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Badenian tuffite levels within the Carpathian orogenic front (Gdów–Bochnia area, Southern Poland): radio-isotopic dating and stratigraphic position

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We present new results of investigation of Middle Miocene Badenian tuffite levels exposed in Southern Poland within the Gdów "embayment" area (tuffites from Wiatowice, upper part of the Skawina Beds, foraminiferal biozone IIγ) and compare them with the well known and extensively described Bochnia Tuffite level at Chodenice near Bochnia (upper part of the Chodenice Beds, foraminiferal biozone IIIA). The $^{40}Ar/^{39}Ar$ ages of the glass separates obtained from these layers were determined applying (standard) incremental heating techniques the Wiatowice and Bochnia tuffites have been dated to be 13.76 ±0.08 Ma, and 13.62 ±0.10 Ma old, respectively.

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INTRODUCTION

The frontal thrust of the flysch Carpathians in the area south-east of Kraków clearly recedes to the south forming a "bay" or "embayment" (Fig. 1). Such geometry prompted Niedźwiedzki (1883–1886) to propose that the frontal orogenic thrust did indeed form a bay of the Miocene sea (named by Niedźwiedzki and others the "Gdów embayment", after the town of Gdów), extending into the Carpathian territory. Subsequent studies showed, however, that the Carpathian Flysch deposits were thrust over the Miocene foredeep strata further to the north also in this segment of the orogenic wedge, and the Gdów "embayment" developed as a result of the tectonic reconstruction (uplift and erosion) of that part of the Carpathians.

The area of the Gdów "embayment" has been well-studied: in total, several dozen deep boreholes have been drilled, and numerous geophysical studies (gravity, magnetic and seismic) have also been completed, mostly during exploration for rock salt and hydrocarbons. In boreholes located within the Gdów "embayment", a thick (up to 1200 m in the Nieznanowice 2 borehole) succession of marine Miocene strata, developed in the form of clays and claystones with sand and sandstone interbeds, were drilled (Moryc, 1976). The Badenian evaporites, developed in sulphate facies (the Krzyżanowice Formation) or in chloride facies (the Wieliczka Formation) are known in the major part of the Carpathian Foredeep in Poland (Garlicki, 1979). Within the Gdów "embayment" these evaporites are present only locally and form isolated patches of gypsum near the surface in the villages of Bodzanów and Kawki (Fig. 1).

The lack of continuous evaporites units in boreholes as well as the different lithology and thickness of the Miocene deposits in the Gdów "embayment" has resulted in various interpretations of this area (e.g., Garlicki, 1960; Olewicz, 1964; Poborski and Jawor, 1987; Połtowicz, 2004).

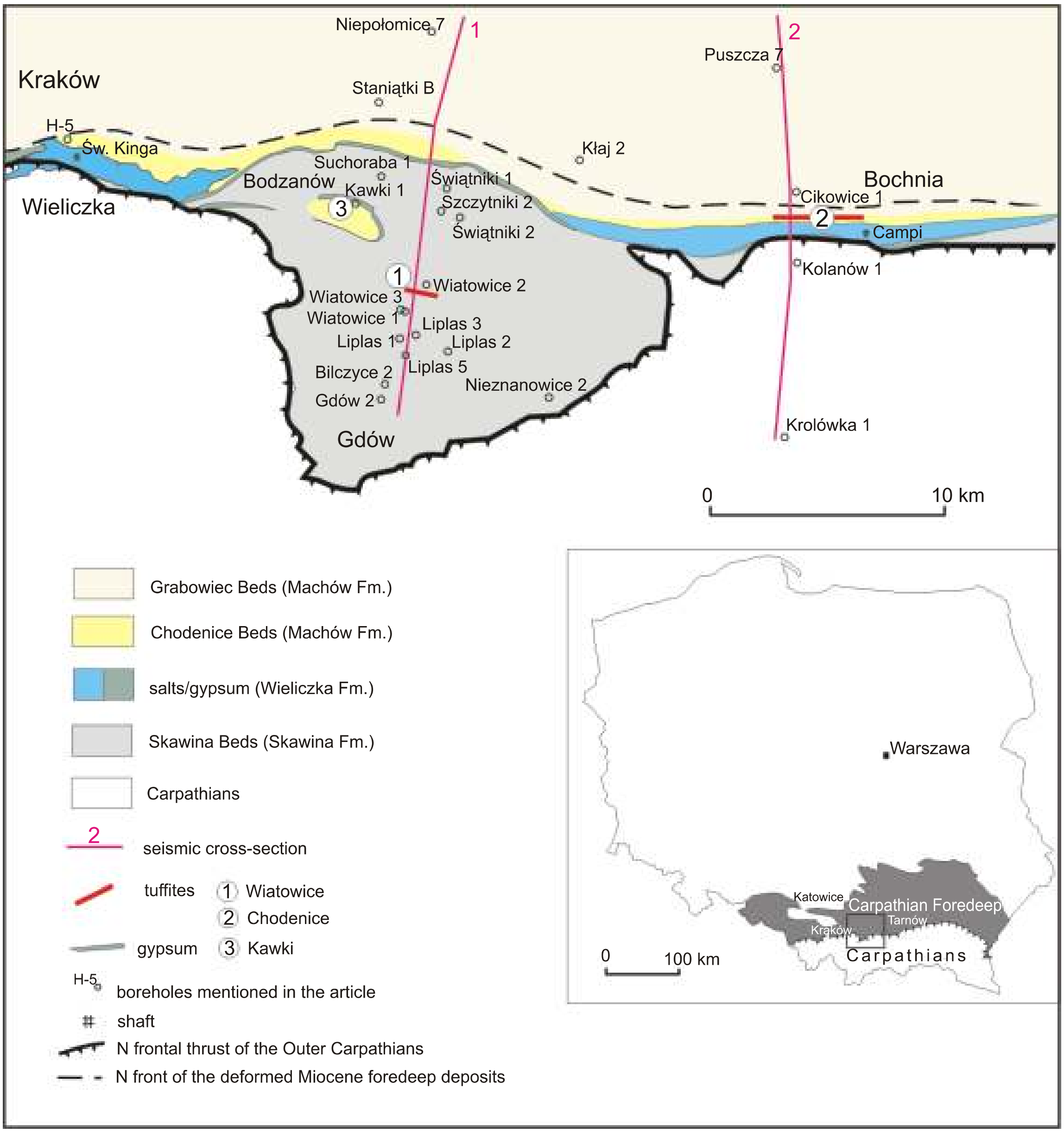

Fig. 1. Location of the study area

Studies focused on the Gdów “embayment” were stimulated by exploration for rock salt deposits located between the Wieliczka and Bochnia mines, within the Łężkowice–Siedlec area (Garlicki, 1960). The tectonic model of the orogenic front in the eastern part of the “embayment” that stems from these studies included uplifted and deformed rock salt deposits contained within the undifferentiated Chodenice and Grabowiec beds, that also contain tuffite layers, with no tectonic deformation within the pre-Miocene basement (Garlicki, 1960).

Połtowicz (1962, see his fig. 4) suggested the presence of low angle reverse faults (thrusts) detached within the Mesozoic basement, cutting also the Miocene infill of the Gdów “embayment”. This infill was subdivided into the Chodenice Beds (containing rock salt deposits) and present within the entire “embayment”, and the overlying Grabowiec Beds to the north of the Carpathian thrust front.

Alexandrowicz (1965; *cf.* also Doktor, 1983) dated the sub-evaporitic succession present within the entire Gdów “embayment” as the Skawina Beds (IIA-D foraminiferal zones), with the Chodenic and Grabowiec beds (IIIA, B foraminiferal zones) located above the evaporitic level (e.g., Łuczkowska, 1958). Such stratigraphic zonation was adapted by Garlicki (1971, fig. 2). According to the refined model of Garlicki (1971, fig. 3) the origin of the Gdów “embayment” was associated with reverse faulting within the pre-Miocene (Meso-Paleozoic) basement.

Those tectonic models have been subsequently challenged by other authors. According to Poborski and Jawor (1987), almost the entire infill of the Gdów "embayment" consists of the supra-evaporitic Chodenice Beds, with only a thin and incomplete cover of the sub-evaporitic Skawina Beds lying directly above the Mesozoic substratum (see Poborski and Jawor, 1987 and their fig. 2). Poborski and Jawor (1987) did not, however, present any stratigraphic evidence that might have been used to modify previous stratigraphic findings of Alexandrowicz (1965) or Łuczkowska (1958). According to Połtowicz (1991, 2004), the uppermost part (up to 200 m) of the sedimentary infill of the Gdów "embayment" consists of the lower Badenian Skawina Beds that form an allochthonous thrust slice tectonically transported above a very flat (almost horizontal) fault to the north. Beneath this slice, the autochthonous infill consists of thick upper Badenian Chodenice and Grabowiec beds and thin lower Badenian Skawina Beds, resting on the Mesozoic substratum. Połtowicz (1991, 2004) did not, however, like Poborski and Jawor (1987), provide any detailed stratigraphic data that would support his structural model; he only quoted archive stratigraphic results of Z. Kirchner from unidentified industry wells. Taking this into account it seems that structural models offered by Poborski and Jawor (1987) and Połtowicz (1991, 2004), while significantly different from the previous models based on detailed stratigraphic studies (Garlicki, 1960, 1971), are not supported by reliable and verifiable stratigraphic data and have to be treated with caution.

Early tectonic models of Garlicki (1960, 1971) depicted a characteristic geometry that, taking into account the results of seismic data interpretation from the nearby parts of the orogenic front (Krzywiec and Verges, 2006; Krzywiec *et al*., 2007), could be re-interpreted as having been caused by wedge tectonics: overthickened and deformed sub-evaporitic Miocene deposits (i.e. lower Badenian Skawina Beds) forming the axial part of the triangle zone, and uplifted rock salt layers together with their overburden of the upper Badenian Chodenice and Grabowiec beds backthrust to the south (see also below).

The subject of this paper is to contribute to the discussion on the tectonic model of the Gdów "embayment" by presenting new data, derived from investigations of tuffite occurring within the Gdów "embayment" area and in its immediate surroundings. Badenian tuffite levels may be used to correlate the Miocene strata in the Carpathian Foredeep. In this study we present results of new petrographic and micropalaeontological analyses, as well as results of radiometric age dating of tuffite levels occurring in exposures in the Carpathian Foredeep between Gdów and Bochnia (Southern Poland). These researches have helped to resolve the issue of the stratigraphic succession of Miocene deposits in the Gdów "embayment".

GEOLOGICAL SETTING

Tuffite levels, as products of individual sedimentation events of volcanic ashes, were uniformly distributed over a large area and form constant horizons of regional extent. Many Miocene sequences of the Carpathian Foredeep contain pyroclastic interbeds. They include tuffites, bentonitized tuffites, concentrations of volcanic glass, authigenic quartz and biotite. They have been described from the Upper Silesia Coal Basin, near Wieliczka and Bochnia, as well as along the southern margin of the Holy Cross Mts. (Alexandrowicz, 1997 and references therein). Generally, nine (tf_1–tf_9) tuffite levels have been identified in the Miocene sediments in the Carpathian Foredeep (Alexandrowicz, 1997). The oldest is found in freshwater deposits of the Kłodnica Fm. at Imielin and Przeciszów. The next five levels (tf_2–tf_6) are within the Skawina Beds, one (tf_7) within the Wieliczka Fm., one (tf_8) within the Chodenice Beds and one (tf_9) within the Kędzierzyn Fm. (Krakowiec Beds; Fig. 2).

In this paper we present new results of investigation of tuffite levels that are exposed within the Gdów "embayment" area (Wiatowice Tuffite) and compare them with tuffite levels located outside the Gdów "embayment", close to the Bochnia Salt Mine at Chodenice (Bochnia Tuffite; Fig. 1).

WIATOWICE TUFFITE

The occurrence of tuffites around the village of Wiatowice has been known since the early 20th century. In the 1950s, during geological investigations in that area, a number of shallow boreholes were drilled and, based on these, the extent of the tuffite outcrop was determined (Olewicz, 1964). Tuffites were found along 165 m of the west side of the Łysa Góra Mountain, and along 250 m on the east slope of the same mountain. Presently, a number of those exposures have been covered with detritus, and only on the northern slope of Łysa Góra (in the bottom part of the ravine extending from the top to the north-east) one can find tuffite chips. A small exploration pit dug in that place revealed several layers of pyroclastic material, namely: granular tuffite (*ca*. 47 cm thick) followed by pelitic tuffite (*ca*. 24 cm thick), sand tuffites, banded tuffite and diagonally layered tuffite (*ca*. 8 cm thick) and then white-banded mud tuffite (*ca*. 11 cm thick, Fig. 3A). In the roof of the bank there were seen a few-minor layers (up to 2–3 cm thick) of light grey pelitic tuffite and granular, rust-weathering tuffite, separated by layers of grey clay of the same thickness. In the granular tuffites there were visible white shards (presumably of glass) and dark minerals.

BOCHNIA TUFFITE

The tuffite level in the Chodenice Beds is probably the most extensive tuffite horizon within the Carpathian Foredeep, and it has been described from many known profiles in that area (e.g., Parachoniak, 1954, 1962; Olewicz, 1964; van Couvering *et al*., 1981; Alexandrowicz, 1997; Wieser *et al.*, 2000; Dudek and Bukowski, 2002; Dudek *et al*., 2004*a*). Most often it is developed as a complex succession of lithologies that differ in their grain-size distribution, and are in places separated by thin clay inserts. The thickness of that tuffite may amount to several metres. In the area between Wieliczka and Bochnia that level was identified in several exposures (Sułków, Chełm upon Raba, Moszczenica, Chodenice and Bochnia Salt Mine) and in numerous boreholes (including, among others, Wieliczka H-5, Kłaj 2). In the Upper Silesia region, that level was described from, among other places, the Ochojec borehole (P-20) near the

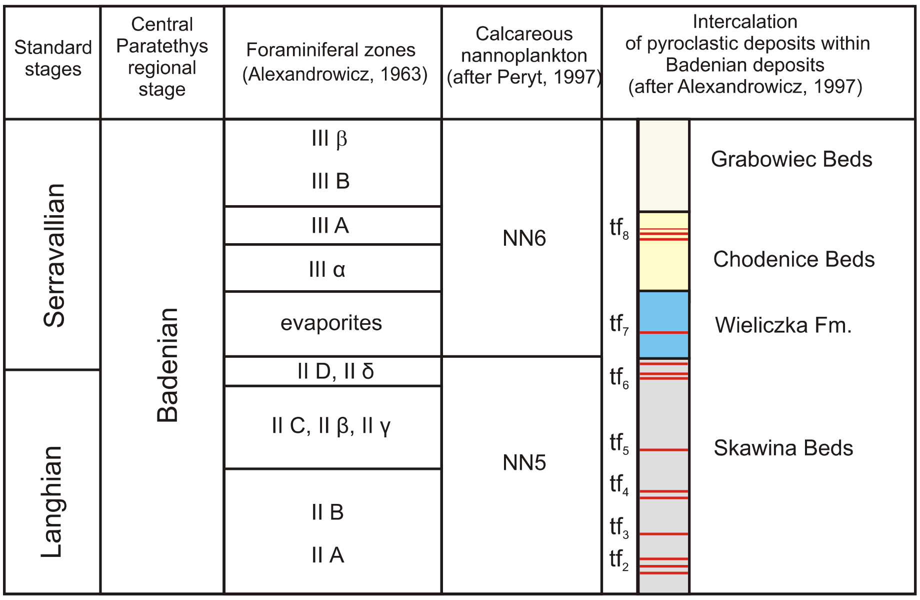

Fig. 2. Stratigraphic position of the Badenian tuffites

Tuffite beds (tf_1) occur in the freshwater deposits of the Kłodnica Fm. (Karpatian); tuffite beds (tf_9) occur in the Krakowiec clays (Sarmatian); position of the Langhian–Serravallian boundary is from Abels *et al.* (2005)

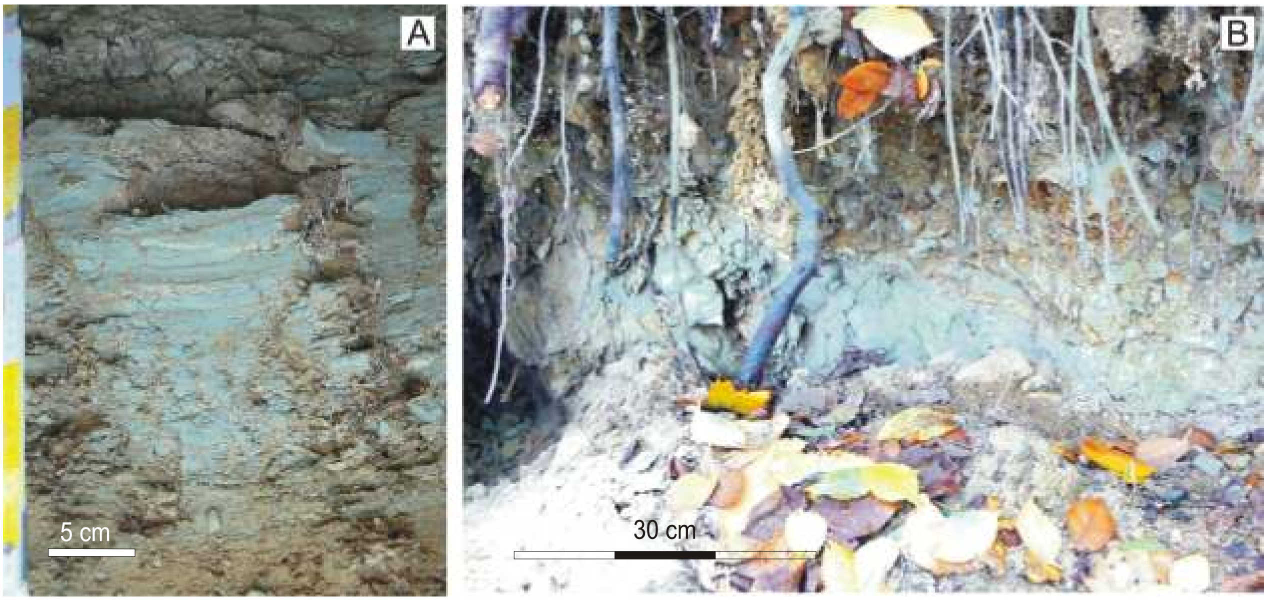

Fig. 3. Exposures of tuffites

A – the bank of Wiatowice Tuffite, which are of the specific blue-grey-white colouring that is maintained only under natural humidity conditions (when dried, tuffites become creamy-white); **B** – the exposure investigated of the Bochnia Tuffite in Chodenice

city of Gliwice (Alexandrowicz and Pawlikowski, 1980). It has also been reported from boreholes near Mielec and near Przemyśl (Parachoniak, 1962).

The natural Bochnia Tuffite exposure in Chodenice is located in the Chodenice creek slope, and was described in detail by Parachoniak (1954) and by Dudek *et al.* (2004*a*). Presently, that exposure is small (1 × 2 m). The tuffite layers dip to the south at the angle of *ca*. 60° and the majority of them represent light grey or even white, medium- or fine-grained tuffites (Fig. 3B). They occur in the form of a series of layers, each of them a dozen or so centimetres or so thick. Medium-grained tuffites are, as a rule, thicker, less distinct and more easily breakable into loose debris. Fine-grained tuffites form thinner beds, they are harder and often laminated. In some of the layers one can notice normal gradation, from medium- to very fine-grained lithologies, which shows the periodicity of sedimentation of the pyroclastic material.

MATERIAL AND METHODS

Three samples of tuffite from the Wiatowice locality were collected for petrographic and radiometric age dating from the upper part of the tuffite succession (Fig. 3A). They come from three layers: rust-weathering, fine-grained, laminated tuffite (Wt1), light grey, fine-grained tuffite of chaotic structure (WAt2), and light grey silty tuffite with a chaotic structure (Wt3). The small clayey layer within the tuffites and the clayey layer a few metres below the tuffite succession provided two samples (Wiatowice 1-2). These samples were used for the investigation on foraminifera and calcareous plankton.

Samples from the natural exposure in Chodenice (Fig. 3B) were collected from two layers of pyroclastic deposits: ChD5, ChD8 (layer names are according to after Dudek *et al*., 2004*a*) and three from adjacent layers of marly clay (Chodenice 1-3).

Chemical analyses of glass using the SEM/EDS microprobe method were performed for both tuffite levels. SEM/EDS analyses were made in the FESEM Laboratory of the Institute of Geological Sciences, Jagiellonian University, using a *NORAN Vantage* spectrometer coupled to a *HITACHI S-4700* scanning electron microscope operating at 15 kV.

Foraminiferal analyses have been performed on specimens extracted from the deposits using standard procedures. Sediment was washed over a 100 μm mesh sieve, the residue dried and revieved. The foraminifera taxa were identified by reference to the literature.

Both tuffites from Wiatowice and Chodenice were sampled for $^{40}Ar/^{39}Ar$ dating (samples: Wt1, ChD5 weight about 1 kg). The bulk samples were crushed, disintegrated in a calgon solution, washed and sieved over a set of sieves between 63 and 250 mm. The residue was subsequently subjected to standard heavy liquid as well as magnetic mineral separation techniques. Although the most suitable minerals, such as K-feldspar and biotite were lacking in both ashes, they did provide volcanic glass. The Bochnia Tuffite contained a large amount in the fraction larger than 300 μm, while the Wiatowice Tuffite contained a few particles in the fraction larger than 160 μm. The latter also contained some biotite crystals in the fraction between 150–200 μm. Unfortunately, these were inappropriate for $^{40}Ar/^{39}Ar$ dating due to weathering, as indicated by yellow-stained crystal edges. The glass separates of both ashes were handpicked, submerged in demineralized water and put in an ultrasonic bath for 5 minutes. The mineral separates were then loaded in a 10 mm ID quartz vial together with *Fish Canyon Tuff (FC-2)*, *Drachenfels* one (f250-500) and *Drachenfels* two (f >500) sanidine. The vial was irradiated in the Oregon State University TRIGA reactor in the cadmium-shielded CLICIT facility for 10 hours.

Next both samples were split into multiple parts. For each tuffite five parts were loaded into a copper sample-tray between *Drachenfels* as well as *Fish-Canyon* standards. The tray was pre-heated under vacuum using a heating stage to remove undesirable atmospheric argon. Thereafter, samples were placed in the UHV sample chamber, degassed overnight and were fused using a *Synrad* CO_2 laser in combination with a *Raylase* scanhead as a beam delivery and beam diffuser system. After purification the resulting gas was analysed with a *Mass Analyzer Products LTD 215-50* noble gas mass spectrometer. Beam intensities were measured in a peak-jumping mode in 0.5 mass intervals over the mass range 40–35.5 on a *Balzers 217* secondary electron multiplier. System blanks were measured every three to four steps. Mass discrimination was monitored by frequent analysis of aliquots of air. The irradiation parameter *J* for each unknown was determined by interpolation using a second-order polynomial fitting between the individually measured standards.

Following these fusion experiments, two more sample parts of each glass separate were loaded in another copper tray. Once again the tray was pre-heated and the samples placed in the UHV sample chamber and degassed. This time, however, samples were incrementally heated in order to examine the argon distribution in the glass crystals. The resulting gas was treated in the same way as in the fusion experiments.

All $^{40}Ar/^{39}Ar$ ages have been calculated with the *ArArCalc* software (Koppers, 2002) and applying the decay constants of Steiger and Jäger (1977). The age for the *Fish Canyon Tuff* sanidine flux monitor used in age calculations is 28.201 ±0.03 My (Kuiper *et al*., 2008). The age for the *Drachenfels* sanidine flux monitor is 25.42 ±0.03 My (Kuiper *et al*., in prep). Correction factors for neutron interference reactions are $2.64 \pm 0.017 \times 10^{-4}$ for $(^{36}Ar/^{37}Ar)_{Ca}$, $6.73 \pm 0.037 \times 10^{-4}$ for $(^{39}Ar/^{37}Ar)_{Ca}$, $1.211 \pm 0.003 \times 10^{-2}$ for $(^{38}Ar/^{39}Ar)_K$ and $8.6 \pm 0.7 \times 10^{-4}$ for $(^{40}Ar/^{39}Ar)_K$. Errors are quoted at the 1σ level and include the analytical error and the error in *J*.

RESULTS

PETROGRAPHIC STUDY

The predominating component in all samples of tuffite from Wiatowice is volcanic glass of the size of shards that seldom exceed 0.2 mm (Fig. 4). Often those are sharp-edged shards of elongated, lamellar or bent shapes. The glass is completely isotropic, or displays a slight anisotropy (devitrification). In the coarse-grained tuffite variety we found volcanic glass in the form of sharp-edged chips of the obsidian type (totally transparent chips) and of the pumice type (with voids and ducts) (Fig. 5A). In addition to glass, also single grains of quartz, biotite and plagioclase are found. Quartz occurs most often in the form of tiny grains (up to 0.1 mm). In certain places, one can note the increase in the share of autogenic quartz in the form of sharp-edged chips, with the biggest of them reaching 0.2 mm. Biotite with the lamella size (up to 0.1 mm) may sometimes be slightly weathered (transformed into vermiculite), and displays distinct pleochroism (from the brownish to greenish colours). Among plagioclases subjected to SEM/EDS analysis, we identified the presence of albite and andesine, sometimes twinned, or of a striped structure. Also present in microsections are bushy concentrations of iron compounds of rust or dark brown

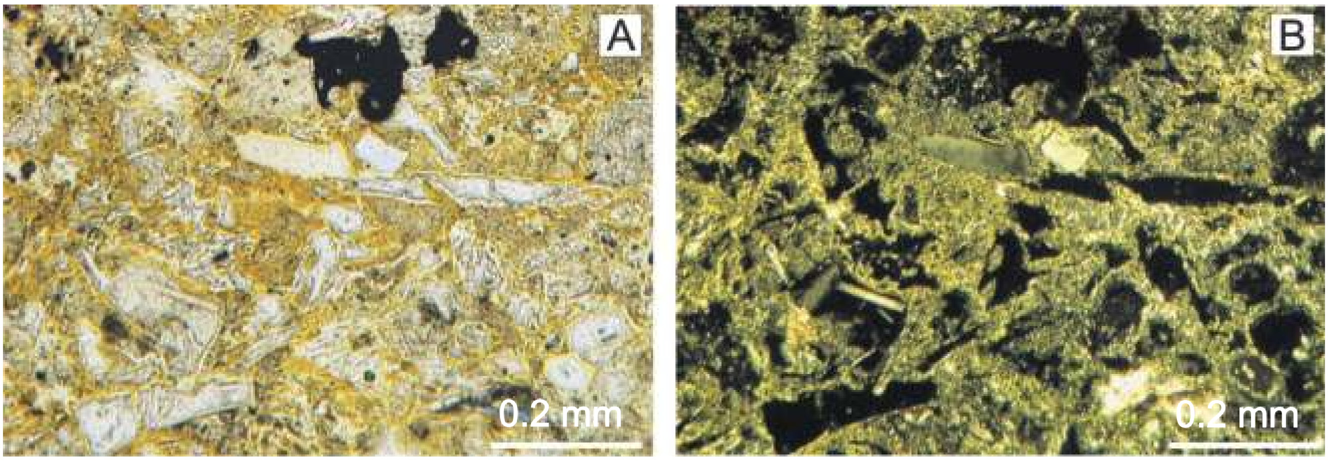

Fig. 4. Microscopic image of tuffite from Wiatowice

A – sharp-edged shards of glass are set in an abundant matrix; visible in the centre is an elongated, idiomorphic quartz grain, plane polarized light; **B** – the same preparation, isotropic glass shards (black), crossed polars

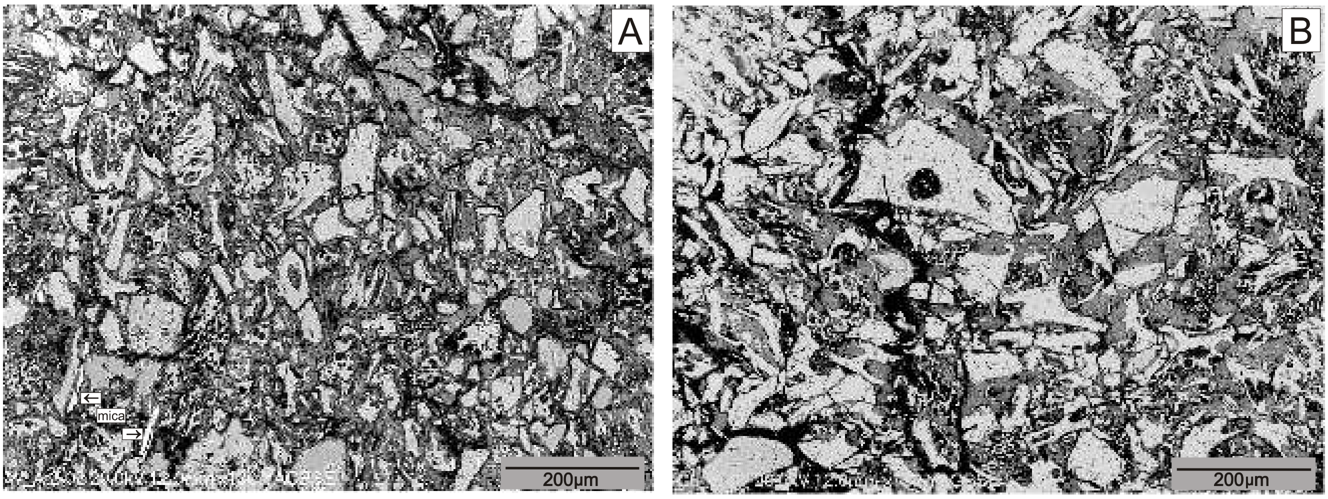

Fig. 5. Microscopic image of tuffites subjected to SEM analysis

A – tuffite from Wiatowice; photo shows two varieties of glass: the pumice-type and the obsidian-type glass; in the bottom left corner two pale mica lamellae are visible; **B** – tuffite from Chodenice, photo shows sharp-edged glass shards

colours. All those components are set in a clayey mass, which forms a kind of a matrix, of a grey-yellow colour (Wt1), or colourless (WAt2, Wt3) with a single polarizer, containing relatively numerous, non-transparent pigments.

Particular tuffite varieties differ, first of all, in the ratio of matrix share and grain component share. In fine-grained, light grey tuffites (WAt2) the share of clayey matrix is clearly lower than in other tuffites, and particular grains of minerals are often in contact with one another. In turn, in tuffites of aleuritic texture (Wt3), the share of clayey matrix is clearly dominating. That tuffite variety contains also much more of partly transformed glass shards and lamellas of weathered biotite.

Tuffites from Chodenice (Bochnia Tuffite) are characterized by a good preservation of their glass shards (Fig. 5B). As far as size is concerned, vitroclasts correspond mainly to fine ash and volcanic dust fractions (usually <0.1 mm). Among relatively few crystaloclasts there dominate quartz, potassium feldspar, acid plagioclase (up to 43% An), and biotite, as far as mafites are concerned. The most representative accessory minerals in terms of quantity are rutile, zircon, apatite, and garnet (Wieser *et al*., 2000; Dudek *et al*., 2004*a*).

The content of SiO_2 in glass from Wiatowice Tuffite was 76.73–77.84%, and that in Bochnia Tuffite was 79.96–80.45% (Table 1). The different content of Na_2O in glass from Wiatowice Tuffite 2.55–3.96% and 2.26–2.98% in Bochnia Tuffite was noted (similar observations on the content of Na_2O did Kamieński and Glińska, 1966). The K/Ca ratio for Wiatowice is around 2.6, while it is 3.3 for the Bochnia Tuffite.

Table 1

EDS chemical analyses of glass, samples from the Wiatowice and Chodenice tuffites

Component [%]	Chodenice/Glass					Wiatowice/Glass							
	Cht8-1a	Cht8-1b	Cht8-1c	Cht8-2b	CHD8	WAt2-1b	WAt2-1c	WAt2-2a	WAt2-2b	WAt2-2c	Wt1-1b	Wt1-1c	Wt1-1d
SiO_2	80.37	80.45	79.96	80.10	80.34	77.24	77.79	77.22	77.49	76.92	76.81	77.84	76.73
Na_2O	2.49	2.26	2.98	2.80	2.01	2.76	2.55	3.11	3.17	2.89	3.37	2.85	3.96
Al_2O_3	11.45	11.71	11.59	11.58	12.15	12.87	12.98	12.69	12.73	13.03	12.86	12.99	12.99
K_2O	3.51	3.41	3.44	3.43	2.89	3.53	3.55	3.61	3.81	3.49	3.64	3.01	5.26
CaO	1.00	0.96	1.02	0.81	0.98	1.56	1.48	1.61	1.16	1.37	1.35	1.40	0.79
Fe_2O_3	1.19	1.21	1.01	1.29	1.63	1.95	1.66	1.75	1.63	2.31	1.97	1.91	0.27
Total	100.00												

Results of one sample, n. CHD8, is after Dudek *et al*. (2004*a*)

MICROPALAEONTOLOGIC STUDY

Sediments from Wiatowice (samples Wiatowice 1-2) contain foraminifers, ostracods, and fragments of mollusc shells. There are also rare fragments of sponge and sea urchin spines, as well as carbonate thalli of green algae (*Acicularia*). Calcareous nannofossils are scarce and poorly preserved. Only a few specimens of *Reticulofenestra pseudoumbilica*, *R. haqii*, *R. minuta*, *Coccolithus pelagicus*, *Umbilicosphaera jafarii* and *Syracosphaera pulchra* could be identified. Scarce *Reticulofenestra umbilica*, *Dictyococcites bisectus* and *Emiliania formosa* represent reworked component of the oryctocoenose. Dominating among foraminifers are the following: *Valvulineria complanata*, *Bulimina elongata*, *Ammonia beccarii* (Figs. 6 and 7).

Individuals belonging to those three taxa constitute in total 45.7% of the assemblage. The accesory taxa include *Globigerina bulloides* (5.1%), *Bolivina dilatata* (6.5%), *Bulimina gibba* (4.5%), *Cibicides pseudoungerianus* (6.5%), *Astrononion perfossum* (6.5%), *Elphidium macellum* (4.3%), *E. crispum* (4.3%). Following taxa are presented as single or rare specimens: *Haplophragmoides* sp., *Dendrophrya* sp., *Miliammina* sp., *Lenticulina inornata*, *Lagena clavata*, *Globorotalia praescitula*, *Globigerina druryi*, *Globigerinoides quadrilobatus*, *Turborotalita quinqueloba*, *Sagrinella lobata*, *Uvigerina aculeata*, *Reusella spinulosa*, *Virgulinella pertusa*, *Caucasina schischkinskayae*, *Nonion commune*, *Elphidium fichtelianum*. This third group of foraminifers constitutes 16.7% of the assemblage.

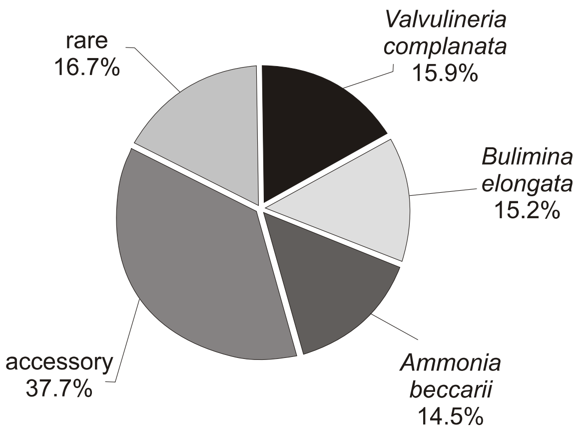

Fig. 6. Cumulative percentage chart of foraminifera in sample from Wiatowice

For explanation to the accessory and rare panels see the text

Samples from Chodenice (Chodenice 1-3) do not contain foraminifers neither calcareous nannoplankton but instead they contain radiolarians and fragments of sponge spicules. Individuals of the sub-order of the *Spumellaria* represent the *Radiolaria*. The most numerous are the *Liosphaeridae* (forms of ball-shaped skeletons) and the *Spongodiscidae* (forms of discoidal skeletons). Rare specimens of the *Euchitoniidae* (forms of three-armed skeletons) are also present.

RADIOMETRIC DATING

The results of radiometric dating are summarized in Table 2, and the full analytical data for the fusion experiments are given in Appendix A.

Both tuffites appeared to be heterogeneous in age in the single fusion experiments. However, we attribute this to differential alteration of the outer parts of the glass crystals. Therefore, we have performed detailed incremental heating experiments with two replicas for each tuffite. Full analytical data for the incremental heating experiments are given in Appendix B. The results of the incremental heating experiments are displayed as age spectra diagrams (Fig. 8). Steps yielding less than 1% of the total $^{39}Ar_K$ were discarded.

For the Wiatowice Tuffite, the first step was excluded because of its low $^{40}Ar^*$ content. We then included all consecutive steps overlapping at the 2 sigma level until MSWD > student's

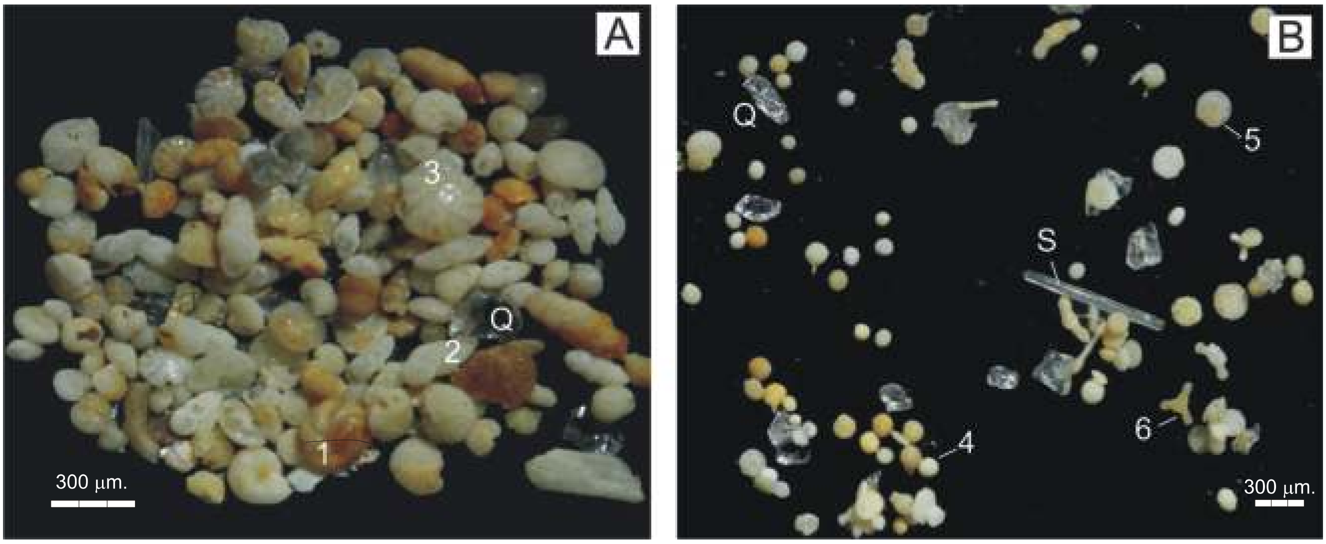

Fig. 7. Microfauna from Wiatowice (A) and Chodenice (B)

A – foraminiferida: 1 – *Valvulineria complanata*, 2 – *Bulimina elongata*, 3 – *Ammonia beccarii*; **B** – radiolaria: 4 – *Liosphaeridae*, 5 – *Spongodiscidae*, 6 – *Euchitoniidae;* S – sponge spicule, Q – pyroclastic quartz

Table 2

Summary of the $^{40}Ar/^{39}Ar$ results

Sample	Mineral	*J*-value	Fraction [μm]	Plateau age [Ma]	MSWD	N	$^{40}Ar^{*}$ [%]	$^{39}Ar_K$ [%]	K/Ca	Total fusion age [Ma]	Isochron age [Ma]	Inverse isochron intercept
Wiatowice Tuffite	glass	0.002685	>160	13.76 ±0.08	1.3	34(15)	63.14	80.89	2.566	13.79 ±0.07	13.48 ±0.13	306.0 ±4.2
Bochnia Tuffite	glass	0.002686	>300	13.62 ±0.10	0.62	22(15)	32.19	73.4	3.28	13.99 ±0.10	13.17 ±0.31	300.3 ±3.1

MSWD – Mean Square Weighted Deviation; N – the total number of repetitions in the single fusion experiments and the total number of steps in the incremental heating experiments; in brackets is the number of experiments used to calculate the weighted mean or peak probability density age; $^{39}Ar_K$ – the percentage of $^{39}Ar_K$ released by plateau steps; $^{40}Ar^*$ – the radiogenic amount of ^{40}Ar; total fusion and isochron ages and inverse isochron intercepts are given for reference; errors are given at 95 per cent confidence level; MSWD, $^{40}Ar^*$ [%], $^{39}Ar_K$ [%], K/Ca, isochron age [Ma] and inverse isochron intercept were determined based on the experiments selected for calculation of the weighted mean age

t-test. The steps included in the plateau on average have 63.14% radiogenic argon.

This yielded plateau ages of 13.77 ±0.08 Ma (MSWD 0.66) and 13.74 ±0.09 Ma (MSWD 1.99, both 1 sigma analytical errors). The $^{40}Ar/^{36}Ar$ inverse isochron intercepts were respectively 298 ±6 and 311 ±6. This last intercept values does indicate a minor amount of excess argon. Combination of both experiments yields a weighted mean plateau age of 13.76 ±0.08 Ma (1 sigma analytical error) representing the crystallization age of the glass fraction of the Wiatowice Tuffite.

For the Bochnia Tuffite, we included consecutive steps overlapping at the 2 sigma level. Visual inspection of the plateau for experiments 239 and 241 made us exclude steps C and D for the former and D for the latter as well. Steps included in the plateau on average have 32.19% radiogenic argon, significantly less than for the Wiatowice Tuffite. This results in larger uncertainties in the age of the Bochnia Tuffite.

This yielded plateau ages for the Bochnia Tuffite of 13.61 ±0.13 Ma (MSWD 0.26) and 13.64 ±0.12 Ma (MSWD 1.02, both 1 sigma analytical errors). The $^{40}Ar/^{36}Ar$ inverse isochron intercepts were respectively 300 ±4 and 301 ±7. The intercept values do not show significant amounts of excess argon. Therefore we concluded that the weighted mean plateau age of 13.62 ±0.10 Ma (1 sigma analytical error) represents the crystallization age of the glass fraction of the Bochnia Tuffite.

DISCUSSION

Final determination of the full number of tuffite levels (horizons) in the Carpathian Foredeep has not yet been completed, and using the list (numbering) of those levels presented by Alexandrowicz (1997; Fig. 2) one can state now that (Wiatowice Tuffite – equivalent tf_6), has been dated at 13.76

±0.08 Ma, while Bochnia Tuffite (equivalent tf_8) is 13.62 ±0.10 Ma.

Recently, $^{40}Ar/^{39}Ar$ dating of two tuffite levels below and within the Badenian salts in Wieliczka Salt Mine (WT-1 and WT-3 – equivalent t7 after Alexandrowicz, 1997) has been completed in the same laboratory. The results obtained indicate that deposition of evaporites within the Carpathian Foredeep started shortly after 13.81 ±0.076 Ma and ended after 13.60 ±0.071 Ma (de Leeuw *et al*., 2010). The $^{40}Ar/^{39}Ar$ dating was carried out on hornblende and biotite separated from these layers. The inconsistency of results presented in this article, slightly different then the dates published by the same team (de Leeuw *et al*., 2010), can be explained by the different minerals used; the age calculation results coincide within error.

The ages obtained for the Wiatowice and Bochnia tuffites represent reasonable estimates of their true crystallisation ages. However, the analyses were performed on glass shards. Hydration resulting in mobility of K and/or Ar in glass, and recoil artifacts produced by neutron irradiation, can severely affect most glass shards from volcanic ashes (Morgan *et al*., 2009). These dates are thus not as reliable as $^{40}Ar/^{39}Ar$ ages acquired from potassium feldspar, biotite or hornblende fractions, which should be taken into account in further interpretation.

The assemblage of foraminifers from Wiatowice represents biozone IIγ (characteristic of the upper part of the Skawina

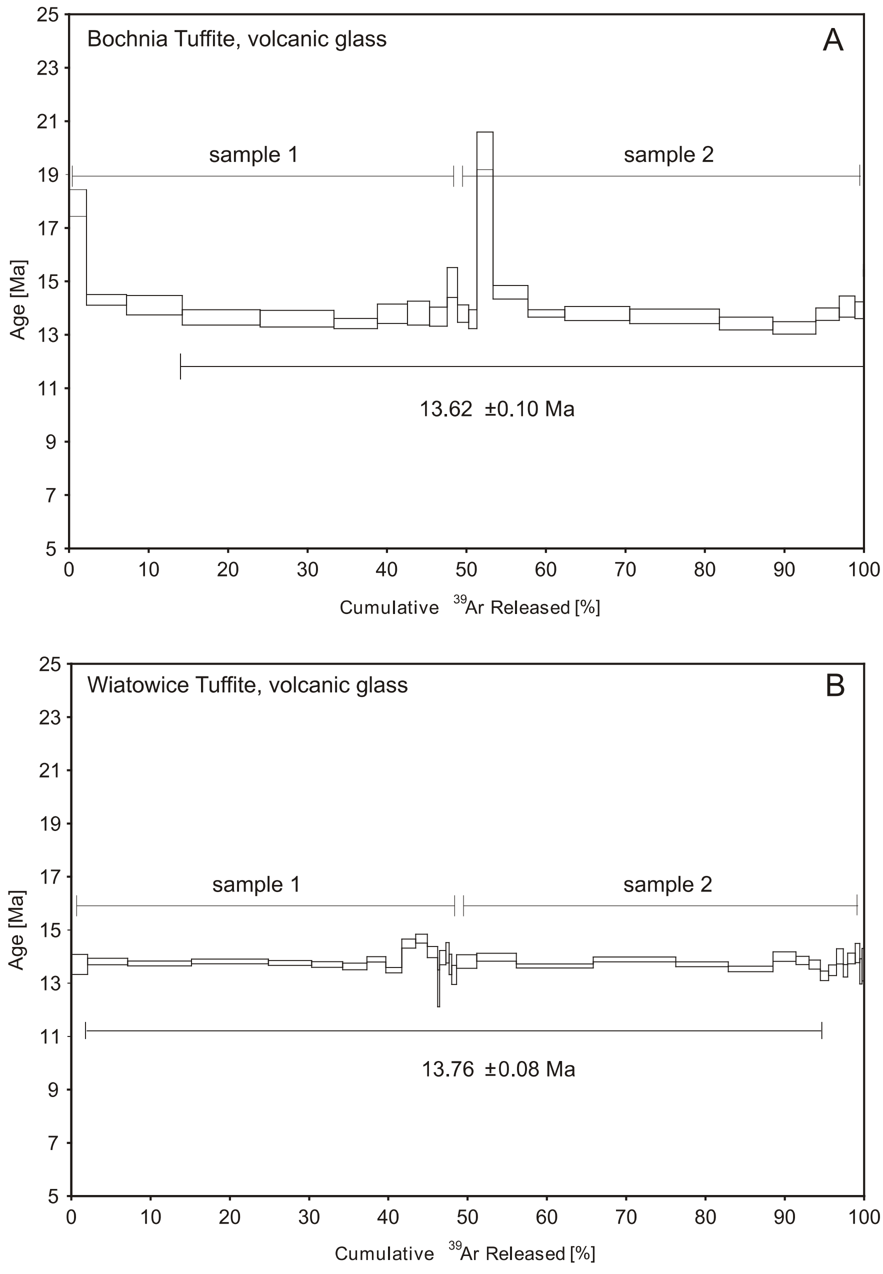

Fig. 8. Incremental heating spectrum for the Chodenice and Wiatowice glass separates

The chosen age plateaus and corresponding weighted mean ages are indicated

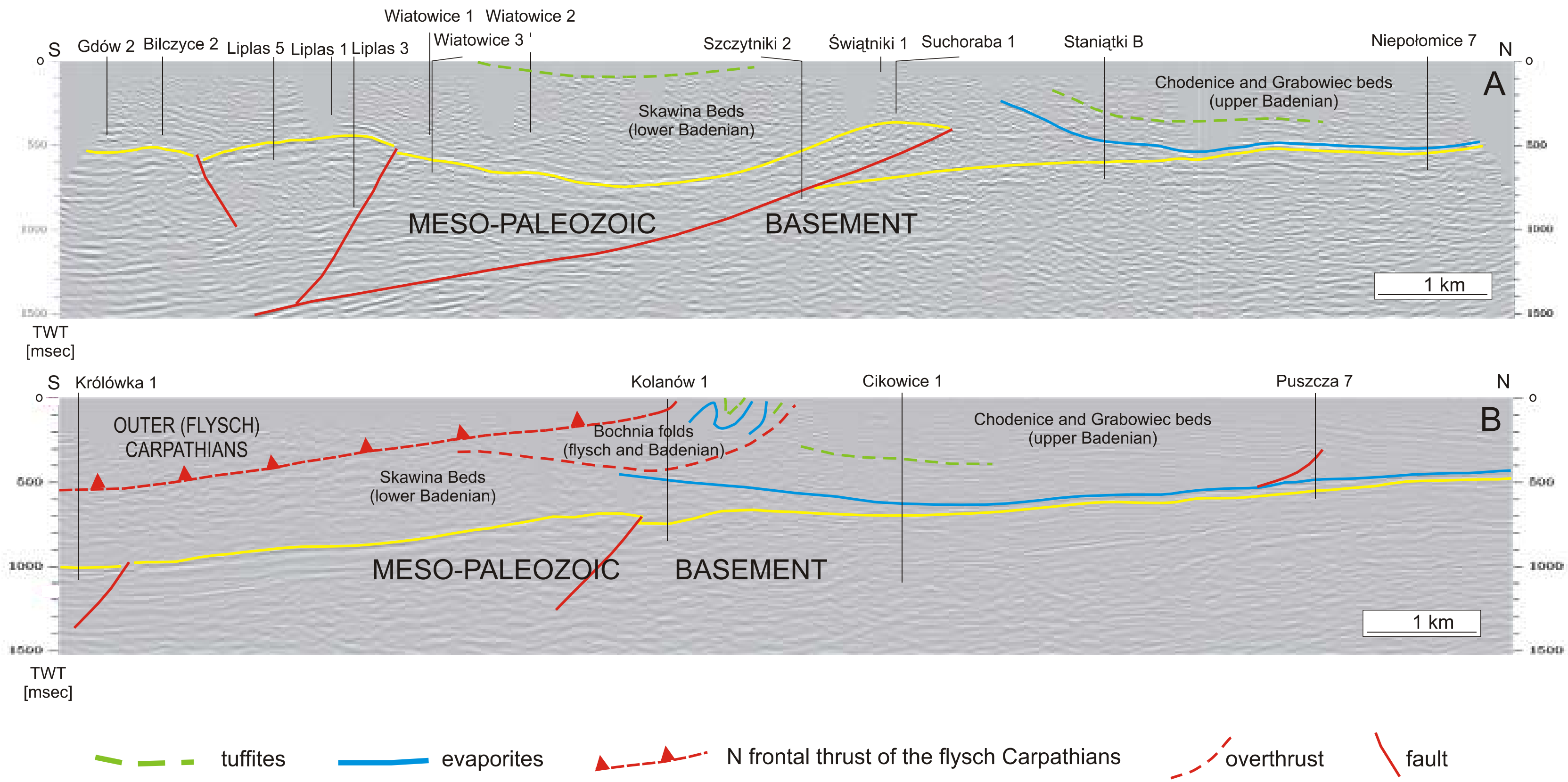

Fig. 9. Interpreted seismic profiles from the study area (location see Fig. 1)

Note that due to the relatively low quality of seismic data, especially at shallower levels, structural interpretation of the thrust front in the vicinity of the Kolanów 1 borehole (profile 2) should be regarding as first-order approximation only, partly based on published models from the Bochnia area (e.g., Poborski, 1952; Garlicki, 1968; Olewicz, 1973)

Beds) and microfauna (radiolaria) from Chodenice biozone IIIA, characteristic of the upper part of the Chodenice Beds (Barwicz-Piskorz, 1996, 1997; Fig. 2). Radiometric dating confirmed by studies of microfauna clearly shows that the sedimentary infill of the Gdów "embayment" consists of the lower Badenian Skawina Beds.

The foraminiferal assemblage zones (Alexandrowicz, 1963) belong to the canon of biostratigraphy of marine sediments of the Carpathian Foredeep. They provide a very functional tool in the peripheral part of the central Paratethys since their stratigraphic sequence is very consistent in that area, and the extent of variability within specific biozones does not hamper their lateral correlation. Those features and trends of changes in the taxonomic composition suggest that assemblage biozones of the Badenian mirrored global rather than local and regional palaeogeographic conditions (Gonera, 2001). Based on the analysis of stable isotopes and comprehensive palaeoecological research it has been shown that those biozones reflect climate changes (Durakiewicz *et al*., 1997), that may be correlated with the global cooling phases Mi-3 and Mi-4 (*sensu* Miller *et al*., 1991*a*, *b*; Gonera, 2001; Bicchi *et al*., 2003; Gonera *et al*., 2003). Results of the age analysis of tuffites from Wiatowice and Chodenice support the first of the above-mentioned cooling phases, but not the second of them. These conclusions are consistent with newly acquired $^{40}Ar/^{39}Ar$ ages (de Leeuw *et al.*, 2010) and older $^{40}Ar/^{39}Ar$ ages (Dudek *et al*., 2004*b*). They indicate that the Badenian evaporites were triggered by the worldwide cooling event Mi3b (e.g., Abels *et al*., 2005; see also: Gonera *et al*., 2000; Gonera, 2001; Oszczypko *et al*., 2006; de Leeuw *et al*., 2010).

The results obtained support interpretations of the geological structure of the Gdów "embayment" area and in its immediate surroundings published by Garlicki (1960), Alexandrowicz (1965) and Doktor (1983). The earliest geological studies of the frontal Carpathian orogenic wedge have been focused on the Wieliczka and Bochnia areas, where rock salt has been mined for many centuries (*cf*. Poborski, 1965, with references therein). Numerous structural models have been proposed for the frontal Carpathians, and almost all of them relied on classical concepts of foreland-verging thrust-and-fold structural models (see Oszczypko *et al*., 2006 for detailed overview and further references). Recently, a model of wedge tectonics and triangle zones was used in order to explain the structure of the Carpathian front imaged on seismic data from the Wojnicz–Tarnów area (Krzywiec *et al*., 2004). Furthermore, it was suggested, using published geological cross-sections from the Wieliczka area (Tołwiński, 1956), that in the Wieliczka part of the Carpathian front wedge tectonics also played an important role, and that entire Wieliczka Salt Mine – one of the classical areas of compressional salt tectonics (*cf*. Jackson, 1995) – is located in the core of the triangle zone formed during the last stages of compression within the Carpathian orogenic wedge (Krzywiec and Vergés, 2007).

The structure of the Carpathian orogenic front in the vicinity of two localities where tuffite levels have been sampled is shown on two seismic profiles (Fig. 9). Profile 1 (Fig. 9A) is located in the central part of the Gdów "embayment" (Fig. 1), within which two major zones of reverse faulting within the sub-Miocene substratum, also affecting the Miocene infill, have been identified. Within the orogenic front, evaporites have been uplifted and backthrust together with the overlying upper Badenian Chodenice and Grabowiec beds. The sedimentary infill of the Gdów "embayment" consists of uplifted and partly faulted and folded lower Badenian Skawina Beds. Tuffite levels sampled at the Wiatowice locality belong to this tectonic unit. The entire structure, observed on seismic data, may be classified as a triangle zone, similar to that occurring in the Wojnicz area *ca*. 40 km to the east (Krzywiec *et al*., 2004) and – possibly – also in the Wieliczka area (Krzywiec and Vergés, 2007).

Profile 2 (Fig. 9B) is located outside the Gdów "embayment", close to the Bochnia Salt Mine (Fig. 1). On this profile, thick-skinned reverse faulting within the Meso-Paleozoic basement is also visible, and it coincides with uplifted and backthrust evaporites. The triangle zone filled by the lower Badenian Skawina Beds, penetrated by the Królówka 1 borehole, has been overriden by a younger in-sequence thrust of the flysch Carpathian nappes, in front of which the so-called Bochnia Fold has formed, that includes both folded flysch succession as well as foredeep Miocene deposits. It should be stressed here that the interpretation of the Bochnia folds shown on Figure 9B should be regarded as tentative, because the quality of available seismic data was to low to precisely image the complex fold-and thrust structures of this area. The proposed model is an approximation based to a large degree on published cross-sections from the Bochnia Salt Mine (Poborski, 1952; Garlicki, 1968). The orogenic thrust front along this profile should be placed in the vicinity of the Puszcza 7 borehole, relatively far from the triangle zone with the deformed evaporitic succession. Compressional deformation visible in the vicinity of Puszcza 7 borehole is equivalent to the frontal deformation of the Biadoliny slice in the vicinity of Wojnicz–Tarnów (Krzywiec, 2001; Krzywiec *et al*., 2004).

CONCLUSIONS

Relatively small but important variations in the chemical composition of two sampled tuffite levels have been distinguished. The results shown a relatively small variation in the silica content of glass originating from the same level, however clearly differing from that of glass originating from another level (about 80% SiO_2 in the case of the Bochnia Tuffite and about 77% in the case of the Wiatowice Tuffite). These levels varied in the content of sodium in the glass (average 2.63% Na_2O in the in the case of the Bochnia Tuffite and 3.06% in the case of the Wiatowice Tuffite). Differences were also noticed in the rate of glass development. The Wiatowice Tuffite has a high proportion of pumice-type glass, which is almost absent from the Bochnia Tuffite.

The $^{40}Ar/^{39}Ar$ ages of the glass separates obtained from these layers were determined applying (standard) incremental heating techniques. The $^{40}Ar/^{39}Ar$ results showed that the Wiatowice Tuffite is older than the Bochnia Tuffite. Tuffite levels sampled in the Wiatowice area belong to the pre-evaporitic succession and tuffite levels sampled in the Chodenice area belong to the post-evaporitic succession. These results support ages based on foraminiferal microfauna and calcareous nannoplankton. Such a stratigraphic position explain that within the "Gdów embayment" Miocene compression led to localized inversion of early normal faults, responsible for the formation of small local basins filled by lower Badenian siliciclastic deposits.

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APPENDIX A

Full analytical data for the Chodenice and Wiatowice single fusion experiments

Wiatowice Tuffite glass fraction												
Single fusion		^{36}Ar(a)	^{37}Ar(ca)	^{38}Ar(cl)	^{39}Ar(k)	^{40}Ar(r)	Age [Ma]	±1σ	^{40}Ar(r) [%]	^{39}Ar(k) [%]	K/Ca	±1σ
09M0167C	7.00 W	0.004114	0.195065	0.002047	1.198406	3.332914	13.42	±0.07	73.26	21.70	2.642	±0.063
09M0167D	7.00 W	0.002995	0.187409	0.002647	1.116440	3.210008	13.88	±0.07	78.37	20.22	2.562	±0.058
09M0167J	7.00 W	0.006779	0.236856	0.003049	1.434212	4.131308	13.90	±0.08	67.33	25.97	2.604	±0.059
09M0167A	7.00 W	0.003929	0.136512	0.001746	0.799505	2.311358	13.95	±0.10	66.55	14.48	2.518	±0.058
09M0167B	7.00 W	0.002345	0.163479	0.002187	0.973802	2.900191	14.37	±0.08	80.70	17.63	2.561	±0.059
Chodenice Tuffite glass fraction												
Single fusion		^{36}Ar(a)	^{37}Ar(ca)	^{38}Ar(cl)	^{39}Ar(k)	^{40}Ar(r)	Age [Ma]	±1σ	^{40}Ar(r) [%]	^{39}Ar(k) [%]	K/Ca	±1σ
09M0168A	7.00 W	0.008780	0.133552	0.003144	1.042152	2.933312	13.59	±0.12	53.06	16.27	3.355	±0.077
09M0168B	7.00 W	0.004179	0.124103	0.002950	0.975685	2.732975	13.52	±0.07	68.86	15.23	3.381	±0.080
09M0168C	7.00 W	0.017369	0.150513	0.002918	1.117896	3.205017	13.84	±0.18	38.44	17.45	3.194	±0.075
09M0168E	7.00 W	0.05114	0.244193	0.004634	1.863516	5.276333	13.67	±0.17	25.87	29.09	3.281	±0.074
09M0168F	7.00 W	0.034424	0.182491	0.003790	1.407021	4.280761	14.68	±0.21	29.62	21.96	3.315	±0.076

APPENDIX B

Full analytical data for the Chodenice and Wiatowice incremental heating experiments

Chodenice Tuffite, glass fraction

Incremental heating		*	^{36}Ar(a)	^{37}Ar(ca)	^{38}Ar(cl)	^{39}Ar(k)	^{40}Ar(r)	Age [Ma]	±1σ	^{40}Ar(r) [%]	^{39}Ar(k) [%]	K/Ca	±1σ
09M0239B	12.50 W		0.013793	0.046449	0.000997	0.361300	1.343879	17.93	±0.50	24.79	2.19	3.345	±0.118
09M0239C	15.50 W		0.011331	0.109927	0.001875	0.828638	2.456599	14.31	±0.20	42.31	5.02	3.241	±0.109
09M0239D	18.50 W		0.033383	0.150758	0.002430	1.157404	3.383310	14.11	±0.36	25.54	7.02	3.301	±0.114
09M0239E	22.00 W	x	0.038582	0.206935	0.003861	1.617752	4.575538	13.65	±0.29	28.64	9.81	3.362	±0.116
09M0239F	26.00 W	x	0.037287	0.199559	0.003531	1.532416	4.319667	13.61	±0.31	28.16	9.29	3.302	±0.118
09M0239G	30.00 W	x	0.011140	0.121645	0.002224	0.902550	2.509084	13.42	±0.19	43.25	5.47	3.190	±0.124
09M0239H	34.00 W	x	0.016356	0.085339	0.001347	0.625214	1.786280	13.79	±0.36	26.98	3.79	3.150	±0.117
09M0239I	38.00 W	x	0.014802	0.061028	0.001060	0.459023	1.313642	13.81	±0.45	23.09	2.78	3.234	±0.124
09M0239J	44.00 W	x	0.007416	0.048650	0.000838	0.361994	1.025970	13.68	±0.36	31.88	2.19	3.200	±0.121
09M0239K	50.00 W		0.006505	0.034504	0.000499	0.215925	0.669533	14.96	±0.56	25.83	1.31	2.691	±0.129
09M0239L	60.00 W	x	0.005446	0.030219	0.000559	0.231188	0.660777	13.80	±0.33	29.11	1.40	3.290	±0.154
09M0239M	75.00 W	x	0.002439	0.023145	0.000458	0.171342	0.482119	13.58	±0.35	40.08	1.04	3.183	±0.182
09M0241B	12.50 W		0.018223	0.044996	0.000645	0.336174	1.387265	19.88	±0.71	20.48	2.04	3.213	±0.118
09M0241C	15.50 W		0.013641	0.094071	0.001764	0.723794	2.188791	14.59	±0.25	35.19	4.39	3.308	±0.116
09M0241D	18.50 W		0.006574	0.098934	0.001890	0.763889	2.183907	13.80	±0.14	52.91	4.63	3.320	±0.115
09M0241E	22.00 W	x	0.027115	0.173332	0.002954	1.347033	3.850345	13.80	±0.27	32.45	8.17	3.342	±0.117
09M0241F	26.00 W	x	0.042639	0.238935	0.003991	1.859526	5.274735	13.69	±0.27	29.51	11.27	3.347	±0.119
09M0241G	30.00 W	x	0.020075	0.143099	0.002501	1.108488	3.082470	13.42	±0.24	34.19	6.72	3.331	±0.123
09M0241H	34.00 W	x	0.015270	0.115254	0.002325	0.891499	2.448977	13.26	±0.23	35.18	5.41	3.326	±0.122
09M0241I	38.00 W	x	0.007895	0.061614	0.001198	0.489156	1.396007	13.78	±0.23	37.43	2.97	3.414	±0.130
09M0241M	75.00 W	x	0.009171	0.041926	0.000575	0.322282	0.938494	14.05	±0.40	25.72	1.95	3.305	±0.142
09M0241O	9.50 W	x	0.003093	0.025026	0.000438	0.187367	0.540444	13.92	±0.31	37.15	1.14	3.219	±0.151

Information on analysis	Results	^{40}Ar(r)/^{39}Ar(k)	±1σ	Age [Ma]	±1σ	MSWD	^{39}Ar(k) [%. n]	K/Ca	±1σ
VU78-33 Glass Chodenice	weighted plateau	2.8225	±0.0152 ±0.54%	13.62	±0.10 ±0.7%	0.57	73.40 15	3.284 ±0.033	
	external error				±0.17	0.97	statistical T ratio		
	analytical error				±0.07	1.0000	error magnification		
Project = VU78 Irradiation = VU78	total fusion age	2.8991	±0.0153 ±0.53%	13.99	±0.10 ±0.7%		22	0.093 ±0.001	
J = 0.0026857 ±0.0000134	external error				±0.17				
Dra = 25.420 ±0.145 Ma	analytical error				±0.07				

App. B cont.

Wiatowice Tuffite, glass fraction

Incremental heating		*	^{36}Ar(a)	^{37}Ar(ca)	^{38}Ar(cl)	^{39}Ar(k)	^{40}Ar(r)	Age [Ma]	±1σ	^{40}Ar(r) [%]	^{39}Ar(k) [%]	K/Ca	±1σ
09M0237B	12.50 W		0.010307	0.072547	0.000738	0.410944	1.166786	13.70	±0.38	27.70	2.05	2.436	±0.081
09M0237C	15.50 W	x	0.008971	0.167803	0.001861	1.012383	2.897279	13.81	±0.12	52.21	5.06	2.594	±0.085
09M0237D	18.50 W	x	0.008381	0.265268	0.002622	1.611021	4.587145	13.74	±0.09	64.93	8.05	2.611	±0.089
09M0237E	22.00 W	x	0.010305	0.316873	0.003407	1.939351	5.550876	13.81	±0.09	64.56	9.69	2.632	±0.091
09M0237F	26.00 W	x	0.004922	0.181903	0.001871	1.094110	3.118182	13.75	±0.09	68.18	5.47	2.586	±0.092
09M0237G	30.00 W	x	0.004532	0.133995	0.001126	0.780510	2.215795	13.70	±0.11	62.32	3.90	2.505	±0.090
09M0237H	34.00 W	x	0.002438	0.102968	0.001082	0.613673	1.732482	13.63	±0.12	70.61	3.07	2.563	±0.099
09M0237I	38.00 W	x	0.002219	0.079905	0.000912	0.480716	1.384046	13.89	±0.10	67.84	2.40	2.587	±0.098
09M0237J	44.00 W		0.001328	0.066438	0.000555	0.406970	1.137155	13.49	±0.10	74.33	2.03	2.634	±0.105
09M0237K	50.00 W		0.001584	0.057970	0.000670	0.348155	1.044964	14.48	±0.17	69.05	1.74	2.582	±0.112
09M0237L	60.00 W		0.002038	0.047365	0.000442	0.290473	0.883156	14.67	±0.16	59.45	1.45	2.637	±0.104
09M0237M	75.00 W		0.001556	0.045636	0.000447	0.263082	0.772314	14.17	±0.21	62.67	1.31	2.479	±0.113
09M0237N	76.00 W		0.000577	0.006286	0.000039	0.049714	0.131862	12.80	±0.69	43.60	0.25	3.401	±0.523
09M0237O	95.00 W		0.001190	0.028341	0.000161	0.160124	0.463128	13.96	±0.27	56.84	0.80	2.429	±0.119
09M0237P	120.00 W		0.000315	0.014548	0.000179	0.080003	0.234441	14.14	±0.38	71.56	0.40	2.365	±0.141
09M0237Q	150.00 W		0.000448	0.012344	0.000261	0.066954	0.190090	13.70	±0.38	58.92	0.33	2.332	±0.159
09M0237R	250.00 W		0.000582	0.021833	0.000169	0.121245	0.334351	13.31	±0.36	66.04	0.61	2.388	±0.138
09M0238B	12.50 W		0.007946	0.086415	0.000796	0.508755	1.455779	13.81	±0.25	38.27	2.54	2.532	±0.083
09M0238C	15.50 W	x	0.010031	0.166755	0.001564	1.001962	2.901576	13.98	±0.15	49.46	5.01	2.584	±0.086
09M0238D	18.50 W	x	0.008794	0.317823	0.003250	1.940076	5.484760	13.64	±0.07	67.84	9.69	2.625	±0.089
09M0238E	22.00 W	x	0.013116	0.342015	0.003628	2.083650	5.998921	13.89	±0.09	60.74	10.41	2.620	±0.090
09M0238F	26.00 W	x	0.006960	0.224637	0.002145	1.326355	3.767472	13.71	±0.09	64.67	6.63	2.539	±0.090
09M0238G	30.00 W	x	0.005134	0.183942	0.001922	1.128711	3.164949	13.53	±0.10	67.59	5.64	2.639	±0.095
09M0238H	34.00 W	x	0.004524	0.099128	0.000901	0.577705	1.675588	14.00	±0.18	55.61	2.89	2.506	±0.092
09M0238I	38.00 W	x	0.001560	0.057648	0.000568	0.332656	0.954946	13.85	±0.15	67.43	1.66	2.481	±0.095
09M0238J	44.00 W	x	0.001173	0.051382	0.000547	0.285011	0.808980	13.70	±0.17	69.99	1.42	2.385	±0.100
09M0238K	50.00 W		0.000452	0.035418	0.000257	0.206188	0.566992	13.27	±0.18	80.93	1.03	2.503	±0.100
09M0238L	60.00 W		0.001238	0.033298	0.000386	0.200415	0.559988	13.49	±0.20	60.47	1.00	2.588	±0.118
09M0238M	75.00 W		0.000787	0.030375	0.000353	0.168741	0.489754	14.01	±0.28	67.78	0.84	2.389	±0.113
09M0238N	76.00 W		0.000443	0.018351	0.000216	0.113309	0.316008	13.46	±0.23	70.69	0.57	2.655	±0.145
09M0238O	95.00 W		0.001046	0.033554	0.000260	0.187162	0.540116	13.93	±0.20	63.60	0.94	2.399	±0.107
09M0238P	120.00 W		0.001000	0.021051	0.000139	0.115309	0.337595	14.13	±0.36	53.31	0.58	2.355	±0.127
09M0238Q	150.00 W		0.000400	0.012386	0.000181	0.057678	0.160645	13.44	±0.47	57.61	0.29	2.002	±0.149
09M0238R	250.00 W		0.000301	0.009258	0.000088	0.052092	0.147818	13.70	±0.61	62.39	0.26	2.420	±0.239
		Σ	0.126597	3.345459	0.033742	20.015202	57.175938						

Information on analysis	Results	^{40}Ar(r)/^{39}Ar(k)	±1σ	Age [Ma]	±1σ	MSWD	^{39}Ar(k) [%n]	K/Ca	±1σ
VU78-32 Glass Wiatowice	error plateau	2.8502	±0.0064 ±0.23%	13.76	±0.08 ±0.5%	1.30	80.98 15	2.566 ±0.024	
	external error				±0.16	0.97	statistical T ratio		
	analytical error				±0.03	1.1423	error magnification		
Project = VU78 Irradiation = VU78	total fusion age	2.8566	±0.0055 ±0.19%	13.79	±0.07 ±0.5%		34	0.072 ±0.001	
J = 0.0026854 ±0.0000134	external error				±0.16				
Dra = 25.420 ±0.145 Ma	analytical error				±0.03				

* – steps included in calculation of the weighted mean and inverse isochron age; Dra – age of the Drachenfels sanidine crystals used as flux monitor