gypsum crystallization (typical cyclonic circulation controlled by the Coriolis effect). Paleogeographical gradient and rapid, well-documented environmental changes controlled by eustatic and tectonic changes make the northern part of the Carpathian Foredeep is regarded as a model example of dynamic stratigraphy.

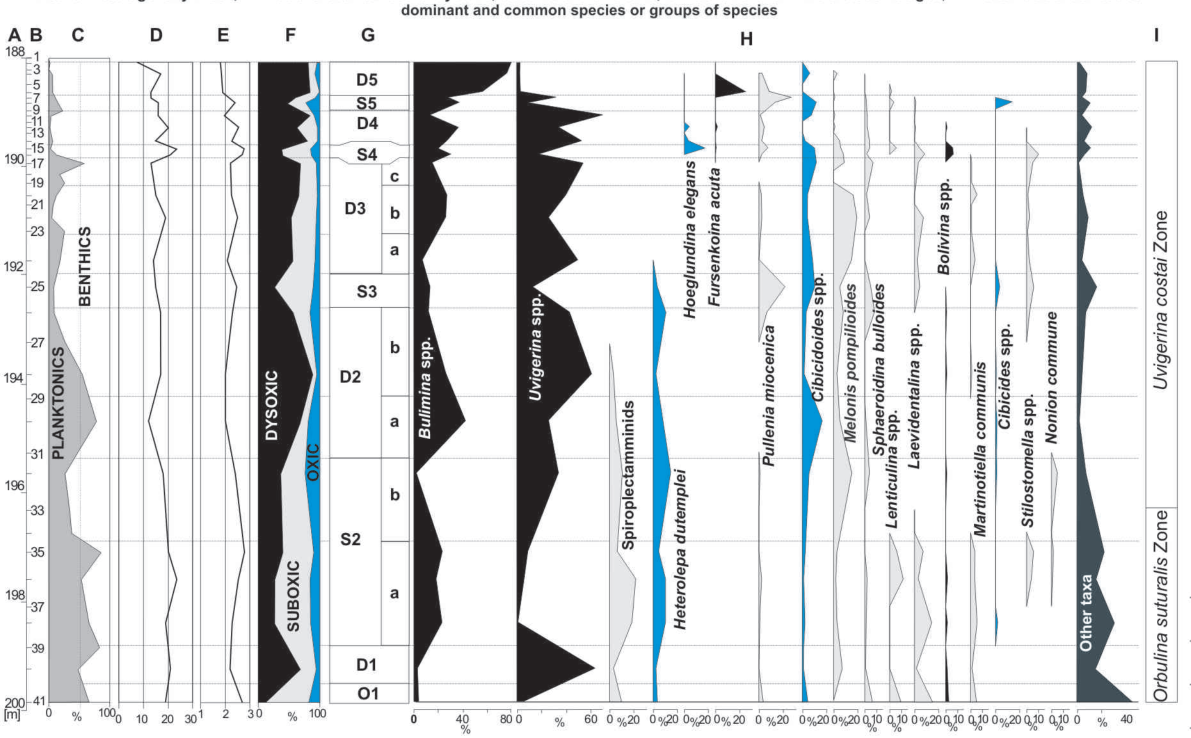
GEOLOGICAL CROSS-SECTIONS THROUGH THE POLISH CARPATHIAN FOREDEEP

(Peryt, 2012, after Oszczypko et al., 2006 and Krzywiec, 2006 - I; Oszczypko et al., 2006 - II and IV; Chowaniec et al., 2010 - III; Buła & Habryn, 2010 - V)



THE BUSKO (MŁYNY) PIG1 BOREHOLE SECTION STUDIED (BELOW GYPSUM)

A – depth; B – sample number; C – relative abundance of planktonic and benthic foraminifers; D – simple benthic diversity (number of species); E – H(S) – Shannon-Weaver heterogeneity index; F – relative abundances of dysoxic, suboxic and oxic taxa; G – benthic foraminiferal assemblages; H – relative abundances of dominant and common species and groups of species

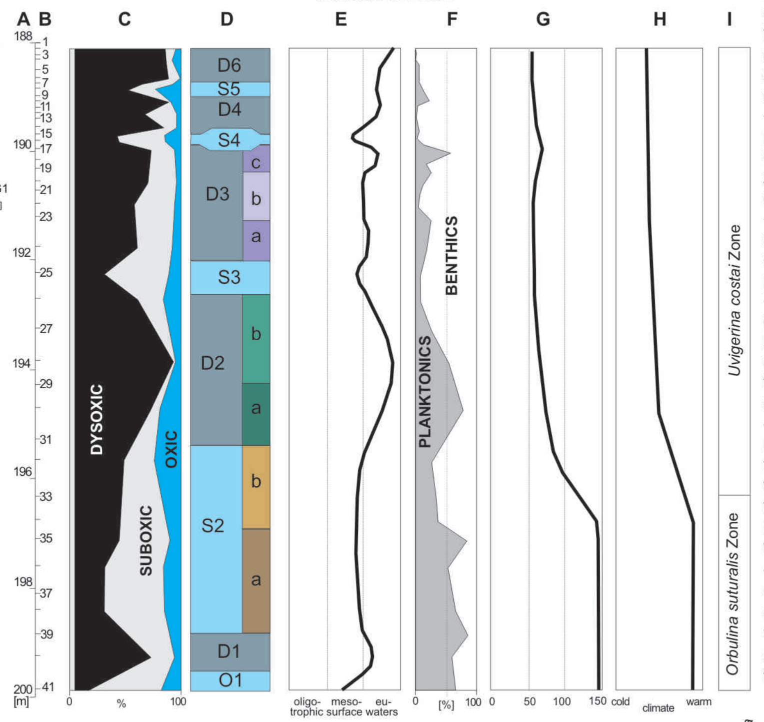


THE ONSET OF BADENIAN EVAPORITE DEPOSITION: FORAMINIFERAL RECORD

The Badenian section in the northern part of the Carpathian Foredeep Basin in Poland is tripartite owing to the occurrence of the Krzyżanowice Formation (gypsum deposits up to 50 m thick) in the middle. Below the gypsum various carbonate and siliciclastic rock units up to several tens of metres thick occur; they are included into the Pińczów Formation. The upper part of the Pińczów Formation is composed of marls of the Baranów Beds. These marls are several to 100 metres thick.

SUMMARY OF ENVIRONMENTAL CHANGES PRIOR TO THE BADENIAN SALINITY CRISIS IN THE NORTHERN PART OF THE POLISH CARPATHIAN FOREDEEP BASED ON CHANGES IN FORAMINIFERAL ASSEMBLAGES IN THE BUSKO (MŁYNY) PIG 1 BOREHOLE

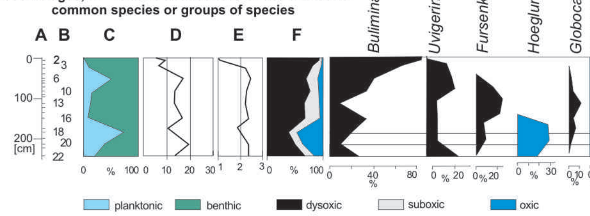
A – depth; B – sample number; C – proportion of dysoxic, suboxic and oxic forms in benthic foraminiferal assemblages; D – benthic foraminiferal zones (see the text for explanation); E – relative abundances of planktonic foraminifers; F – abundance fluctuation of planktonic and benthic forms in foraminiferal assemblages; G – benthic foraminiferal assemblages; H – climatic changes; I – foraminiferal zones



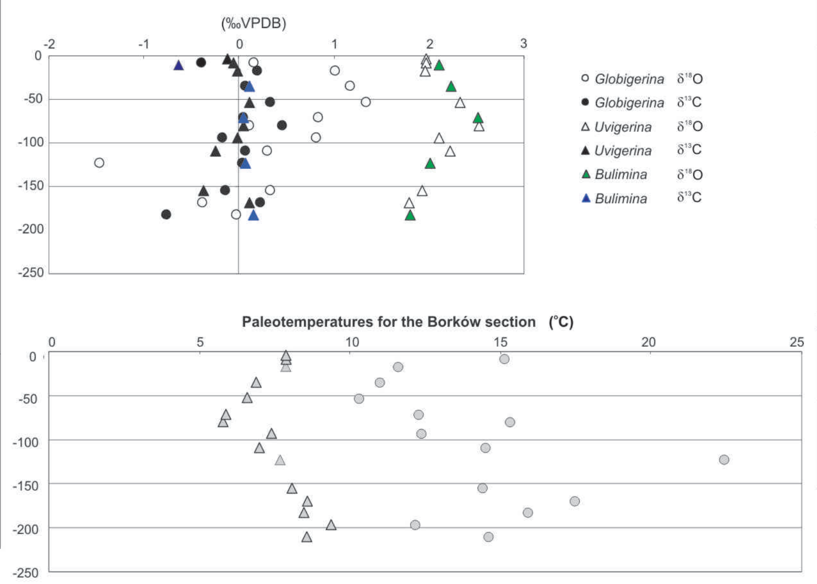
- Seventy-four samples of marls occurring below the mid-Badenian gypsum in three sections from the northern part of the Połaniec Trough: Busko (Młyny) PIG 1 borehole section and Leszcze and Borków quarries, yielded rich foraminiferal assemblages. In the Busko (Młyny) PIG 1 borehole, sixty-seven benthic and twenty one planktonic taxa were found.
- Benthic foraminiferal assemblages (mostly calcareous forms; agglutinated foraminifera are represented only by four species) of the studied interval (12 m thick) in the Młyny borehole are characterized by the dominance of *Bulimina* and *Uvigerina*. Planktonic foraminifers are composed mainly of warm-water orbulinids (*Orbulina suturalis* and *O. bilobata*) and *Globigerinoides* spp. in the lower part of the section and by cool-water *Globigerina* spp. in the upper part.
- Taxonomic composition of foraminiferal assemblages makes it possible to distinguish two foraminiferal zones in the Młyny borehole: Orbulina suturalis and Uvigerina costai. The boundary between the two zones is located at a depth of 196.3 m. In the Leszcze and Borków quarries only the Uvigerina costai Zone is accessible.
- The foraminiferal record from the Uvigerina costai Zone of the Młyny section indicates a longer period of high primary productivity and eutrophication of surface waters interrupted by a few short lasting periods with a return to mesotrophic or nearly oligotrophic conditions.
- The benthic foraminiferal successions in the studied interval suggest oxygenation and productivity changes in the Carpathian Foredeep Basin prior to the Badenian salinity crisis. Four intervals of dysoxic conditions alternated with intervals with good oxygenation at the sea-floor, and eight assemblages have been distinguished in the Młyny section.
- The upsection decrease in the proportion of planktonic foraminifers reflects the shallowing of the basin accompanied by a decrease in the temperature gradient between the upper (warmer) and deeper (colder) waters. The replacement of intermediate warm-water planktonic foraminiferal assemblages by *Globigerina*-dominated assemblages (mainly *G. bulloides*) is related to the Middle Miocene climate transition widely recorded in the middle Badenian of the Paratethys area.
- The $\delta^{18}O$ and $\delta^{13}C$ ratios of two foraminiferal taxa: *Globigerina* (in most cases, *G. bulloides*) and *Uvigerina* (mostly *U.* ex gr. *peregrina*), were studied in 52 samples. Total foraminiferal samples had a mean $\delta^{13}C$ value of –0.31 ± 0.43 for *Uvigerina* and 0.15 ± 0.49‰ for *Globigerina*, and a mean $\delta^{18}O$ value of 1.99 ± 0.64‰ for *Uvigerina* and 0.77 ± 0.95‰ for *Globigerina*.
- There is a clear change in the paleotemperature of water in which foraminifers lived at the boundary between the Orbulina suturalis and Uvigerina costai zones. The observed changes in the water paleotemperature are in concert with the stronger signal of the Badenian cooling trend in the Carpathian Foredeep assumed previously.
- Below the gypsum, the $\delta^{18}O$ values of both benthic and planktonic foraminifers show quite large variations that are possibly due to the salinity increase.

THE BORKÓW SECTION STUDIED BELOW GYPSUM

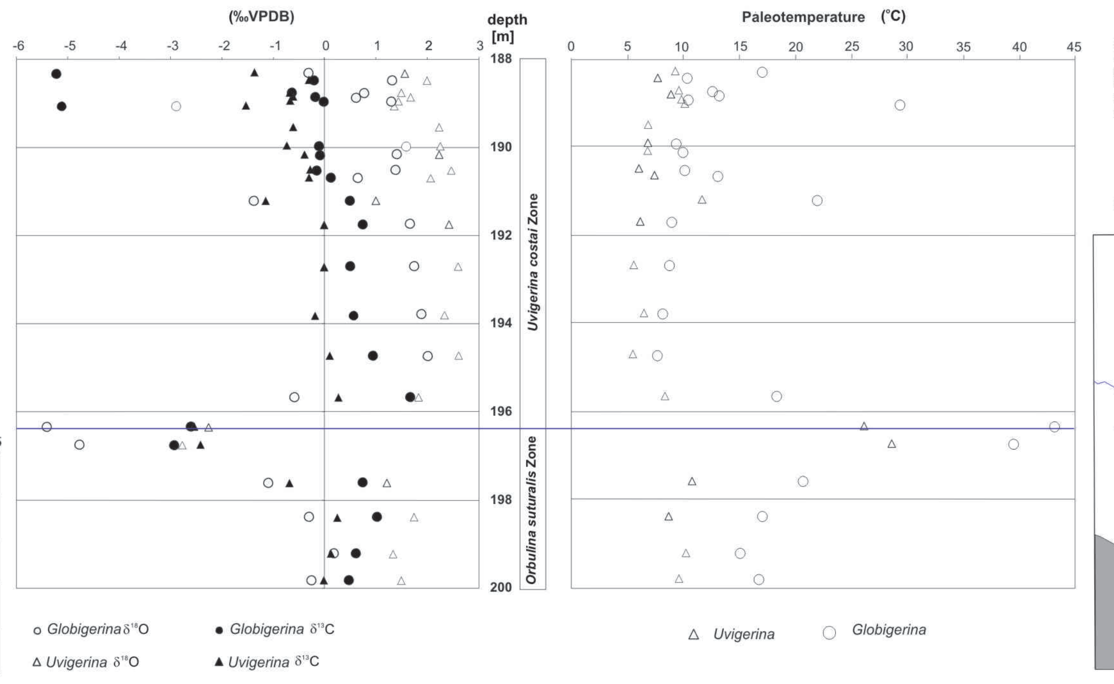
A – depth; B – sample number; C – relative abundance of planktonic and benthic foraminifers; D – simple benthic diversity (number of species); E – H(S) – Shannon-Weaver heterogeneity index; F – relative abundances of dysoxic, suboxic and oxic taxa; G – benthic foraminiferal assemblages; H – relative abundances of dominant and common species or groups of species



BENTHIC AND PLANKTONIC $\delta^{13}C$ AND $\delta^{18}O$ ISOTOPE RECORDS FOR THE BORKÓW SECTION AND CALCULATED PALEOTEMPERATURES OF AMBIENT SEA WATER

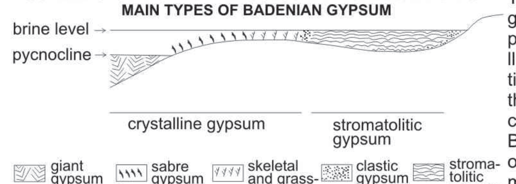


BENTHIC AND PLANKTONIC $\delta^{13}C$ AND $\delta^{18}O$ ISOTOPE RECORDS FOR THE MŁYNY (BUSKO) PIG 1 BOREHOLE SECTION AND CALCULATED PALEOTEMPERATURES OF AMBIENT SEA WATER



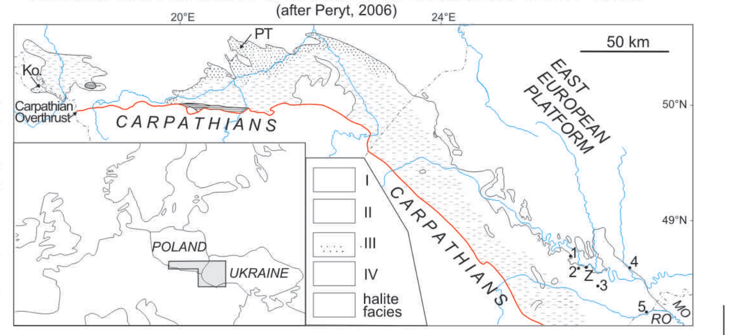
BADENIAN EVAPORITE DEPOSITION AND RANGES OF $^{87}Sr/^{86}Sr$ RATIOS

SCHEME SHOWING THE PALEOGEOGRAPHICAL ZONATION OF MAIN TYPES OF BADENIAN GYPSUM

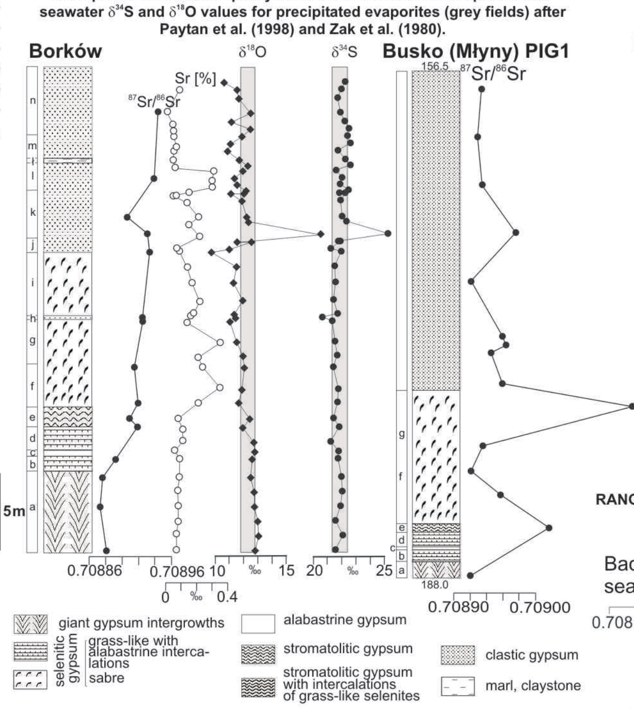


There are three principal gypsum facies in the Carpathian Foredeep: crystalline gypsum, stromatolitic gypsum (both: autochthonous) and clastic (allochthonous) gypsum, in the Badenian gypsum, the oldest widespread primary marine gypsum.

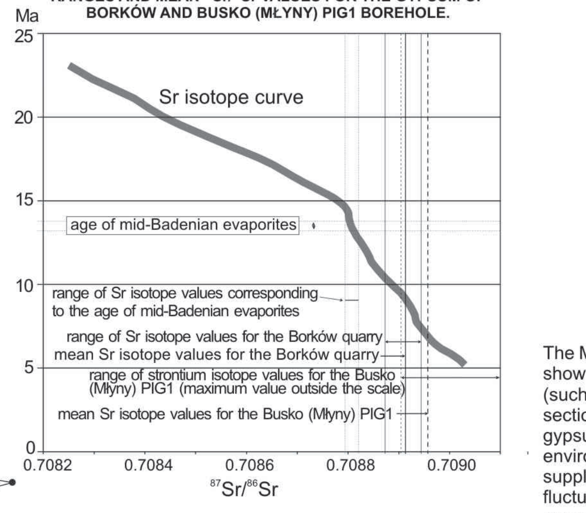
BADENIAN EVAPORITE FACIES IN THE NORTHERN CARPATHIAN FOREDEEP BASIN (after Peryt, 2006)



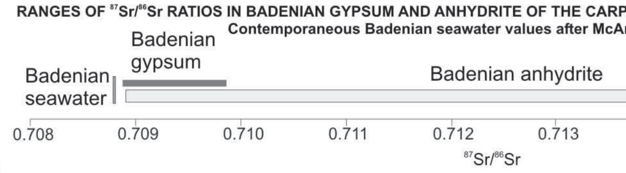
BORKÓW GYPSUM QUARRY SECTION AND THE GYPSUM SECTION OF THE BUSKO (MŁYNY) PIG1 BOREHOLE, AND THEIR $^{87}Sr/^{86}Sr$ RATIOS. In addition, strontium content (after Peryt et al., 1994) and sulfur and oxygen isotopes of the Borkow quarry section are shown. Contemporaneous seawater $\delta^{34}S$ and $\delta^{18}O$ values for precipitated evaporites (grey fields) after Paytan et al. (1998) and Zak et al. (1980).



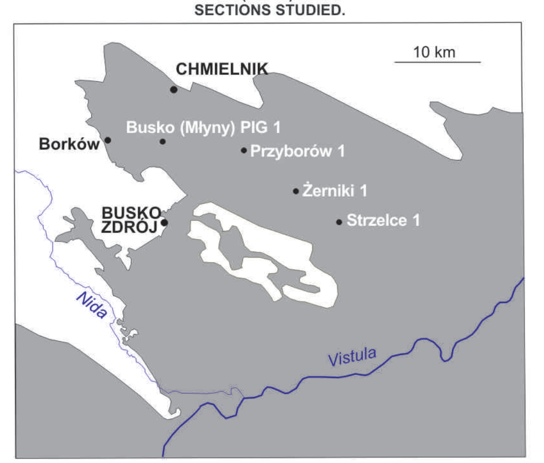
Sr ISOTOPE CURVE (after McArthur et al., 2001) SHOWING THE RANGES AND MEAN $^{87}Sr/^{86}Sr$ VALUES FOR THE GYPSUM OF BORKÓW AND BUSKO (MŁYNY) PIG 1 BOREHOLE.



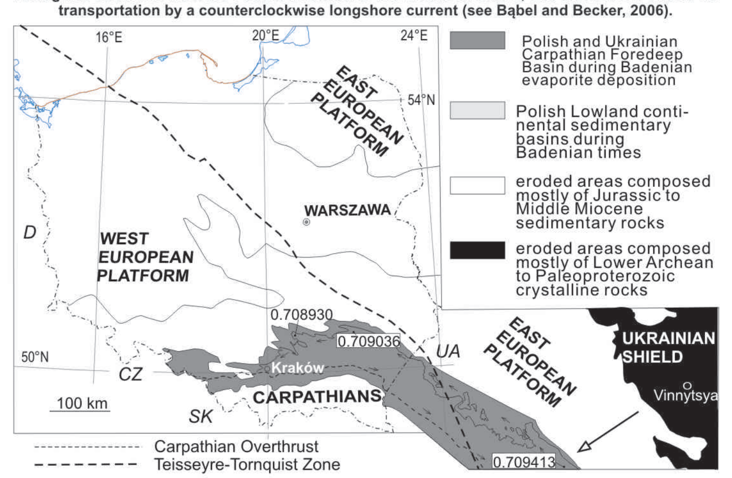
RANGES OF $^{87}Sr/^{86}Sr$ RATIOS IN BADENIAN GYPSUM AND ANHYDRITE OF THE CARPATHIAN FOREDEEP IN POLAND AND UKRAINE. Contemporaneous Badenian seawater values after McArthur et al.. (2001).



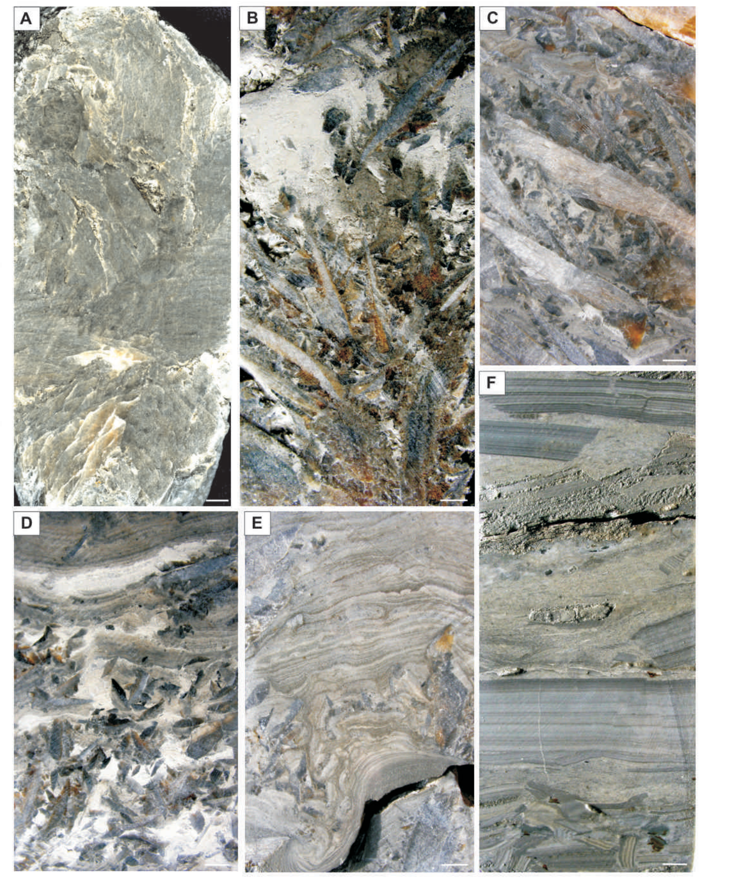
NORTHERN PART OF THE POŁANIEC TROUGH SHOWING THE OCCURRENCE OF GYPSUM (GREY) AND THE LOCATION OF THE SECTIONS STUDIED.



GEOLOGICAL FRAMEWORK OF THE BADENIAN EVAPORITE BASINS. The average $^{87}Sr/^{86}Sr$ ratios for gypsum from three areas: the Połaniec Trough, the Pysznica U-19 borehole and Mamalyha are shown. Thick arrow shows possible direction of riverine supply of radiogenic strontium from the Podolian domain of the Ukrainian Shield, and black arrow shows its transportation by a counterclockwise longshore current (see Bąbel and Becker, 2006).

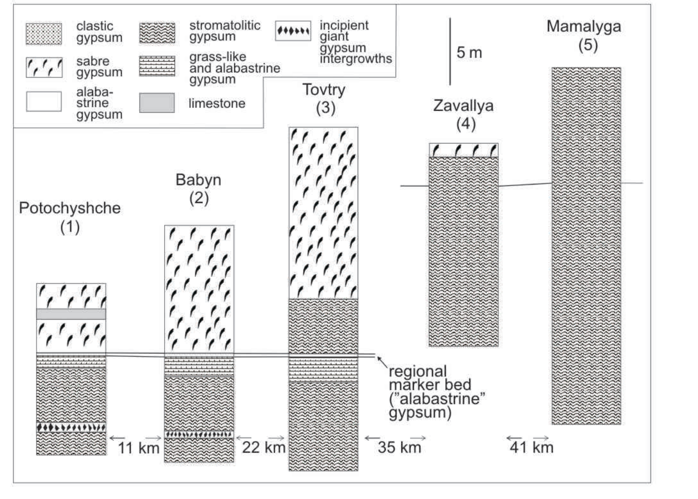


GYPSUM FACIES IN THE BUSKO (MŁYNY) PIG 1 BOREHOLE.
A - Giant gypsum intergrowths (partly distorted); B and C - Sabre gypsum; D - Skeletal gypsum, with elongate rod-like and chaotically arranged selenite crystals in a matrix of granular gypsum. Between the gypsum crystals clay and carbonate grains forming distinct partings and pockets occur; E - Laminated, distorted gypsum above sabre gypsum (lower right corner); F - Clastic gypsum composed on intercalated gypsum breccia and laminated gypsum.

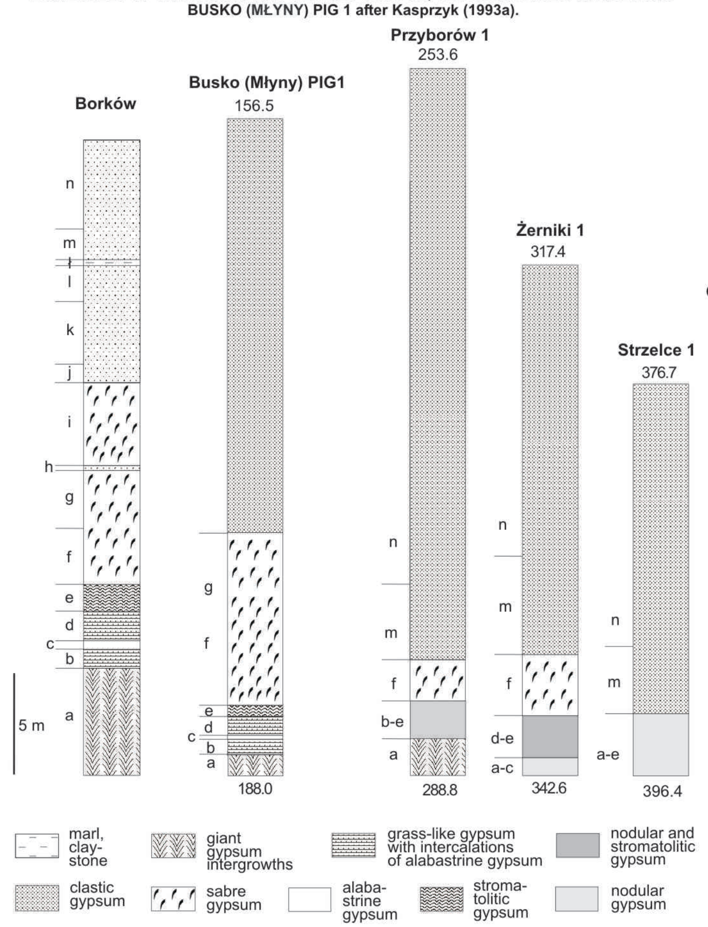


The Middle Miocene Badenian primary gypsum faciesin northern part of Central Paratethys show a distinct palaeogeographical zonation. In particular, characteristic gypsum facies (such as giant gypsum intergrowths or sabre gypsum) and their frequency in the vertical section are useful environmental indicators. Some gypsum units (in particular, "alabastrine" gypsum beds) as well as intercalations of fine siliciclastic deposits register important environmental changes such as the subaerial exposure of vast part of the basin or increased supply of clay materials, which could be climatically-driven. In addition to pycnocline level fluctuations which were an important control on the development of gypsum facies and the appearance of incipient giant gypsum intergrowths within the stromatolitic gypsum unit in western Ukraine, the following factors exerted the control on the development and the correlation potential of gypsum units: brine level fluctuations including brine sheets and floods; rare marine transgressions; pedogenesis leading to alabastrine gypsum development; rate of inflow of continental water. There were two main phases of gypsum basin development. During the first phase autochthonous gypsum types (mostly crystalline and stromatolitic) were dominant, and the second phase was dominated by allochthonous gypsum deposition. In southern Poland, a distinct basinward trend for the decrease of sharing autochthonous gypsum and the increase of sharing allochthonous gypsum in the vertical section is observed. This implies that during their major part the sulphates in the basin zone were coeval with allochthonous, later part of the gypsum section in the marginal part of the Badenian Basin.

GYPSUM SECTIONS BETWEEN POTOCHYSHCHE (LOCATED 18 KM NW OF ZALYSHCHYKY) AND MAMALYGA (LOCATED 75 KM SE OF ZALYSHCHYKY)



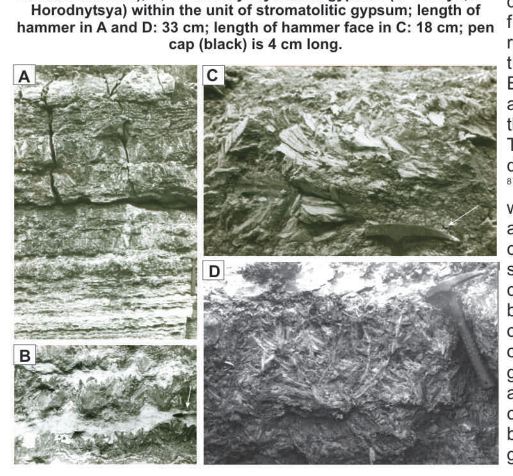
BADENIAN GYPSUM SEQUENCE IN BORKÓW (after Peryt and Jasionowski, 1994) AND IN BOREHOLES OF THE NORTHERN POŁANIEC TROUGH; SECTIONS OTHER THAN BUSKO BUSKO (MŁYNY) PIG 1 after Kasprzyk (1993a).



Primary gypsum carries and generally retains the strontium isotopic composition of the water from which it precipitated. Post-depositional alteration of the strontium isotopic signature is very unlikely in the Badenian primary gypsum as the passage of large amounts of water containing foreign strontium would be necessary to change the ratio. Thus, the Sr isotopic composition of the Badenian gypsum sections reflects the original salina water gypsum formed from brines of marine origin that were subject to an important inflow of continental waters (cf. Cendon et al., 2004). The studied sections are characterized by consistently increasing $^{87}Sr/^{86}Sr$ values. Assuming that the Badenian gypsum was formed between 13.8 Ma and 13.2 Ma, and taking into consideration the upper and lower confidence limits (McArthur et al., 2001), the resulting $^{87}Sr/^{86}Sr$ values are expected to be between 0.708798 and 0.708810. The Borkow gypsum section shows steadily higher $^{87}Sr/^{86}Sr$ values than expected for a Middle Miocene open ocean and even higher values are recorded in the Busko (Mlyny) PIG1 borehole. The riverine runoff in Middle Miocene times was from two main directions: The first was the West and East European platforms and the second was the Carpathian area. There is a distinctive decreasing trend of $^{87}Sr/^{86}Sr$ ratios from western Ukraine toward the NW. This is in concert with a reconstruction of counterclockwise longshore brine circulation based on the measurements of upstream-directed gypsum crystals that are the product of a consistent direction of brine inflow during gypsum crystallization.

ASPECTS OF THE LOWERMOST PART OF GYPSUM SEQUENCE IN WESTERN UKRAINE

A - Oleshiv (stromatolitic gypsum unit overlain by intercalated stromatolitic and selenitic gypsum and then the alabastrine gypsum of the regional marker bed 1), B - Dubivtsi (intercalations of stromatolitic and selenitic gypsum showing flat laminations of selenite clusters), C, D - blocky crystalline gypsum (C - Babyn, D - Horodnytsya) within the unit of stromatolitic gypsum; length of hammer in A and D: 33 cm; length of hammer face in C: 18 cm; pen cap (black) is 4 cm long.



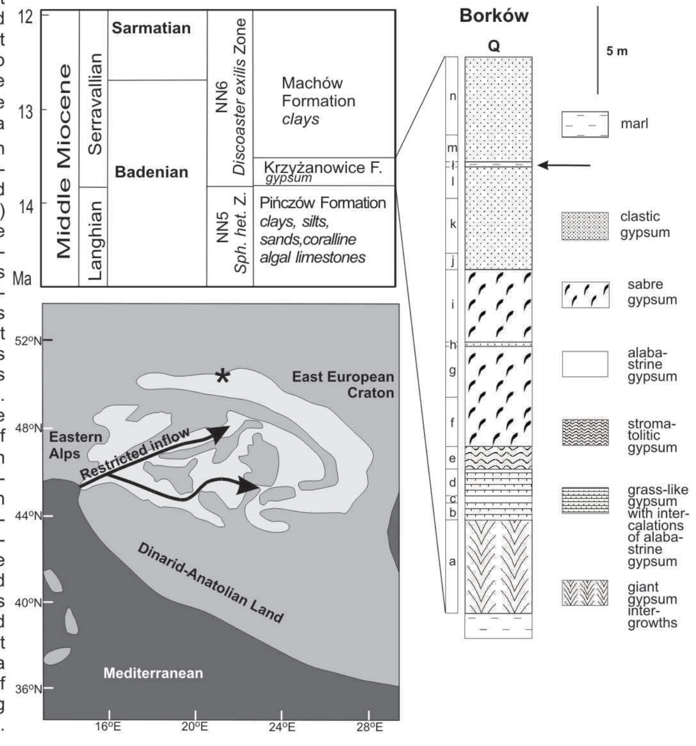
MARINE TRANSGRESSION DURING DEPOSITION OF BADENIAN EVAPORITES

Particular Paratethyan basins, such as the Carpathian Foreland Basin, were intercommunicating, with periodical phases of isolation, until by the end of the Middle Miocene (Late Badenian) Paratethys communications with the Mediterranean and Indian Ocean restricted and eventually closed. One of severe restrictions of the Central Paratethys at 13.81 Ma (de Leeuw et al., 2010) induced hypersaline conditions that led to the deposition of evaporites in various basins of the Carpathian region; the direct trigger of the restriction was global climatic cooling attributed to the Middle Miocene climate transition at ~13.95 to 13.76 Ma. The Badenian evaporite basin was located below the contemporaneous sea level and thus it could be subject to rapid floods when the sea level rose or when the physical barrier blocking the basin from the Tethys/Paratethys reservoir was temporarily removed. The occurrence of fauna was reported from the clay intercalations in the upper part of the Badenian gypsum sequence of various parts of the northern Polish Carpathian Foredeep Basin. It is possible that these intercalations are fillings of the karst voids by the Upper Badenian Pecten Beds.

Geological setting

The fossiliferous intercalation at Borków, one of the key sections in the Badenian evaporite basin of Central Paratethys, contains well preserved foraminiferal assemblages that have originated during deposition of gypsum sequence. The strata which underlie and overlie this fossiliferous intercalation have originated in a very shallow environment typical of evaporitic shoals (<1 m deep); hence the intercalation indicates important transgression and a short-time paleoenvironmental change to significantly lower, close to normal-marine, salinities. The aim of this paper is environmental analysis of the foraminifers that are important, sensitive indicators in coastal and marginal marine settings. The gypsum deposits are 32 m thick in the Borków quarry. The gypsum top is eroded and covered with the Quaternary clastics, but in the sinkholes, Upper Badenian strata occur containing foraminiferal assemblage with numerous and very well preserved benthic and planktonic foraminifers. The gypsum deposits of the Carpathian Foredeep Basin form a laterally extensive sequence, and particular gypsum units can be traced in the marginal part of the mid-Badenian evaporite basin at the distance of 700 km, from Moravia, Czech Republic in the west through southern Poland and western Ukraine to the Ukrainian-Romanian borderland. Eighteen lithological units, from a to r, have been distinguished in the gypsum profile, and fifteen of them (a - n) occur in the Borków quarry section. The lower member (a to c), rock in the Borków section contains crystalline gypsum with intercalations of alabastrine and stromatolitic gypsum. The upper member of the gypsum sequence (units j-n of total thickness of ca 12 m in Borków) consists primarily of gypsum-arenites, gypsum-rudites and laminated gypsum. Remarkable outcrop features are the irregular bottom surfaces distinctive of the units i and m are interpreted as the result of dissolution-related deformation. Bąbel (1999) assumed that gypsified organic mats in the lower part of unit m represent environment of an evaporitic shoal (<1 m deep), similar to that in which local intercalations of grass-like gypsum with thin crusts and patches of bottom-grown gypsum crystals in the layer k have originated. Unit k-m are representative of the shallow-water facies association which is very similar to that formed recently in ephemeral salinas and mudflats of South and Western Australia and along the Mediterranean coast.

STRATIGRAPHIC POSITION OF AND GYPSUM SUCCESSION IN THE BORKÓW QUARRY SECTION AND SIMPLIFIED PALEOGEOGRAPHIC RECONSTRUCTION OF CENTRAL PARATETHYS (light grey) ca. 13.8 Ma (after de Leeuw et al., 2010); black arrow shows the stratigraphic position of foraminifers discussed.



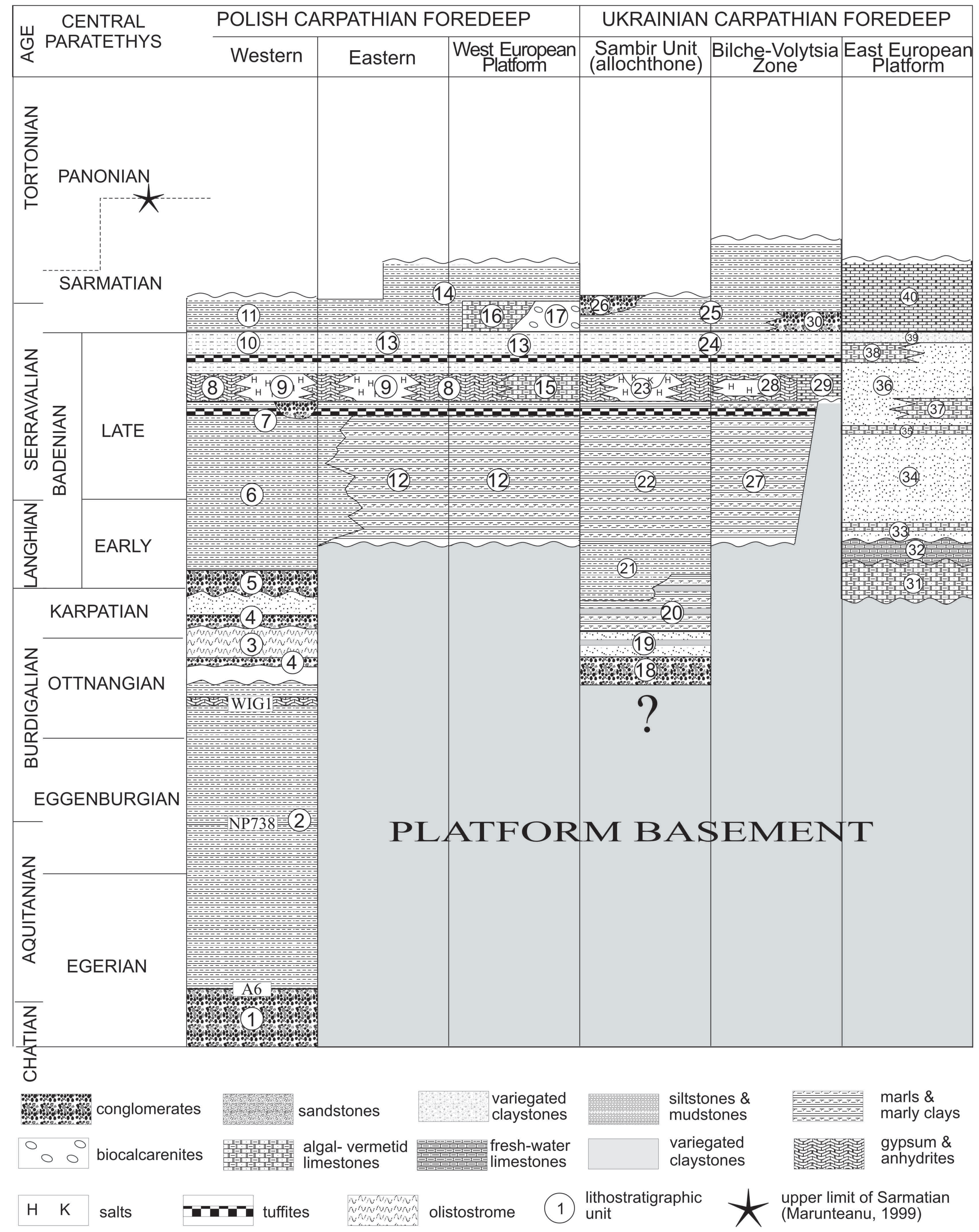

POSITION OF THE POLISH & UKRAINIAN CARPATHIAN FOREDEEP IN THE ALPINE-CARPATHIAN SYSTEM (after Picha, 1996)

GEOLOGICAL BACKGROUND

The Paratethys was an epicontinental sea that developed as a relic of the Tethys. It existed from the Early Oligocene to late Middle Miocene times, and until the Middle Miocene it was in communication with the normal marine environments of the Mediterranean Basin and Indian Ocean. The repeated occurrence of isolation resulted in several salinity crises in the Carpathian region and other places in the Eastern Paratethys as well as in the Red Sea and the Middle East. The Middle Miocene salinity crisis in the Central Paratethys started shortly after 13.81 ± 0.08 Ma, as indicated by $^{40}Ar/^{39}Ar$ dating of volcanic tuffs below and within the Badenian salts in southern Poland (de Leeuw et al., 2010). The major step in Middle Miocene global cooling is dated at 13.82 ± 0.03 Ma in the Mediterranean and because of this temporal relationship the cooling is interpreted to be the trigger of evaporite deposition (de Leeuw et al., 2010). The temperature decline after the Miocene climatic optimum that preceded evaporite deposition found its expression in the disappearance of warm-water planktonic foraminiferal assemblages and the expansion of the cool-water populations that was recorded both in the Paratethys and the Tethys area. The signal of the Badenian cooling trend in the Carpathian Foredeep is stronger than in the Mediterranean possibly due to the changing circulation.

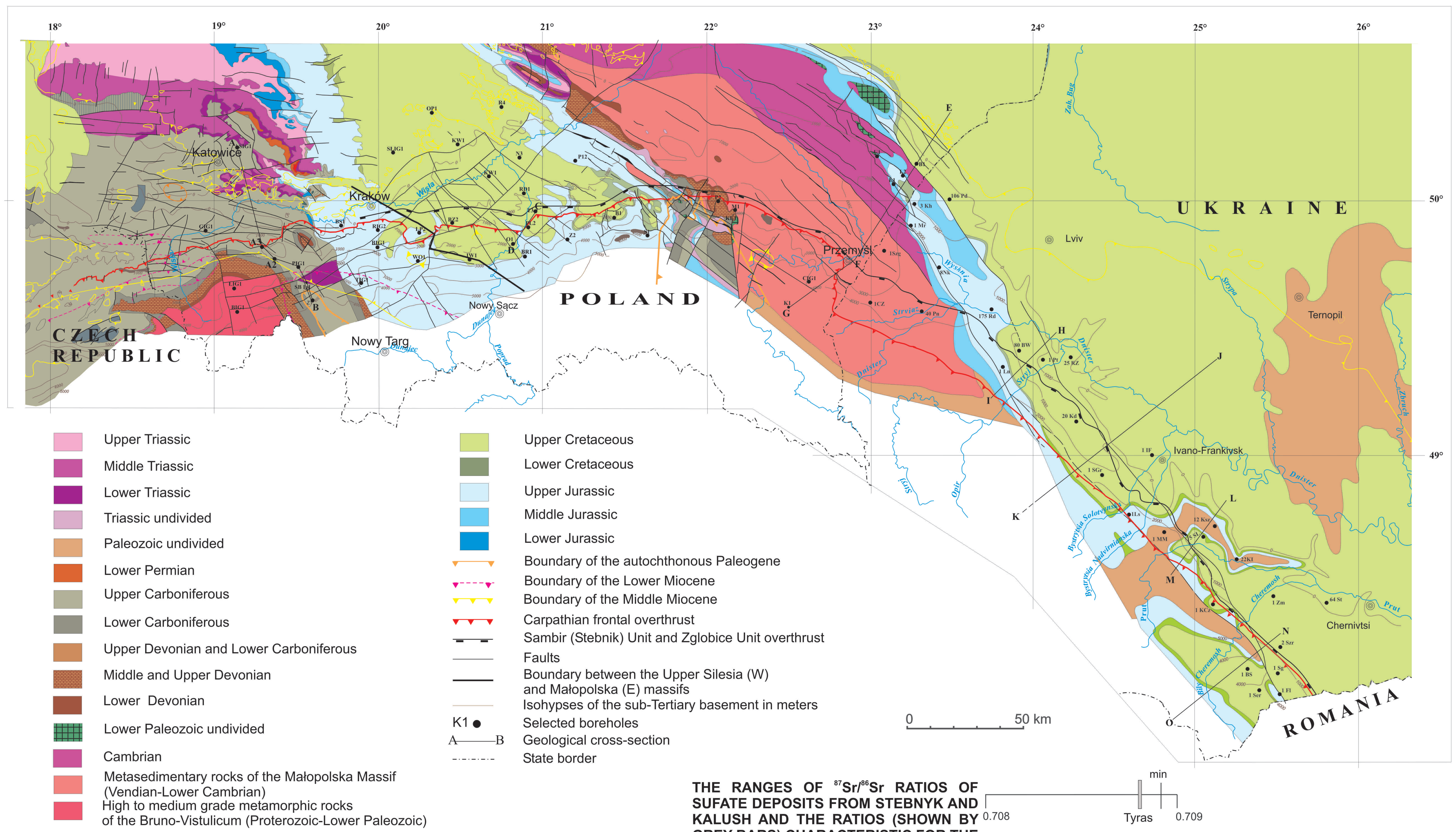
The Middle Miocene salinity crises was preceded by other, Early Miocene salinity crises which are recorded in the Ukrainian Carpathian Foredeep.

REGIONAL STRATIGRAPHIC SCHEME OF THE MIOCENE DEPOSITS OF THE POLISH AND UKRAINIAN CARPATHIAN FOREDEEP (after Oszczypko et al., 2006)



Lithostratigraphic unit: 1 - Andrychów Fm., 2 - Zebrzydowice Fm., 3 - Sucha Fm. - flysch olistoplaque, 4 - Stryszawa Fm., 5 - Debowiec Cgl., 6 - Skawina Fm., 7 - Sypka Góra Cgl., 8 - Krzyzanowice Fm., 9 - Wieliczka Fm., 10 - Gliwice beds, 11 - Kedzierzyn beds; 12 - Baranów beds, 13 - Chodenice and Grabowiec beds, 14 - Krakowiec beds, 15 - sulphur-bearing limestones, 16 - algal -vermetid reef limestones, 17 - biocalcarenites of the Chmielnik Fm.; 18 - Sloboda Conglomerate, 19 - Dobrotiv Formation, 20 - Stebnyk Formation, 21 - Balych Formation, 22 - Bohorodchany Formation, 23 - Kalush (Tyras) Formation, 24 - Kosiv Formation, 25 - Dashava Formation - 26 - Radych beds, 27 - Zhuriv Formation, 28 - Tyras Formation, 29 - Ratyn Limestone, 30 - Pistyn conglomerates, 31-Nahoryany (Oncophora) beds, 32 - Berezhany beds, 33 - Baraniv beds, 34 - Mykolaiv beds, 35 - Naraiv beds, 36 - Rostoche and Kaiserwald beds, 37 - Kryvchytsi beds, 38 - Ternopil beds, 39 - Buhliv beds, 40 - Volyn beds,

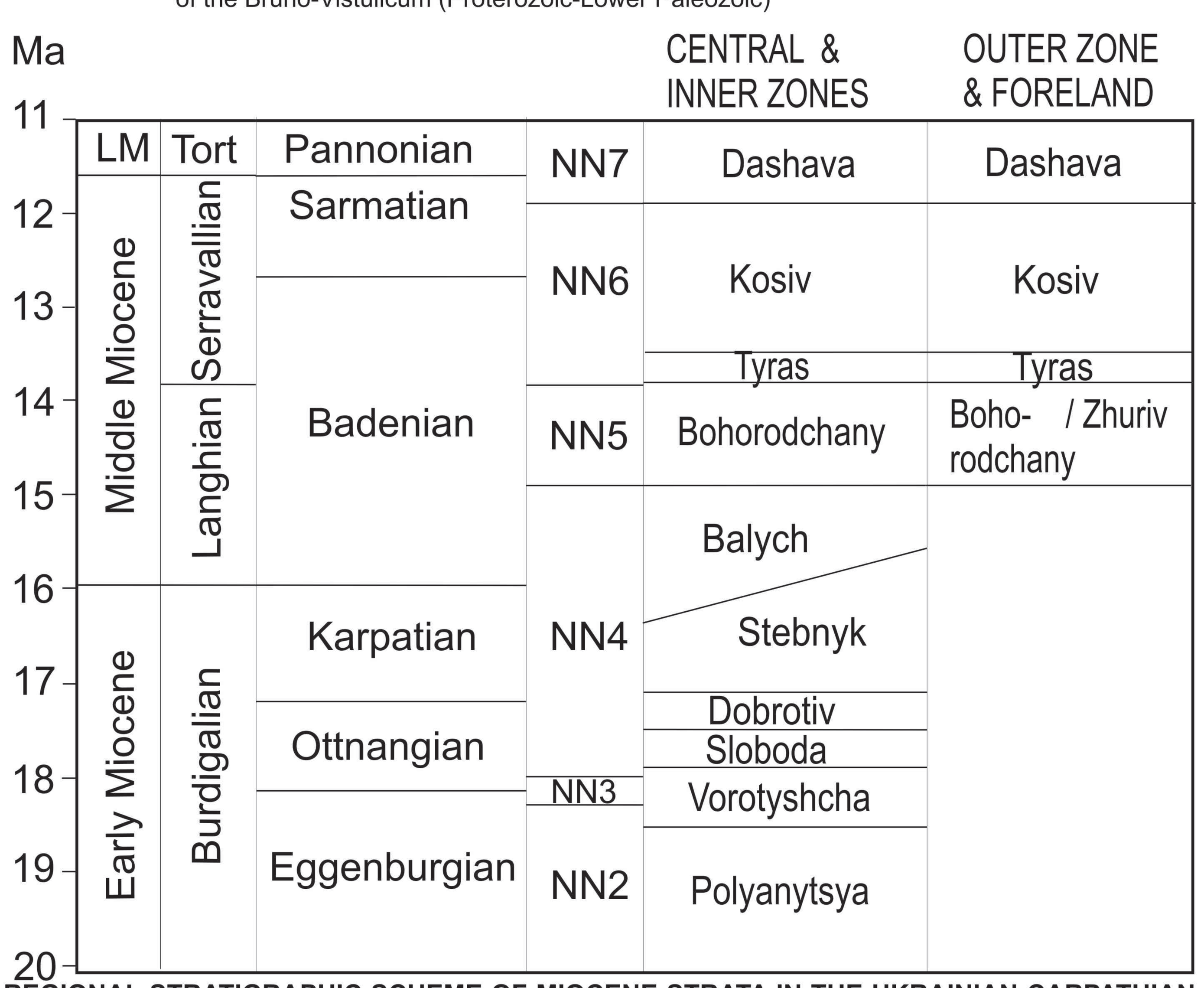
GEOLOGICAL MAP OF THE PRE-TERTIARY BASEMENT IN THE POLISH & UKRAINIAN CARPATHIAN FOREDEEP (after Oszczypko et al., 1996)



The early to middle Miocene Carpathian Foredeep developed as a peripheral foreland basin related to the moving Carpathian front (Oszczypko et al., 2006). The molasse deposits of the Ukrainian Carpathian Foredeep are up to 6 km thick. Three tectonic zones are distinguished: outer (Bilche-Volytsya), central (Sambir Nappe thrusted over the foreland) and inner (Boryslav-Pokutt'a Nappe, thrusted over the Sambir Nappe and the underlying foreland).

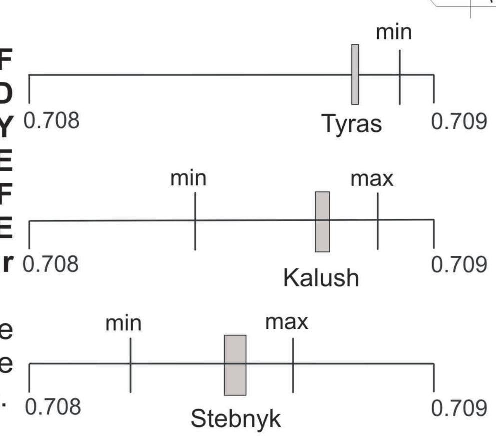
The potash-bearing sequence of the Kalush deposit occurs in the central tectonic zone and consists of interbedded salt claystones, salt breccias, potash and rock salt, up to 500 m thick but ithe unfolded thickness of this sulfate potash complex is 38.5 m. The Vorotyshcha Formation hosting the Stebnyk deposit of the inner zone shows a total thickness more than 2000 m but the original section was 100-125 m thick.

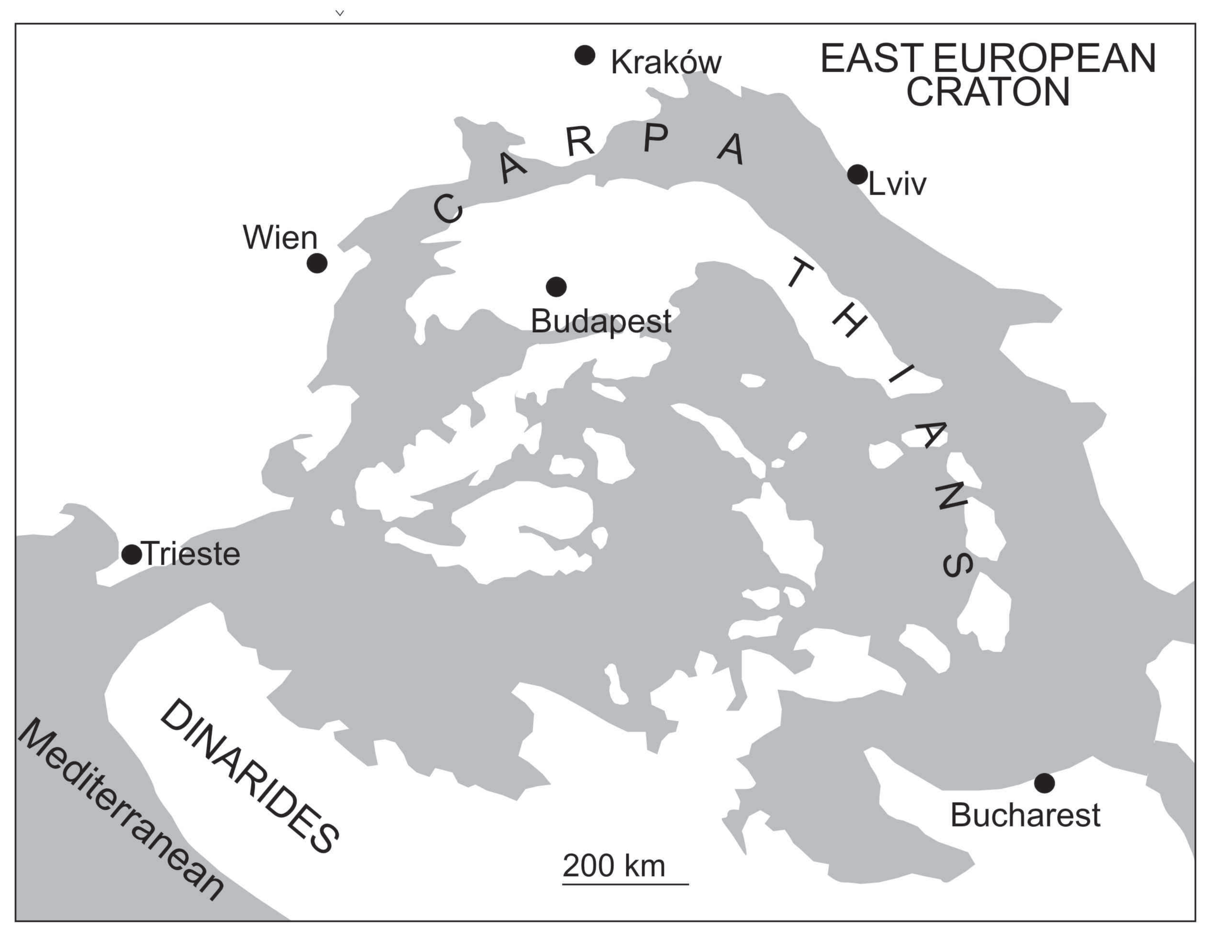
Sr isotope data indicate that the Miocene evaporites of the Carpathian Foredeep show a major variation of their $^{87}Sr/^{86}Sr$ ratios that are clearly lower or higher than the ratios of the contemporaneous seawater. The higher $^{87}Sr/^{86}Sr$ ratios could be explained by the incorporation of more radiogenic Sr during diagenetic alteration, and the lower $^{87}Sr/^{86}Sr$ ratios in turn reflect the impact of riverine inflow from the Carpathians (built of mostly Cretaceous and Palaeogene rocks) although they could have been modified during subsequent recrystallisation being related to major tectonic events that affected the area. The $^{87}Sr/^{86}Sr$ ratios for the Stebnyk and Kalush evaporites differ, although their ranges overlap in part. In turn, the Badenian anhydrites show invariably high radiogenic Sr, and thus the Badenian age for the Kalush evaporites is not supported by the Sr isotopic data that rather indicate their Karpatian age.



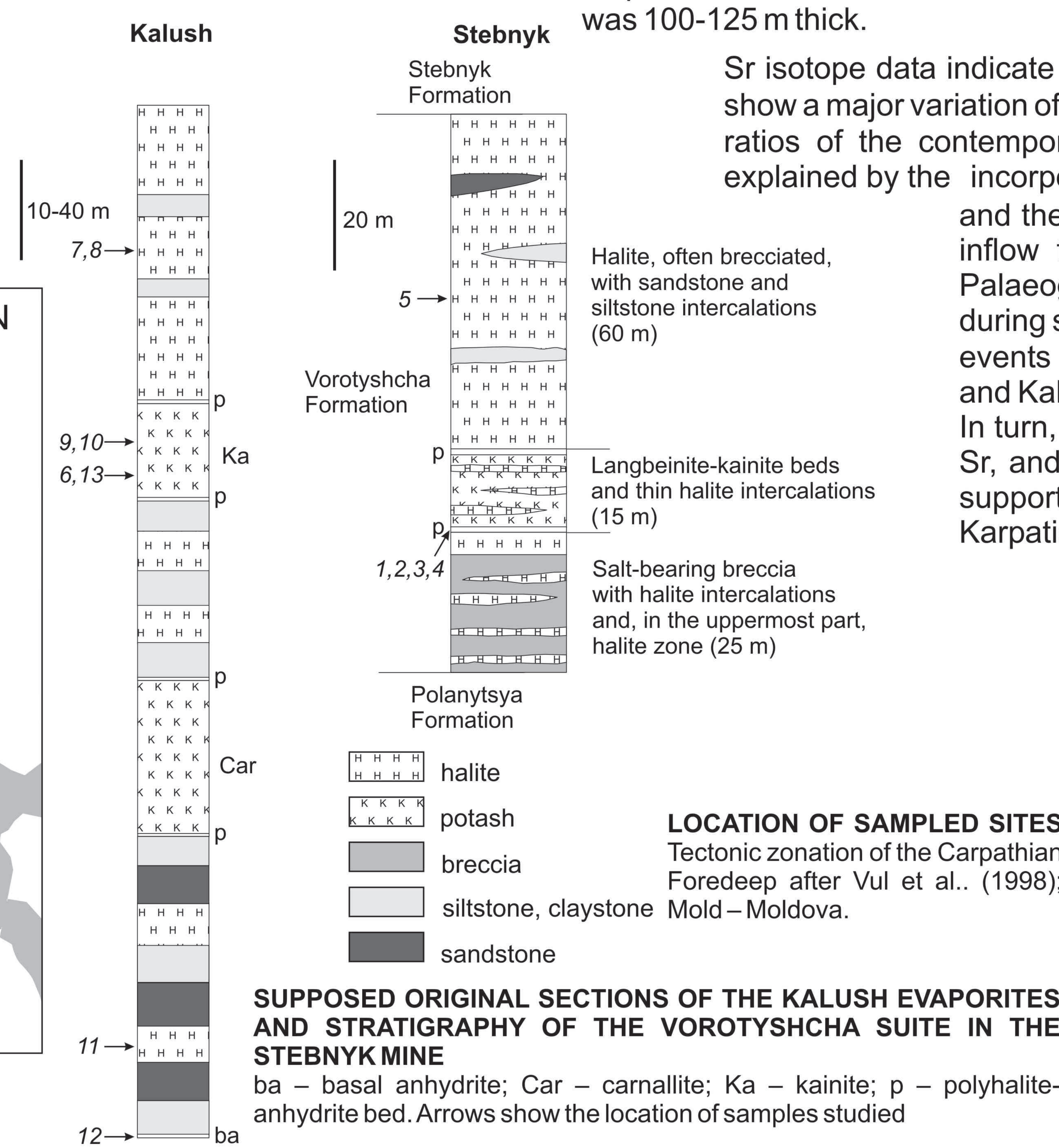
REGIONAL STRATIGRAPHIC SCHEME OF MIOCENE STRATA IN THE UKRAINIAN CARPATHIAN FOREDEEP (after Oszczypko et al., 2006; Andreyeva-Grigorovich et al., 2008; Vashchenko & Hnylko 2003; supplemented). The boundaries of formations are strongly diachronous but this is here visualized only in the case of the boundary of the Stebnyk and Balych formations.

THE RANGES OF $^{87}Sr/^{86}Sr$ RATIOS OF SUFATE DEPOSITS FROM STEBNYK AND KALUSH AND THE RATIOS (SHOWN BY GREY BARS) CHARACTERISTIC FOR THE EGGENBURGIAN (IN THE CASE OF STEBNYK) AND KARPATIAN (IN THE CASE OF KALUSH) SEAWATER (after McArthur et al., 2001).
In addition, the ratios characteristic for the Late Badenian seawater (grey bar) and the minimum ratio of the Tyras sulfates are shown.



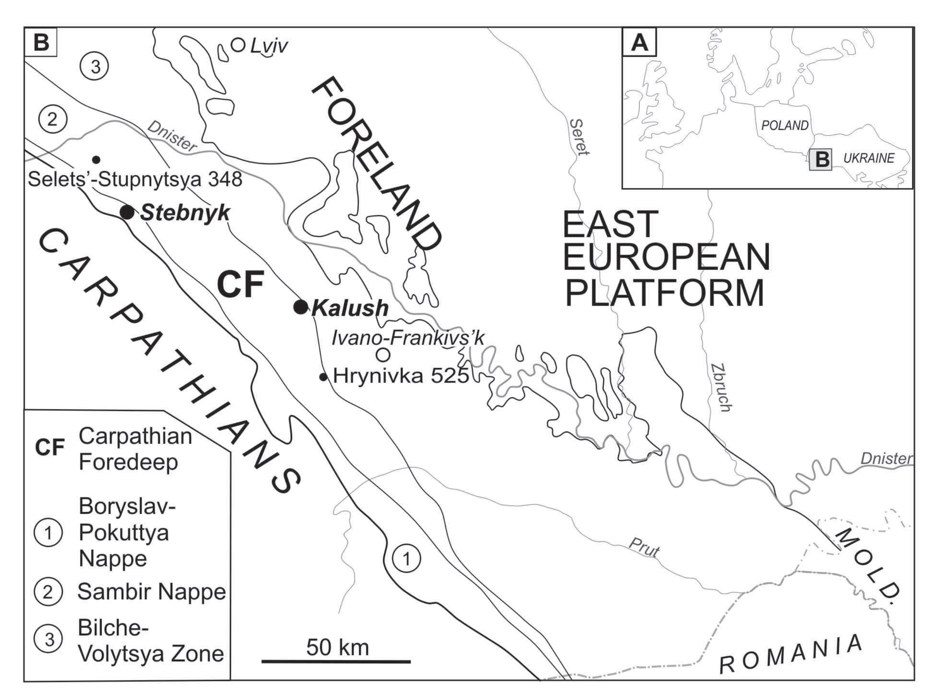


PALEOGEOGRAPHIC RECONSTRUCTION OF THE CENTRAL PARATETHYS (EARLY BADENIAN MARINE SEDIMENTATION; after Rögl, 1998)



SUPPOSED ORIGINAL SECTIONS OF THE KALUSH EVAPORITES AND STRATIGRAPHY OF THE VOROTYSHCHA SUITE IN THE STEBNYK MINE
ba – basal anhydrite; Car – carnallite; Ka – kainite; p – polyhalite-anhydrite bed. Arrows show the location of samples studied

LOCATION OF SAMPLED SITES
Tectonic zonation of the Carpathian Foredeep after Vul et al. (1998); Mold – Moldova.

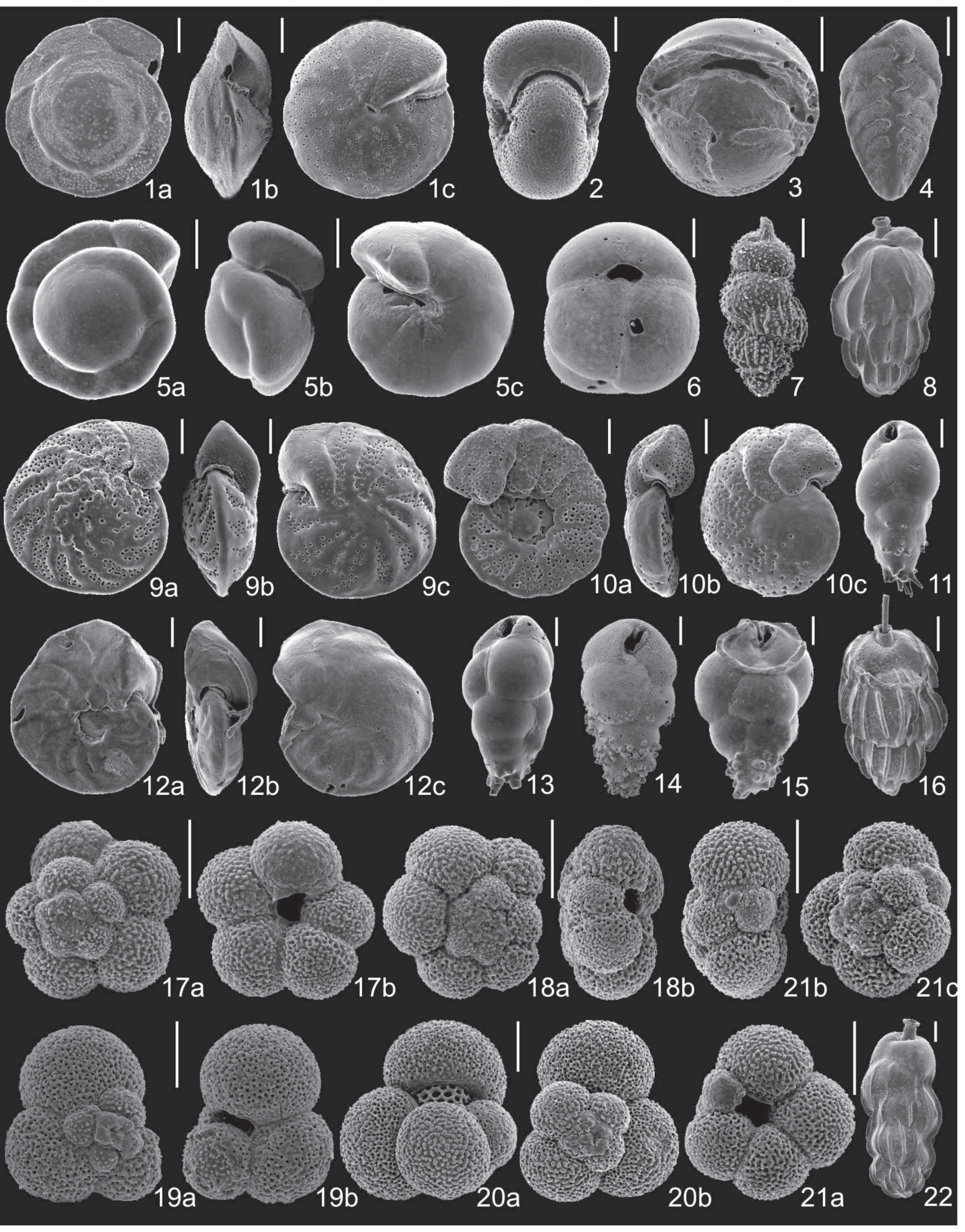


Results

Samples 1 and 2 were barren of foraminifera; samples A and 3 to 7 yielded very well-preserved of low diversity and very low abundance foraminiferal assemblages. Both benthic and planktonic foraminifers are recorded.

BENTHIC AND PLANKTONIC FORAMINIFERS FROM THE UPPER BADENIAN DEPOSITS FILLING THE KARST CAVITY IN THE CLASTIC GYPSUM UNIT AT BORKÓW.

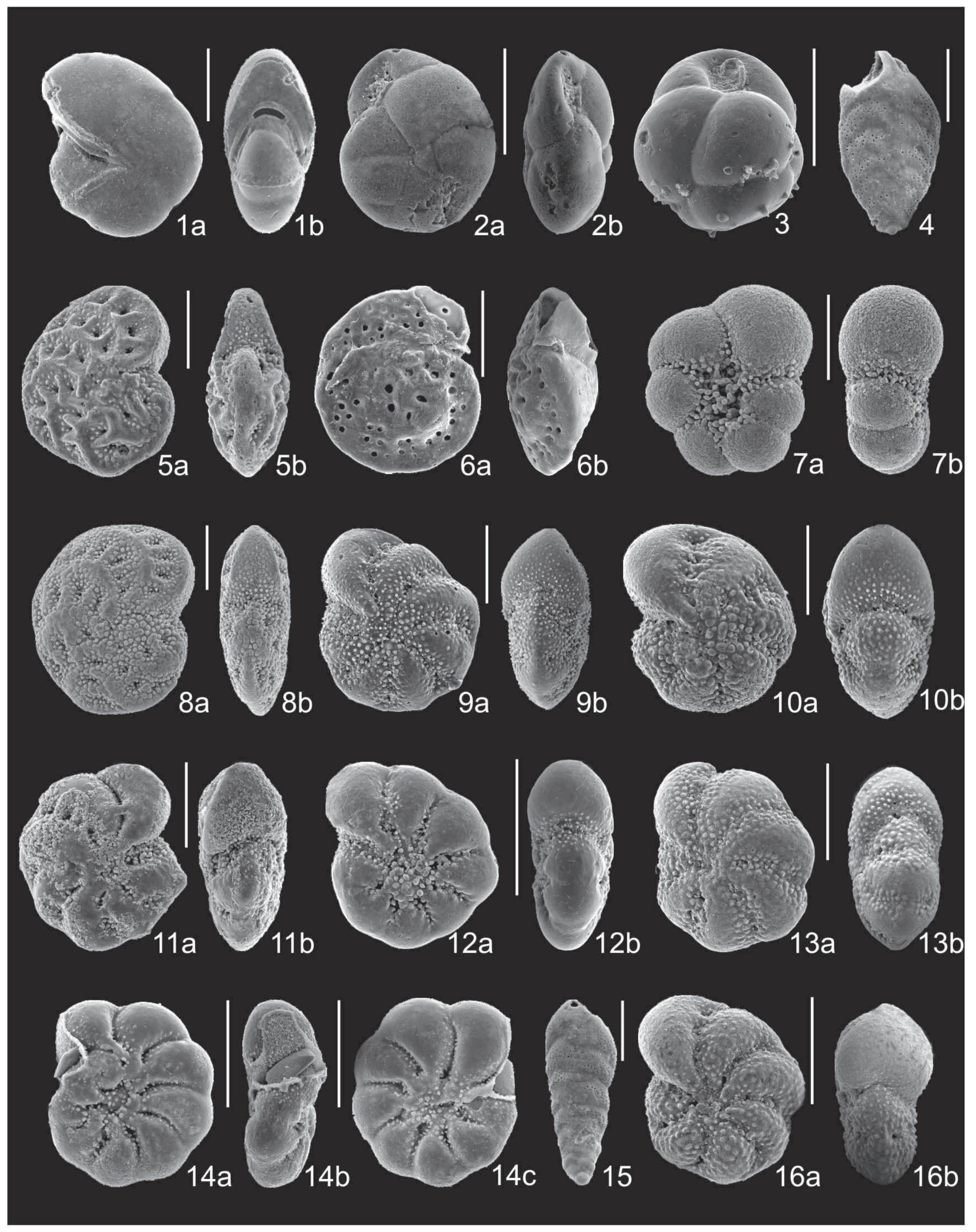
Scale bar is 0.1 mm. 1a–c – *Heterolepa dutemplei* (d'Orbigny); 2 – *Melonis pompilioides* (Fichtell & Moll); 3 – *Pullenia bulloides* (d'Orbigny); 4 – *Bolivina dilatata* Reuss; 5a–c – *Hansenisca soldanii* (d'Orbigny); 6 – *Sphaeroidina bulloides* d'Orbigny; 7 – *Uvigerina aculeata* d'Orbigny; 8, 16 – *Uvigerina bellicostata* Łuczkowska; 9a–c – *Cibicidoides ungerianus* (d'Orbigny); 10a–c – *Cibicidoides austriacus* (d'Orbigny); 11, 13 – *Bulimina insignis* Łuczkowska: 12a–c – *Hanzawaia boueana* (d'Orbigny); 14, 15 – *Bulimina aculeata* d'Orbigny; 17a–b, 18a–b – *Globigerina tarchanensis* Subbotina and Chutzieva; 19a–b – *Globigerina praebulloides* Blow; 20a–b – *Globigerina bulloides* d'Orbigny; 21a–c – *Globigerina* sp.; 22 – *Uvigerina gracilliformis* Papp & Turnovsky.



recorded. Benthic foraminiferal numbers per gram dried sediment vary from 0.4 to 1.4 individuals/gram. H(S) diversity index is 1.3 to 1.4. Eighteen species of calcareous benthic foraminifers have been recorded in studied material. Dominant species are *Elphidium angulatum* (Egger) and *Elphidium clavatum* Cushman, common - *Elphidium incertum* (Williamson), *Elphidium excavatum* (Terquem), *Porosononion parvus* (Bogdanowicz), *Porosononion bogdanowiczi* (Voloshinova), and *Porosononion martkobi* Venglinsky, subsidiary - *Elphidium albiumbilicatum* (Weiss), *Elphidium pseudoinflatum* Cushman, *Elphidium joukovi* Serova, *Bolivina dilatata* Reuss, *Bolivina* sp., *Cassidulina laevigata* d'Orbigny, *Globocassidulina subglobosa* Brady, *Cibicidoides* sp., *?Haynesina* sp., *Lobatula lobatula* (Walker and Jacob) and *Pullenia quinqueloba* (Reuss). No agglutinated species have been found. Planktonic foraminifera are scarce. They are represented by ten species, small-sized: *Globigerina druryi* Akers, *Globigerina glutinata* (Egger), *Globigerina praebulloides* Blow, *Globigerina quinqueloba* Natland, *Globigerina tarchanensis* Subbotina and Chutzieva, *Globigerina* sp., *Globorotalia bykovae* (Aisenstat), *Globoturborotalita woodi* (Jenkins), *Tenuitella* sp., *Tenuitellinata pseudoedita* (Subbotina). Their contribution to the assemblage is very low (0-5%). The planktonic species are interpreted as cool-water indices. In addition, there occur redeposited foraminifers that can be clearly recognized as they are broken and of larger sizes.

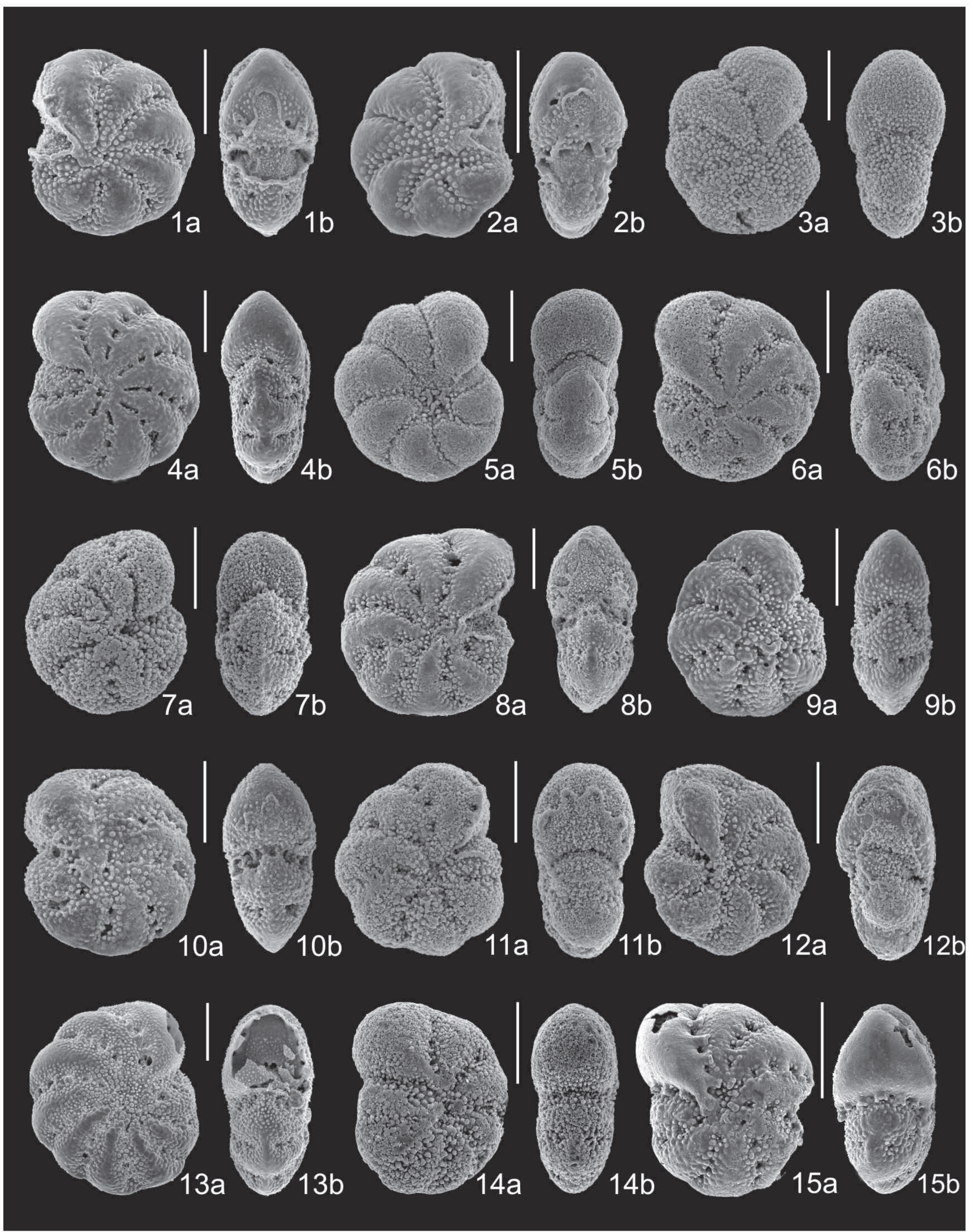
BENTHIC FORAMINIFERS FROM THE MARLY CLAY INTERCALATION IN GYPSUM AT BORKÓW.

Scale bar is 0.1 mm. 1a–b – *Pullenia quinqueloba* (Reuss), sample 3; 2a–b – *Cassidulina laevigata* d'Orbigny, sample 4; 3 – *Globobulimina* sp., sample 3; 4 – *Bolivina dilatata* Reuss, sample 4; 5a–b – *Elphidium pseudoinflatum* Cushman, sample 4; 6a–b – Cibicidoides sp., sample 3, 7a–b – *Porosononion* sp., sample 3; 8a–b – *Elphi-dium joukovi* Serova, sample 3; 9a–b, 10a–b, 11a–b, 13a–b, 16a–b – *Elphidium angulatum* (Egger), sample 5; 12a–b – *Porosononion bogdanowiczi* (Voloshinova), sample 5; 14a–c – *?Haynesina* sp., sample 3; 15 – *Bolivina* sp., sample 4



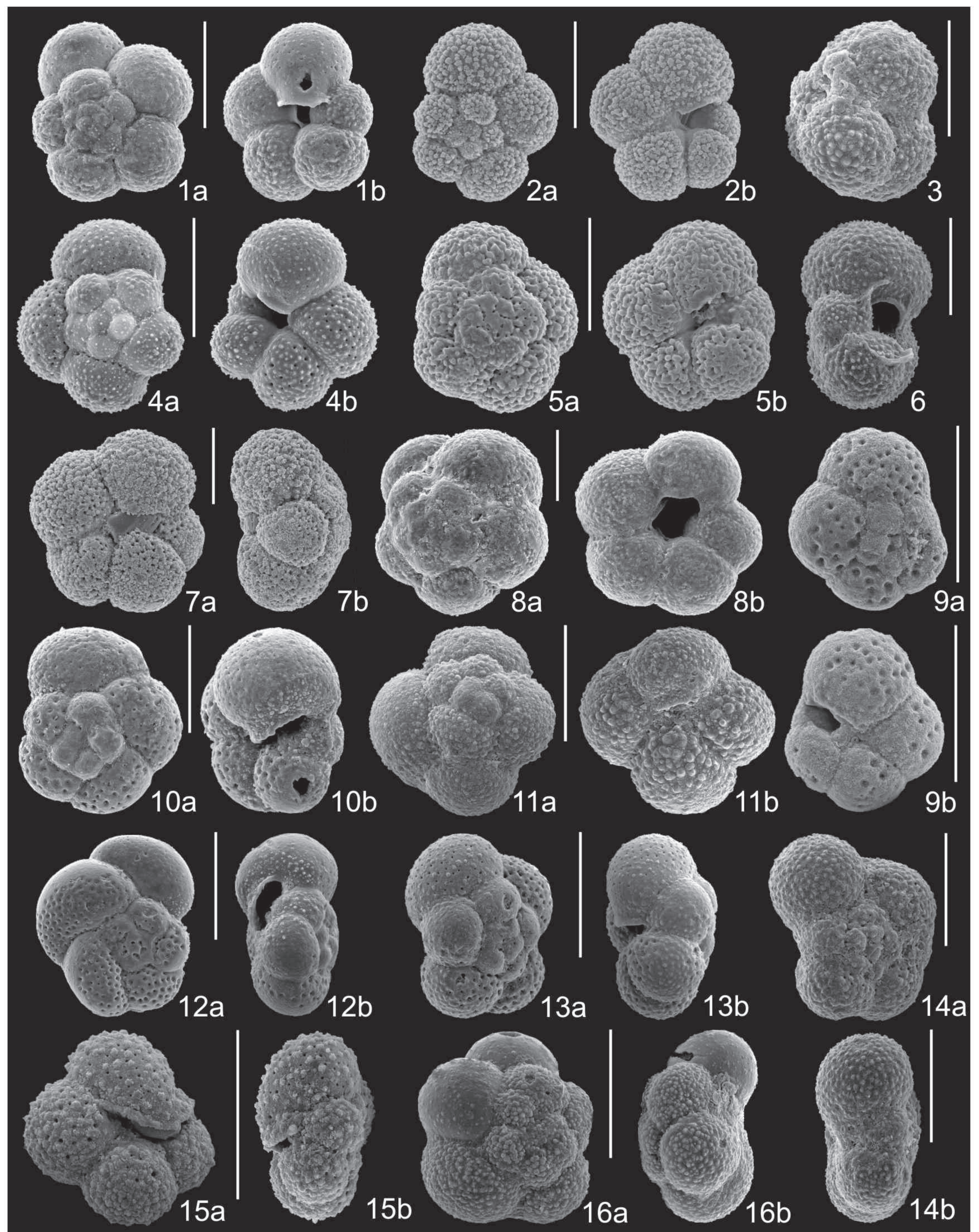
BENTHIC FORAMINIFERS FROM THE MARLY CLAY INTERCALATION IN GYPSUM AT BORKÓW

Scale bar is 0.1 mm. 1a–b, 15a–b – *Elphidium clavatum* Cushman, sample 3; 2a–b – *Porosononion parvus* (Bogdanowicz), sample 3; 3a–b, 11a–b – *Elphidium albium-bilicatum* (Weiss), sample 5; 4a–b, 13a–b – *Elphidium incertum* (Williamson), sample 3; 5a–b – *Porosononion martkobi* Venglinsky, sample 5; 6a–b, 8a–b, 9a–b, 10a–b, 12a–b – *Elphidium angulatum* (Egger), sample 5; 7a–b, 14a–b – *Elphidium margaritaceum* Cushman, sample 3



PLANKTONIC FORAMINIFERS FROM THE MARLY CLAY INTERCALATION IN GYPSUM AT BORKÓW

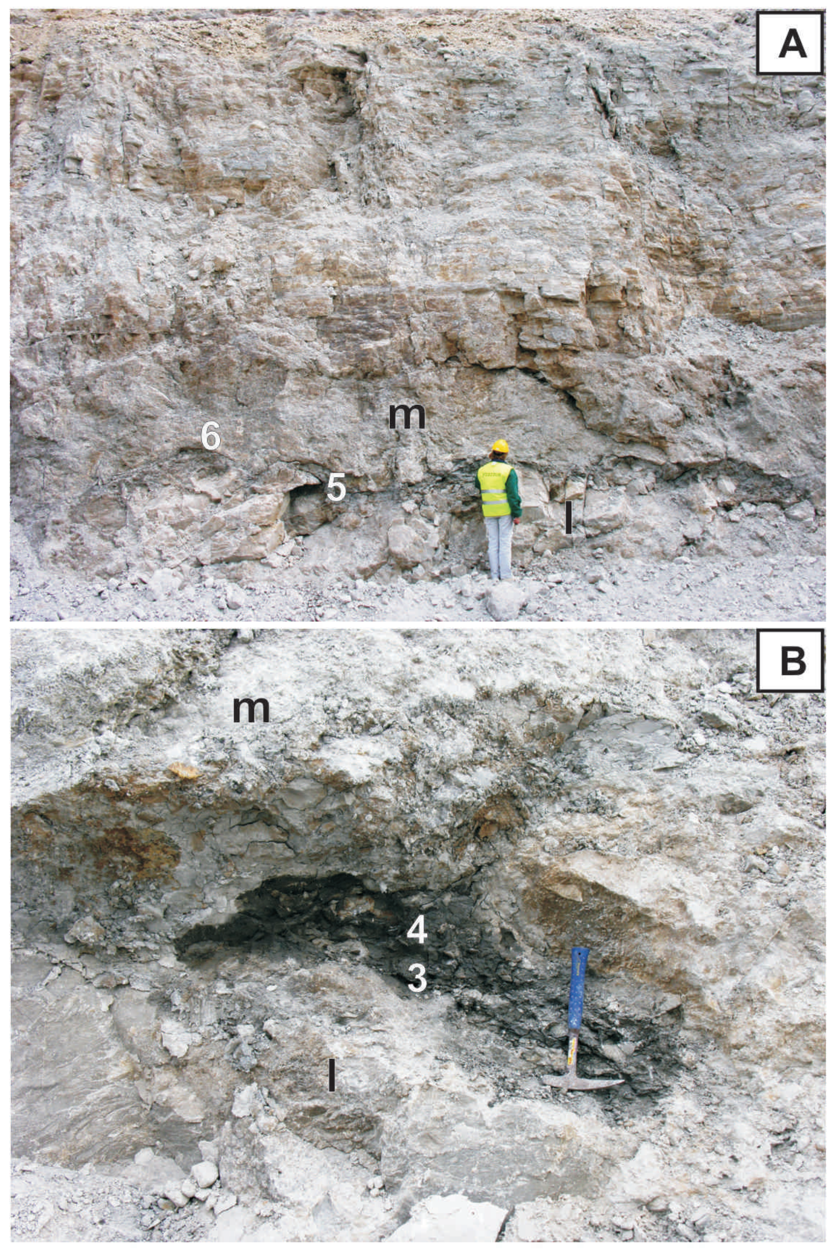
Scale bar is 0.1 mm. 1a–b, 2a–b, 4a–b, 13a–b – *Tenuitella pseudoedita* (Subbotina), sample 3; 3 – *Globigerinita uvula* (Ehrenberg), sample 5; 5a–b, 7a–b – *Globotur-borotalita* sp. ex gr. *ciperoensis* (Bolli), sample 4; 6 – *Globigerina praebulloides* Blow, sample 5; 8a–b, 16a–b – *Globigerina tarchanensis* Subbotina and Chutzieva, sample 4; 9a–b – *Tenuitellinata* cf. *brevispira* (Subbotina), sample 5; 10a–b, 12a–b – *Globorotalia bykovae* (Aisenstat), sample 5; 11a–b – *Globigerina* cf. *druryi* Akers, sample 5; 14a–b – *Globigerina* sp., sample 5; 15a–b – *Turborotalia quinqueloba* (Natland), sample 5.



Interpretation and discussion

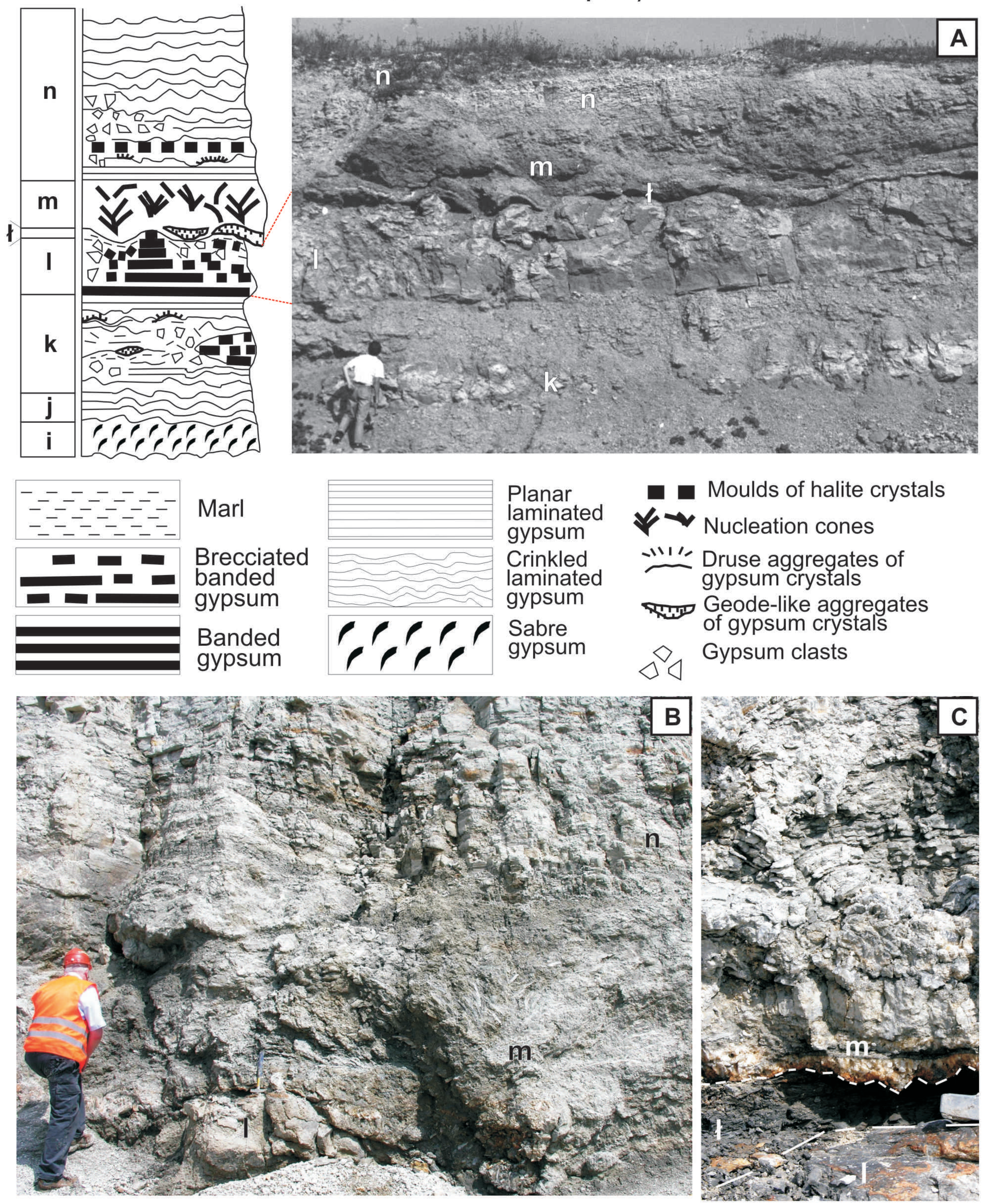
Main features of the recorded assemblages are: (1) The benthic foraminiferal number is extremely low. (2) The specific diversity is low. (3) The assemblages consist entirely of calcareous species. (4) The assemblages are dominated by elphidiids (*Elphidium angulatum* and *Elphidium clavatum*). (5) The species are of small size compared to usual dimensions within the genera. These characteristics indicate that the assemblages are composed of pioneer, opportunistic, r-selected species. Opportunistic species are most prominent during the early stages of ecological succession, when species that are more competitive in the long run are not very abundant.

FIELD PHOTO SHOWING THE NATURE OF STUDIED MARLY CLAY INTERCALATIONS AND LOCATION OF SOME SAMPLES



During deposition of Badenian gypsum the environment was virtually defaunated. After the flood by marine water, benthic foraminifers started to colonize a new niche. Planktonic foraminifers (if not redeposited) indicate that the water column was at least 50 m deep, and taken into account a relative scarcity of planktonic foraminifers it was not much more. Details on the migration patterns and rates of migration of benthic foraminifera from the geological record are scant. Within the 30 of the >10,000 extant species of foraminifera of which complete life cycles are known there are four different ways of dispersion: release to the water column of gametes, zygotes or of embryonic agamonts or gamonts; adaption to a meroplanktonic juvenile life stage with subsequent passive spread by currents; self locomotion along the sea floor; through passive (physically or biologically induced) entrainment into the water column and subsequent transport of different growth stages. The meroplanktonic stage in the life cycle of foraminifera is probably the most efficient dispersal method but so far has been proved in five genera only. This facility has not been recognised within the Miocene benthic foraminiferal assemblages. Therefore it seems likely that the distribution of gametes from the species involved in this study would have been limited. This would have permitted slow migration of foraminiferal taxa. The study area located far from the supposed area of connection with open seawater, and hence, even if rapid rate of such colonization is accepted, it took probably few hundred years before the benthic foraminifers could reach the Borków area after the flood of the Fore-Carpathian Basin by seawater that halted the evaporite deposition. The species composition established in the new area depends on the species pool in the source(s) area, the type and availability of food, and the species' ability to survive and reproduce in the new habitat. Pioneer macrobenthic colonizers are often typically epifaunal or shallow infaunal. Observations on dispersion of benthic foraminifera in defaunated sediments recorded that the free living species of benthic foraminifera with an inbenthic life style had a higher susceptibility for redistribution than epifaunal forms.

(A) A FRAGMENT OF THE GYPSUM SECTION IN BORKOW (after Peryt and Jasionowski, 1994); (B), (C) FIELD PHOTOS (C shows the enlargment of a fragment of B, with the hammer, and the location of sample A).



Implications and conclusions

The marine transgression during mid-Badenian gypsum deposition in the Fore-Carpathian basin heralds that general Late Badenian transgression. In the Early Badenian, the Central Paratethys was connected with Western Paratethys, and the "Trans-Tethyan Trench Corridor" via Slovenia connected the Mediterranean Sea with the Pannonian basin system. During the middle Badenian the eastern seaways were sealed, and water supply for the Central Paratethys was only available via the "Corridor" until this seaway was finally closed in the late Badenian when the Central Paratethys reconnected with the Eastern Paratethys that occupied the current Black Sea and Caspian Sea regions. This major change resulted in that the composition of foraminifer assemblage recorded in Borków within and above the gypsum differs greatly from assemblages occurring in the marls below the gypsum at Borków.

The flood of Badenian Carpathian Foredeep basin during deposition of evaporites is similar to reflooding of evaporite basin which terminated the Badenian evaporite deposition in various Paratethyan basins. Such refloodings by marine waters were characteristic for other bared evaporite basins such as the Messinian Sorbas basin of SE Spain when each episode of gypsum deposition was ended with a desiccation event followed by a rapid reflooding of the basin by marine waters corresponding to infralittoral to upper bathyal environments.

Main sources:
Oszczypko, N., Krzywiec, P., Popadyuk, I., Peryt, T., 2006. AAPG Memoir, **84**: 293-350; Peryt, D., 2013. Geol. Quart., **57**: 141-164; Peryt, D., 2013. Terra Nova, **25**: 298-306; Peryt, T.M., 2006. Sedim. Geol., **188-189**: 379-396; Peryt, T.M., 2013. J. Palaeogeogr., **2**: 225-237; Peryt, T.M., Anczkiewicz, R., 2015. Terra Nova, **27**: 54-61.