Discovery of the Badenian evaporites inside the Carpathian Arc: implications for global climate change and Paratethys salinity

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Abstract: Massive evaporites were discovered in the Soltvadkert Trough (Great Plain, Hungary) correlating to the Badenian Salinity Crisis (13.8 Ma, Middle Miocene) on the basis of nannoplankton and foraminifera biostratigraphy. This new occurrence from Hungary previously thought to be devoid of evaporites is part of a growing body of evidence of evaporitic basins inside the Carpathian Arc. We suggest the presence of evaporites perhaps in the entire Central Paratethys during the salinity crisis. Different scenarios are suggested for what subsequently happened to these evaporites to explain their presence or absence in the geological record. Where they are present, scenario A suggests that they were preserved in subsiding, deep basins overlain by younger sediments that protected the evaporites from reworking, like in the studied area. Where they are absent, scenario B suggests recycling. Scenario B explains how the supposedly brackish Sarmatian could have been hyper/normal saline locally by providing a source of the excess salt from the reworking and dissolving of BSC halite into seawater. These scenarios suggest a much larger amount of evaporites locked up in the Central Paratethys during the salinity crisis then previously thought, probably contributing to the step-like nature of cooling of the Mid Miocene Climate Transition, the coeval Mi3b.

Keywords: Miocene climate, evaporites, Paratethys, stratigraphy, Badenian, Sarmatian, palaeosalinity.

Introduction

The evidence presented here is the first account of Badenian evaporites from inside the Carpathian Arc from Hungary with a detailed stratigraphy, that correlates these layers to the Badenian Salinity Crisis (BSC) of the Wielician. Evaporites from Hungary have previously been explained by emphasis on local salt tectonics (Palotai & Csontos 2012), or occurrences only listed in data repositories (Jámbor et al. 1976; Cserepes-Meszéna et al. 2000, 2004). It has generally been believed that the Pannonian Basin was disconnected from the evaporitic basins and thus devoid of evaporite formation, (Balintoni & Petrescu 2002; Báldi 2006; Kováč et al. 2007; Piller et al. 2007) although the existence of widespread thick evaporitic successions deposited during the BSC in the Carpathian Foredeep (CFD) and the Transylvanian Basin (Fig. 1) is well documented (Bąbel & Becker 2006; Peryt 2006; Bukowski et al. 2007; Śliwiński et al. 2012; de Leeuw et al. 2013). Most of the historical salt mines in the region generally belong to the arc of the Fore-Carpathian (Carpathian Foredeep, CFD) evaporitic belt ranging across many countries starting in the foreland, in upper Silesia in Poland and in the Opava region of the Czech Republic in the NW Carpathians, followed by the well-known Wieliczka-Bochnia area (Bicchi et al. 2003; Gonera & Bukowski 2012) of Poland to continue further into Ukraine and ending in the South Carpathians of Romania (Peryt & Peryt 2009). Exceptions are in different geological settings, the historical mining towns of the Transylvanian Basin of Romania (e. g., Turda, Praid, Ocna Mureș etc) and the similarly famous Solotvyna in the Transcarpathian Trough in Ukraine. Besides these well-known localities, there is increasing evidence of more evaporites in the Pannonian Basin system of the Central Paratethys (CP). For example, it is not so long ago, that it turned out, that there are evaporites of the Transcarpathian Trough besides Solotvyna occurrence on the surface, continuing NW into the East Slovak Basin transected by drilling (Franců et al. 1989; Kováč et al. 1995; Túnyi et al. 2005; Bukowski et al. 2007) and correlated to the BSC by magneto- or biostratigraphy (do not mix with older Carpathian evaporites of the Transcarpathian Trough). Not long ago, a massive salt deposition, previously thought to be older, was identified as BSC on the southern margin of the CP in the Tuzla Basin in North Bosnia and Herzegovina (Ćorić et al. 2007). In the sediments overlaying the salt formation the species *Helicosphaera waltrans* Theodoridis, 1984 is absent, and therefore these layers can be placed into the uppermost NN5.

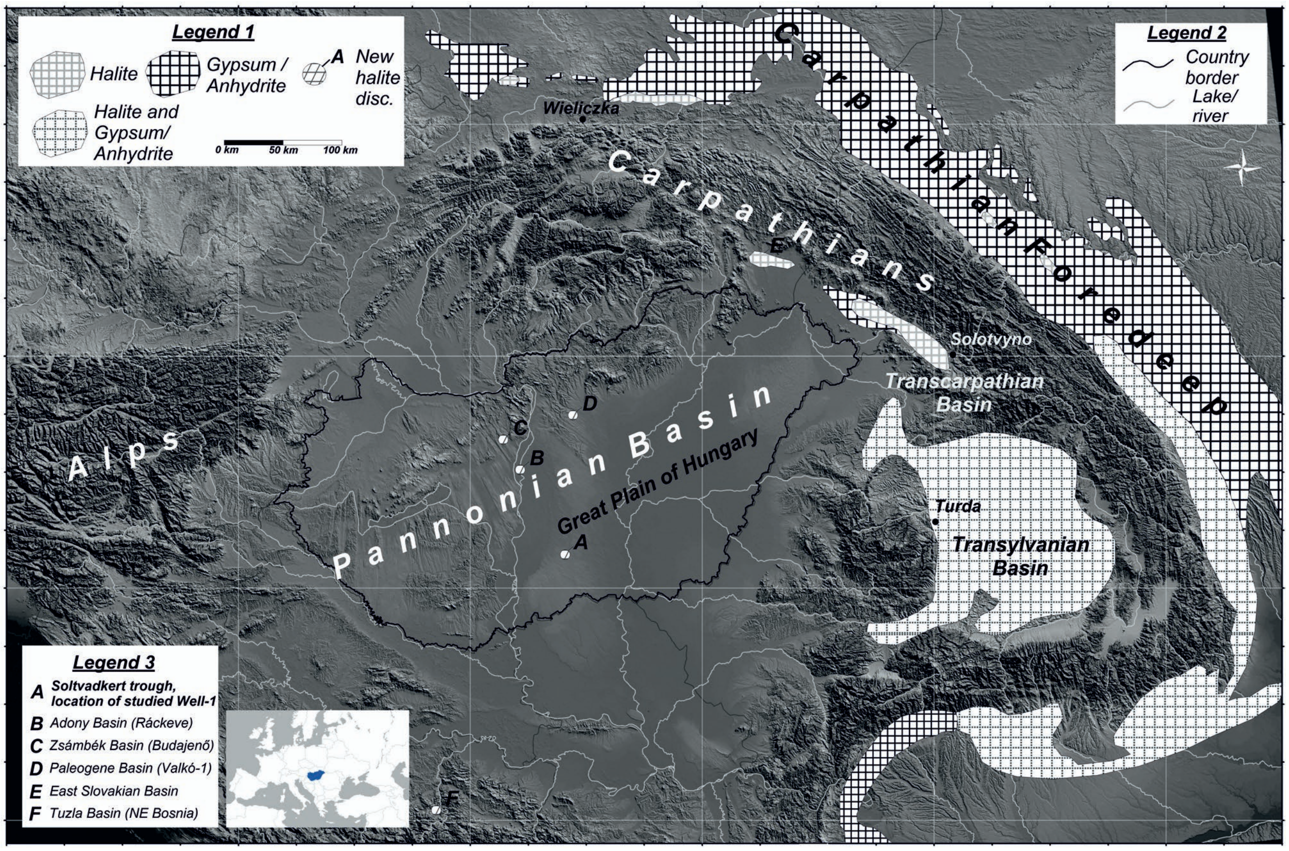

Fig. 1. Evaporite occurrences in the Central Parathetys region with classical evaporite localities in the Carpathian Foredeep and Transylvania. The studied evaporite location of the Soltvadkert Trough is in legend A and the recently discovered evaporite locations mentioned in text are in legend B–F. The figure was prepared by Golden Software Surfer-9. The map is modified after Horváth et al. (2004) available at http://geophysics.elte.hu/atlas/geodin_atlas.htm and after Rögl (1998), Bąbel & Becker (2006), Peryt (2006), Bukowski et al. (2007) among others. The thumbnail map of Europe with Hungary is modified https://commons.wikimedia.org/wiki/File:Europe_map_hungary.png.

This implies, that the salt deposits of Tuzla are indeed the result of the BSC and this classic salt mine is adding to the number of BSC occurrences all over the CP.

Recent new contributions have helped to refine the time-frame of the BSC period (de Leeuw et al. 2010, 2013; Hohenegger & Wagreich 2011; Hohenegger et al. 2014) and its relation to global climate and oceanographic changes (Bicchi et al. 2003; Böhme 2003; Báldi 2006; de Leeuw et al. 2010; Karami et al. 2011; Gebhardt & Roetzel 2012). In terms of chronostratigraphy, the Badenian has traditionally been divided into three parts by Papp et al. (1978), the Lower Badenian (Moravian), Middle Badenian (Wielician), and Upper Badenian (Kosovian), but according to the latest contribution on evaporite stratigraphy (Hohenegger et al. 2014), this division does not coincide with traditional chronostratigraphic boundaries, where the Middle Badenian evaporites resulting from the BSC would belong not to the Middle Badenian, but to the Early Late Badenian. To avoid misunderstanding, in the present work evaporites are referred to in the chronostratigraphic sense as Wielician BSC deposits, or simply by the time interval of the BSC. The time interval before the BSC, but already in the Badenian is called the Moravian (pre-BSC period of the Badenian), whereas units deposited after the BSC and Badenian are Kosovian (post-BSC period of the Badenian).

The aims of the present work are threefold:

- To document the discovery in a hydrocarbon exploration well in Hungary of the occurrence of massive layers of evaporites from the Soltvadkert Trough (pre-BSC period of Badenian) and describe its biostratigraphy and depositional environment.
- To draw attention to the increasing number of evaporite occurrences in the CP correlated to the BSC, and to explain their late recognition in the geological record.
- To attempt to understand better the spatial distribution of BSC evaporites in the CP, including the new discoveries, and discussing the hypothesis of recycling BSC evaporites in a new and original perspective concerning salinity conditions and global cooling.

Revival of hydrocarbon exploration with modern techniques

Our data come from an oil and gas exploration well transecting a 50 m thick evaporitic sequence in the Soltvadkert Trough on the Great Plain of Hungary. This area is located in the Danube-Tisza Interfluve (Fig. 1) and has been the focus of oil and gas exploration for a long time. In the last fifty years numerous wells were drilled mainly on the structurally controlled basement highs and significant oil and gas deposits were found in Miocene and older reservoirs. Application of high resolution and/or 3D seismic measurements was not necessary as long as the focus of exploration was the robust, 4-way dip closures, which were mappable on a basic quality 2D grid.

The revival of interest in exploration in the area dates from 2010, with the introduction of 3D seismic surveys using the most modern processing methods to detect smaller scale structural, stratigraphical or combined hydrocarbon traps. Based on pilot studies and with the help of modern exploration tools, a 3D seismic acquisition of 400 km^2 was carried out, revealing the geological phenomenon described here.

Geology and basin history

The pre-Miocene basement with its Palaeozoic–Mesozoic NE–SW nappes of alpine origin are not the concern of this study. The sedimentary cycle of our interest started in the Karpatian (Early Miocene) according to Hámor (1998, 2001). This area and its larger region belongs to a NE–SW strike slip displacement zone, where small half grabens and/or pull-apart basins were formed at different times and locations.

In the Paratethys at the end of the Karpatian a regression took place due to compression and the studied area was elevated above sea level (Hámor 2001). The succeeding Badenian stage is characterized by transgression enclosing a sedimentary half-cycle. At the base of this half-cycle a conglomeratic lag is found, as a result of the initial part of the marine transgression. The transgression affected the sediment budget of the basin by reducing terrigenous input from the land surrounding the basin, making sediments gradually more and more enriched in carbonates and clays. Thus, the sedimentary sequence generally observable in this area started with a 10–30 m conglomerate lag or breccia at the base of the sequence followed by Lithothamnium-containing limestones of different facies. These shallow-water sediments shifted rather quickly into deep-water carbonate-rich marlstones and limey marls, as a result of the subsidence and sea level rise (Császár et al. 1997; Hámor 1998, 2001). The southern periphery of the studied basin had rather steep and high banks, very well observable on the base Badenian surface of Figure 2. Thus, even the deep water deposits contained resedimented shallow water fauna, biogene limestone fragments and fine sand and silt layers, most likely mass transported from a higher, shallower part of the basin (Fig. 2).

After the evaporitic event, deepening of the basin slowed down and sedimentation continued in a shallower marine environment without much change concerning lithology, in which the only conspicuous change is the appearance of thin volcanic tuff layers testifying to the onset of acidic to neutral magmatic activity in the area. The entire Badenian sequence can reach a thickness of 450–500 m.

Succeeding the Badenian half-cycle, an approximately 55–60 m thick Sarmatian layer was deposited above a non-depositional surface or erosional unconformity. According to the literature (Randazzo et al. 1999; Wiedl et al. 2012) in the Sarmatian, a half-cycle of a transgressive sequence similar to the Badenian should have been deposited in an environment of continuously decreasing salinity. However, in the studied area such layers cannot be identified beyond doubt. The probable reason for not finding typical Sarmatian deposits in the area is the intensifying volcanism producing large amounts of tuffs and tuffites, which overwrote the original sedimentation. Apart from the presence of volcanoclastic sediments, also altered and reworked, the lithology is similar to the Badenian dominated by marls and limey marls, but formed in a shallower environment, than in the previous period.

Following the Late Middle Miocene Sarmatian in the Late Miocene the Pannon Lake reigned leaving behind its very thick (1.5–2.5 km) prograding shelf-margin sediments over an erosional surface covering the Early to Late Miocene sediments (Magyar et al. 2013; Sztanó et al. 2013)

Results

An unpredictable pitfall of seismic interpretation

The freshly acquired 3D seismic data mentioned earlier revealed at first glance a strong amplitude phenomenon at the base of the Miocene sediments (Fig. 3a,c). This seismic phenomenon was a soft kick indicating a geophysical anomaly caused by lower density rocks, or a media slowing down the acoustic waves compared to its surroundings. This phenomenon was interpreted as an AVO (Amplitude Versus Offset) class III anomaly, which is a favourite target for exploration in the Neogene sediments of the Pannonian Basin. Based on the geological model of the area, it was thought that the compact, high-density, high acoustic velocity, limey marl would contain a softer, high porosity, hopefully hydrocarbon-saturated sandstone layer, forming a stratigraphic trap, which would fully explain the strong anomaly observed. The experts working in the area knew of the sporadic occurrence of gypsum and anhydrite stringers in the offset wells, at a location shown on Fig. 3c, while photo of gypsum occurrence in Fig. 4. They were well-aware of such evaporites having a similar effect on the seismic data, but given the sporadicity of these thin occurrences had no reason to doubt the prospect.

However this anomaly, the potential prospect, turned out to consist of evaporitic sediments of considerable thickness unknown to this region, and conformable with the base and the top with no sign of strong tectonic effect revealed by the seismic data (Fig. 3a,b). The studied anomaly on the 3D map can be identified as a monocline structure (Fig. 2), and based on the seismic section it is clear that the evaporite was indeed deposited undisturbed in this small depression and neither tectonized nor transported (Figs. 2, 3).

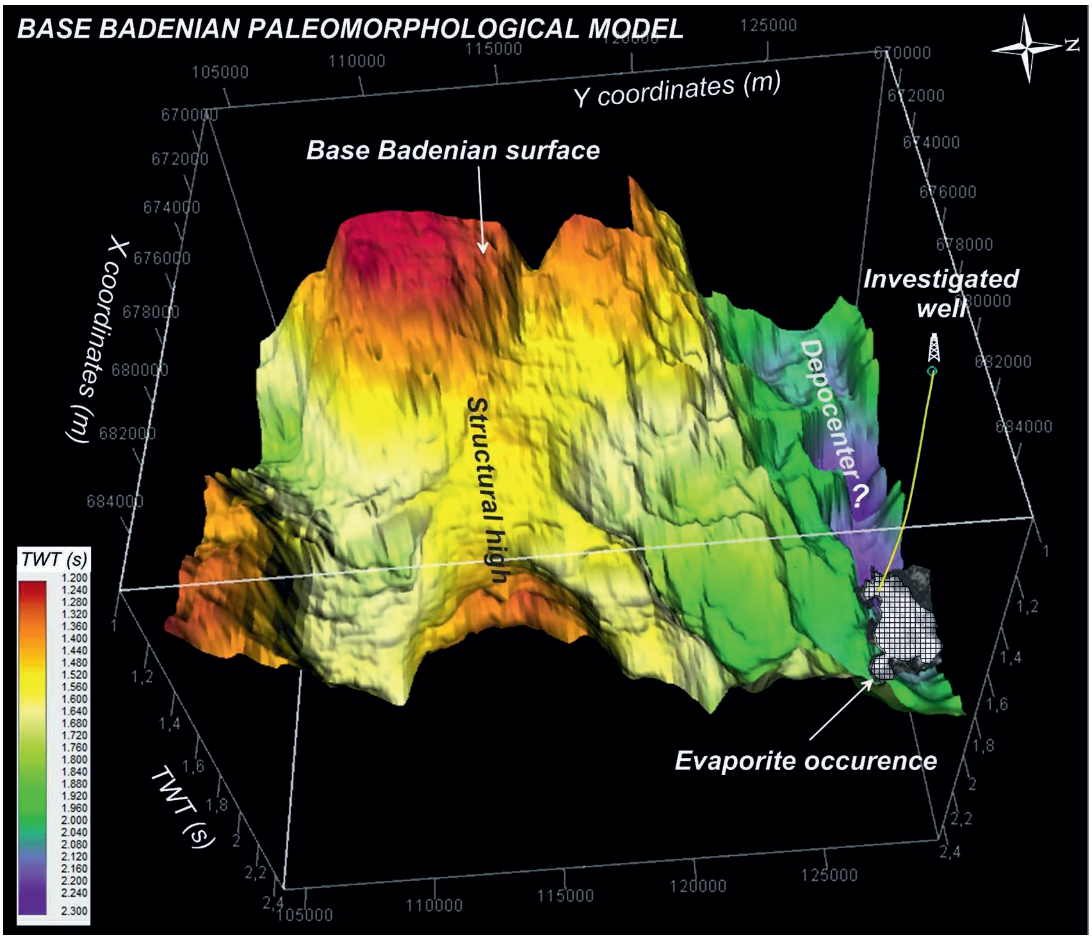

Fig. 2. Perspective 3D view of the evaporite accumulation on top of the reconstructed base Badenian palaeo-morphology. The discovered evaporite deposit is positioned in the depocenter of the basin, close to the toe of the slope. The questionmark shows another possible location for a yet undiscovered evaporite layer. TWT: Two ways travel time in seconds (s). The Golden Software Surfer-9 was used to prepare figure.

The studied well transected an evaporite horizon between 2495 and 2445 m (Figs. 3, 5). The sequence starts with a massive halite accumulation (2460–2495 m), interrupted by an approximately 4 metres thick, acidic tuffite layer (2462–2466 m). Overlying the halite are approximately 15 metres of anhydrite-rich sediment, described mainly from cuttings. The anhydrite occurrence is recognized from cuttings in the clean halite sequence too, but the process of halite dissolution in the water-based drilling mud makes it harder to reconstruct original evaporite composition. Gypsum occurrences are known not only from cuttings, but from cores taken in offset wells (Fig. 4). The lithology of the evaporite-rich layers with the log display is presented in Figure 5.

Previously known evaporite occurrences of uncertain age in Hungary

The discovery in an oil exploration well of massive evaporites at an unexpected location led us to look for other such occurrences and we discovered information from oil exploration wells Budajenő-2, Ráckeve-1 and Valkó-1 in the Hungarian Geological and Geophysical and Mining Data Repository. Find locations are shown in Figure 1.

The Budajenő-2 well transected 40 m of fine clastics and dacite tuff succession with anhydrite and gypsum from the Kosovian/Wielician (post-BSC or BSC, 334.2–374.2 m). It is believed that this was the first report of possible BSC evaporites from the Pannonian basin. The overlying beds (249.9–334.2 m) consist of alginitic siltstone with gypsum and sulphur intercalations and was determined as Sarmatian (Jámbor et al. 1976).

The Ráckeve-1 well is discussed from the tectonic point of view in a publication, where the age of evaporites is given as Badenian and/or Sarmatian? (Palotai & Csontos 2012). According to the public database 196 m of halite and anhydrite were reported (1827–2023 m) with intercalating clay in the upper part. The underlying clay (2023–2086 m) also contained nodules of anhydrites of Badenian age based on foraminifera and pollen (Cserepes-Meszéna et al. 2004). In the Valkó-1 well a 10 m thick anhydrite layer (1196–1206 m) is followed by 33 m of anhydrite with clay marl and marl intercalations. Based on the poor foraminifera, its age is most probably Kosovian/Wielician (Cserepes-Meszéna et al. 2000).

Micropalaeontology of the Soltvadkert Trough oil exploration well (Fig. 6)

A sample set of 25 nannoplankton sediment samples were used to prepare smear slides, using standard methods of treating small amounts of sediments in distilled water with ultrasound for few seconds. These were analysed with a light microscope (Leica DMLP) under 1000 magnification (cross and parallel nicols). The sample set of 18 foraminifera samples were processed by the standard technique, first disintegrating the samples with H-peroxide solution and then wet-sieving them. All fractions were examined for foraminifera to avoid ignoring small- or large-sized species, although the quantitative investigation of foraminifera under the light microscope was conducted upon the 125μm–2mm fraction. The nannoplankton assemblages from the investigated borehole were preserved well enough for determination, but many of the samples analysed for foraminifera were barren. Very few foraminifera were found in an extremely large amount of sediment, though they had acceptable preservation. In spite of these difficulties, micropalaeontological analyses were essential to our interpretation of this sequence concerning age and palaeoenvironment which is summarized in Figure 6.

Biostratigraphy

Calcareous nannoplankton

The attribution to nannoplankton zone NN5 (Martini 1971) is based on the occurrence of *Sphenolithus heteromorphus* and the absence of *Helicosphaera ampliaperta*. The NN5/NN6 boundary is defined by the last occurrence of *Sphenolithus heteromorphus*. Due to changed palaeo-ecological conditions on the top of NN5, the appearance of *S. heteromorphus* discontinues and this boundary cannot always be precisely determined. Therefore this boundary is positioned on the basis of the nannoplankton assemblage changes, as already observed at other localities in the CP. Nannoplankton Zone NN5 is generally dominated by small reticulofenestrids (*Reticulofenestra minuta* and *R. haqii*), whereas high percentages of *Reticulofenestra pseudoumbilicus* and *Coccolithus pelagicus* characterize nannoplankton zone NN6.

Foraminifera

The lowermost samples containing foraminifera yielded a rich planktonic assemblage, where in spite of bad preservation *Orbulina suturalis* can be identified with very high certainty and *Globigerinopsis grilli* with some doubt. This makes the age determination from the upper-half of the Late Moravian (Moravian: pre-BSC period of Badenian) to the end of the Wielician (Wielician: BSC), where the species *O.suturalis* has its last occurrence (LO) at 15.1 Ma (Cicha et al. 1998; Hohenegger et al. 2014). Just below the evaporites (2540 m) in addition to *O. suturalis* the species *Globorotalia bykovae* appears with a last common occurrence (LCO) at the end of the Wielician making the onset of evaporite formation later than 15.1 Ma. The highest sample with some limited biostratigraphic significance concerning foraminifera is from above the evaporites (2382 m) lacking planktonic forms, but a benthic Paratethyan species *Quinqueloculina bogdanowitzi* was determined with some ambiguity. If the Central Paratethys age distribution of this benthic species (Cicha et al. 1998) is accepted for the here presented material, then a Kosovian age is indicated with high uncertainty.

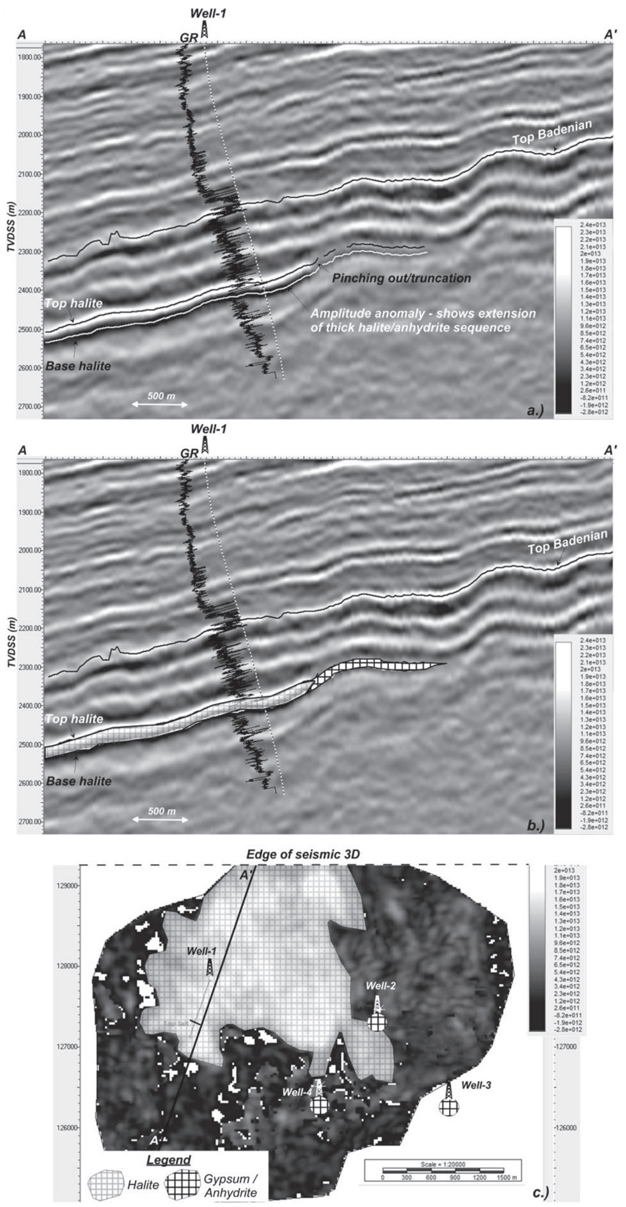

Fig. 3. Seismic sections and extension of halite. **a** — interpreted seismic section across explored amplitude anomaly; **b** — the identified salt accumulation which caused the phenomena (TVDSS: representing TVD minus the elevation above mean sea level of the depth reference point of the well); **c** — extension of halite layer based on amplitude mapping. The investigated well is well-1, while the offset wells are well-2, 3, 4 previously known to transect gypsum and anhydrite laminae. The Golden Software Surfer-9 was used to prepare figure.

Based on the calcareous nannoplankton and foraminifera evidence combined, the evaporitic layers from the Soltvadkert

Fig. 4. Gypsum/anhydrite stringer in black laminated marl, calcareous marl layer from Well-3 offset well (find location in Fig. 3c).

Trough discussed here can be correlated with the rather isochronous evaporites of the classical sites of the Wielician deposited during the BSC, top of NN5 or lowermost NN6 (de Leeuw et al. 2010; Hohenegger et al. 2014).

Palaeoenvironment

The panel on the right is the environmental interpretation in Figure 6. Generally foraminifera tests were present in low numbers per unit of sediment. There are two possible reasons for the scarcity of foraminifera. The foraminifera living at the time of deposition could be rare due to stress (low standing stock), or the foraminiferal tests may be diluted in sediments with high sedimentation rates (160–230 m compacted sediment/MY). Fortunately samples with low numbers of foraminifera due to salinity stress can be used to reconstruct environments, as in the case of a Messinian evaporite sequence (Kouwenhoven et al. 2006).

Pre-evaporitic environment

Before the onset of evaporite formation the lowermost samples contain a rich planktonic foraminifera assemblage, with *O. suturalis* and *Globigerina praebulloides* well-known indicators of eutrophy in the surface water (Rossignol et al. 2011; Sousa et al. 2014). Many authors emphasized other aspect of the same assemblage in the same level interpreting it together with stable isotope results as an indicator of global cooling (Bicchi et al. 2003; de Leeuw et al. 2010; Gonera & Bukowski 2012; Bukowski et al. 2013). Cooling has possible implications in changes of nutrient budget, as the appearance of agglutinated forms (e.g., *Haplophragmoides sp.)* in samples below the evaporite horizon might be indicative of high nutrient supply. The benthic assemblage has a few undoubtedly deep, open marine bathyal elements like *Siphonina reticulata* or *Cibicides kullenbergi*, previously called *C. mundulus* (Van Morkhoven et al. 1986). The palaeo-water depth must have reached 200–600m, or even deeper. Similar assemblages with similar reconstructed depth range have been found in Hungary (Báldi 2006; Báldi et al. 2002) and in the Mediterranean (Van Hinsbergen et al. 2005; Kouwenhoven & Van der Zwaan 2006). Episodic dysoxy and/or anoxy resulting in high organic matter content and microlaminated sediments can be assumed

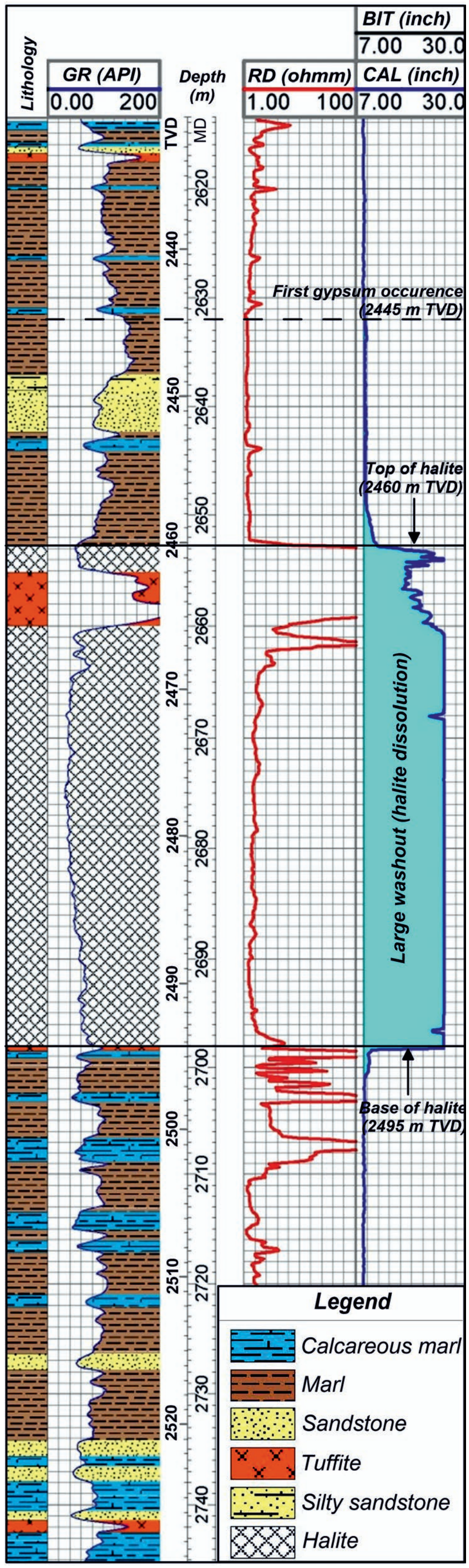

Fig. 5. Lithological and log display of studied well. GR is natural Gamma ray, RD is deep resistivity, BIT is size of drilling bit and CAL is caliper logs. The large scale wash-out (cyan shading on BIT vs. CAL track) clearly highlights the position of dissolved halite. The Golden Software Surfer-9 was used to prepare figure.

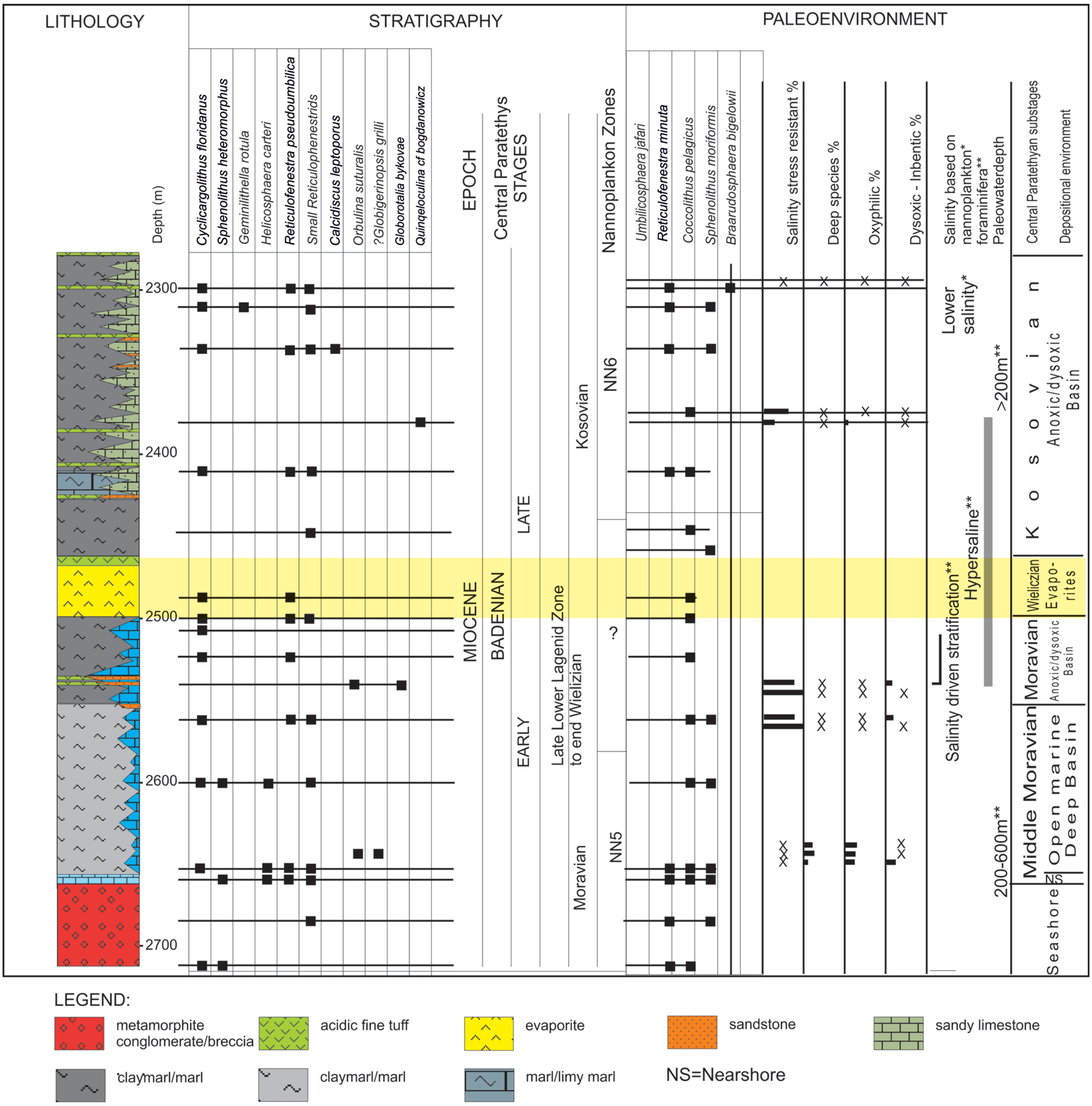

Fig. 6. Lithology, biostratigraphy and palaeo-environmental reconstruction of the Soltvadkert Trough evaporite occurrence. The evaporite horizon is highlighted in yellow. Palaeo-environment reconstructions are based on the percentage of the following **salinity stress tolerant** benthic foraminifera species in the total assemblage: *Ammonia beccarii tepida, Elphidium crispum, Elphidium granosum, Elphidium spp, Triloculina sp, Spiroloculina sp, Quinqeloculina cf bogdanowicz, Miliolid spp, Adelosina schreibersi* (max. 80 %); **deep species**: *Siphonina reticulata* and *Cibicides kullenbergi* (max. 25 %); **oxyphilic:** *Cibicides lobatulus, Heterolepa dutemplei, Lenticulina sp* (max. 25 %); **dysoxic or inbenthic:** *Bulimina elongata, Pullenia bulloides* (max. 25 %).

based on the presence of some dysoxy tolerant taxa (*Bulimina elongata, Pullenia bulloides*).

Hypersalinity stress — the evaporitic event of the BSC (Badenian Salinity Crises)

Below and above the evaporite horizon (foraminifera samples from 2541 m and 2377 m) salinity stress tolerant taxa occur. Based on the observed abnormal growth of *A. beccarii tepida*, salinity stress is more likely to be hypersaline than hyposaline (Stouff et al. 1999). The *Elphidiids* and *Miliolids* are also present in low numbers: these are salinity stress-resistant taxa. As the stressful environment prevents the occurrence of depth-indicating normal marine deep taxa, reconstructing water depth is not possible.

Post-evaporitic environment

Common occurrences of *Braarudosphaera bigelowii* were observed on the top of the investigated boreholes, within NN6. High percentages of this species point to decreasing salinity, usually caused by fresh water inflow.

Above the evaporite horizon there are not many samples available with foraminifera content. However, based on the absence of planktonic forms and the few benthic specimens found, it was likely to be shallower. On the other hand, the presence of *Cassidulina oblonga* might suggest greater water depth (Singh & Gupta 2004), while shallow forms are easily transportable.

Similarities of CFD evaporites and the newly discovered Soltvadkert Trough occurrence

Correlation of Badenian evaporites

Dating the Badenian evaporites from classical sites are in the forefront of Paratethys research, due to developments in determining absolute age, astronomical tuning or magnetostratigraphy (Peryt 2006; Bukowski et al. 2010; de Leeuw et al. 2010; Śliwiński et al. 2012; Hohenegger et al. 2014). Thinking of BSC evaporites as one isochronous evaporitic event seems a plausible explanation for many of the observed phenomena. Hohenegger et al. (2014) suggest that the BSC is restricted to the uppermost NN5 and lowermost NN6. In North Bosnia salt deposits were dated as uppermost NN5 (Ćorić et al. 2007) making them BSC evaporites. Based on calcareous nannoplankton and foraminifera the age of the thick evaporites discussed here is also top of NN5 or lowermost NN6, making this occurrence the first well-documented BSC evaporites discovered in Hungary.

Depositional environments of evaporites

There are many similarities between the classical evaporites of the Carpathian Foredeep and the Hungarian occurrence presented here. At both localities the evaporitic succession starts generally with halite and is succeeded by sulphates extending the basin centre to the margins of the evaporitic basin. In this occurrence halite formation also predates sulphate formation (Fig. 5), where sulphates in the form of anhydrites occur in nearby wells on the basin margin (Peryt 2006; Bukowski et al. 2007).

There is a general agreement that, according to the deep water model, the prerequisite of evaporite formation is an oversaturated and highly-dense brine. Such brines have much higher density than normal saline water, and thus are always found in the deepest part of the basin, with water of lower salinity layered above. In spite of the low number of foraminifera found due to stress and dilution in sediment, it provides crucial evidence on the environmental constraints before and after the evaporite formation in the Soltvadkert Trough (Fig. 6). Based on the foraminiferal assemblage the evaporitic event was preceded by a rather deep normal marine environment thought to be shelf break or upperslope giving a depth estimate of about 400 m or deeper based on Late Miocene Mediterranean analogues (Van Hinsbergen et al. 2005; Kouwenhoven & Van der Zwaan 2006). The pre-evaporitic sediments also contain high numbers of planktonic foraminifera, indicating a pelagic, open marine environment. The dominance of *Globigerina bulloides* in layers below the evaporites in Wieliczka (CFD, Poland) (Gonera 2014) and in the lowermost samples preceding the evaporite deposition in the presented sequence from Hungary is remarkable. The species *G. bulloides* is a typical upwelling species pointing to high surface water productivity in our case (Sousa et al. 2014). The benthic species *Siphonina reticulata* and deep-living Cibicides species like *Cibicides kullenbergi,* a member of the *C. kullenbergi-mundulus* complex with a depth range deeper then 500–600 m (Van Morkhoven et al. 1986; Van Hinsbergen et al. 2005; Kouwenhoven & Van der Zwaan 2006) all indicate upper bathyal depth. Based on the same two species of *S. reticulata* and *C. kullenbergi* and on a high plankton/benthos ratio similar water depths were suggested in Hungary in Báldi et al. (2002) and Báldi (2006). Concerning reconstruction of the dissolved oxygen levels of bottom water during deposition, the dysoxy indicators among the benthic foraminifera species such as *Bulimina elongata* described here and also in the CFD (Peryt 2013) strongly suggest enhanced vertical stratification coupled with high-productivity surface water and increased organic flux to the bottom. This is supported by the seismic section and palaeogeographical reconstruction showing the evaporites in the deepest depression (Figs. 2, 3). Occasional bottom water anoxy is further corroborated by the formation of microlaminites common around the evaporitic horizon in the investigated well. These similarities of classical CFD and Pannonian Basin evaporites possibly point to the existence of continuous connections between these evaporitic basins during deposition in the entire CP.

Explanation of the late recognition of evaporites in the Pannonian Basin

The rather late recognition of BSC evaporites in Hungary is due to many factors:

- all our information on the local Miocene geology of the Great Plain is based on seismic data and mostly just cuttings, as in the present work.
- the evaporitic sequence presented here is covered by thousands of metres of younger sediments like all the Middle Miocene of the Great Plain.
- there is the possibility that 10–15 metres of halite beds would be overlooked on old, low resolution 2D seismic sections, as it is below the resolution of what is now an outdated method.
- most oil exploration wells in the area were drilled into tectonic highs, and not into structures like the Soltvadkert Trough discussed here.
- as halite is perfectly soluble in the water-based drilling fluids generally used, there is a high possibility of a few

metres of evaporites being missed in the old, mainly hydrocarbon exploration wells, in the absence of modern mud and wireline logging control.

- problems arising with biostratigraphic methods are twofold:
  - poor preservation of the highly consolidated samples from great depths makes the identification of biostratigraphic markers difficult, thus delaying the recognition of these evaporites.
  - the high sedimentation rates in the investigated area during the Middle and Late Miocene diluted the stratigraphic marker fossils making the recognition of evaporites difficult. In the absence of good stratigraphic control the evaporitic layers found in Hungary were thought to be younger or older then fully-marine Badenian.

Discussion

A novel approach to understanding evaporites in the geological record of the CP (Fig. 7)

The discovery of this new, massive evaporite occurrence and the growing evidence of more occurrences in proximity (Jámbor et al. 1976; Cserepes-Meszéna et al. 2000, 2004; Palotai & Csontos 2012) and in the CP (Túnyi et al. 2005; Bukowski et al. 2007; Ćorić et al. 2007) has inspired a new way of thinking of evaporites in the geological record. Though the geographical extent (<10 km^2) of the evaporites discussed here is small (Fig. 3 c), we can assume that these occurrences are remnants of a widespread evaporitic layer formed during the short period of the BSC (0.2–0.6 Ma, de Leeuw et al. 2010). Based on our observations the Soltvadkert salt basin was formed in a deep, rapidly sinking basin with high sedimentation rates, where anoxia developed due to the oversaturated heavy hypersaline brine accumulating at the bottom of the basin. This sort of depositional environment is believed not to be unique and restricted only to the Soltvadkert Trough, but possibly in all deep salt basins in the CP reaching a certain water depth evaporites were formed during the BSC.

In the Pannonian Basin and generally in the CP there are different fates awaiting any evaporites formed during the BSC that determine their future presence or absence in the geological record later. These are the two scenarios presented here (Fig. 7).

In scenario A the evaporites are preserved in the geological record, as in the historical evaporite sites of the CFD, and the more recent East Slovakian Basin occurrence, or the here presented Pannonian Basin or the Transylvanian Basin. These are just remnants of a once widespread evaporitic layer formed during the BSC in all deep basins of the entire CP. In this scenario evaporites were preserved in actively subsiding basins overlain by younger sediments that protected the evaporites from being recycled. Some scenario A evaporite occurrences, though present in the geological record, appear to have been overlooked, as discussed above.

In scenario B evaporites are absent from the geological record, because salt deposited during the BSC is presumed to be reworked and dissolved in most of the CP area later during the Badenian and Sarmatian. It is easy to imagine the reworking of evaporites so that they do not leave much evidence behind in the geological record, as halite dissolves in water, while sulphates are soft and grind to nothing in a shallow water high energy environment. Recycling of evaporites is probably a more important process then thought before as it has been recorded from the East Slovakian Basin (Bukowski et al. 2007), and from the Carpathian Foredeep (Kolasa & Slaczka 1985; Cendón et al. 2004; Głuszyński & Aleksandrowski 2016) repeatedly. However, recognizing any original sedimentary structures of resedimentation might be difficult as evaporites are often tectonized also in Hungary (Palotai & Csontos 2012) or in the Transylvanian Basin where salt diapirism is typical of the region (Krézsek & Filipescu 2005; Krézsek & Bally 2006).

The traditionally accepted view of Sarmatian salinity emphasizes its transitional in-between nature as brackish,

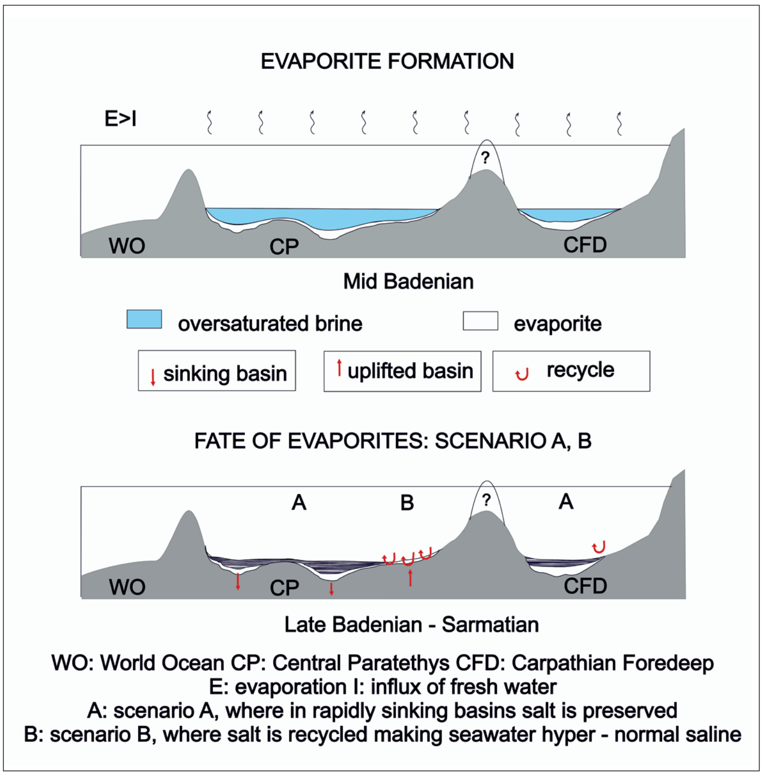

Fig. 7. The fate of the BSC evaporites inside the Carpathian Arcs. According to **scenario A** evaporites were preserved in deep basins with high sedimentation rates, while in **scenario B** evaporites were recycled making the Late Badenian or Sarmatian Sea hyper- or normal saline.

following the fully-marine Badenian and preceding the very low-salinity Pannonian. This has been challenged by some authors, who call Sarmatian brackishness a mere "myth" (Piller & Harzhauser 2005). Their doubt was based on isotope evidence and the presence of hypersaline species along with the commonly observed phenomena of heavy calcification that cannot happen in a brackish environment, all of which point to a normal marine or even hypersaline environment in the Sarmatian. The carbonate-factory nature of the Sarmatian was established based on oolites and heavily calcified molluscs (Harzhauser & Kowalke 2002; Piller & Harzhauser 2005). Other authors confirmed this idea by reconstructing hyper- or normal saline conditions in the Sarmatian based on palaeoecologic evidence of fossil assemblages (Cornée et al. 2009; Tóth et al. 2010; Bitner et al. 2014; Harzhauser et al. 2014).

Our suggested scenario B sheds new light on this "myth" of the brackish Sarmatian Sea by explaining the origin of salt in a hyper- or normal saline Sarmatian (Harzhauser & Kowalke 2002; Piller & Harzhauser 2005; Cornée et al. 2009; Tóth et al. 2010; Bitner et al. 2014; Harzhauser et al. 2014) as being recycled BSC halite dissolved into the sea water. This scenario makes feasible the idea of a Sarmatian Sea of variable salinity in both space and time from brackish to hypersaline. Widespread Sarmatian oolites are well known in Hungary (e.g., Tinnye Formation), and particularly NW from the Soltvadkert location in the Zsámbék Basin, where a hypersaline lagoon was described as part of the brackish Sarmatian Sea in a highly-unlikely oceanographic setting. Hypersalinity was explained by renewed connections to the Mediterranean (Cornée et al. 2009; Tóth et al. 2010). Ever since, more and more evidence has accumulated for normal salinity or hypersalinity of the Sarmatian (Bitner et al. 2014; Harzhauser et al. 2014) but without a plausible climate-related driving force of evaporation such as aridity or lowered fresh water influx. Notwithstanding the role of changing seaways in the Paratethys, and a conceivable Kosovian Mediterranean connection (Bartol et al. 2014) after the BSC but still in the Badenian, it is suggested that these oolites and hypersaline shallow-water Sarmatian facies in the entire CP developed locally due to recycling of BSC evaporites.

There is a recent analogue for the recycling of the BSC evaporites and for deep-basin evaporite formation during the BSC — the deep, hypersaline evaporitic basins in the Eastern Mediterranean (the Bannock and Tyro basins) where Messinian (Late Miocene) salt layers are currently dissolving into the present-day sea (Camerlenghi 1990; De Lange et al. 1990). The analogy is far from perfect as recycling in the Sarmatian probably happened more generally in shallow environments as the widespread oolite shoals indicate. On the other hand these deep Mediterranean basins with strong density stratification, where bottom-water brines can become supersaturated and evaporites can precipitate are good analogues for the BSC evaporite occurrence presented here. In these Mediterranean basins microlaminites are formed under anoxic conditions, similar to the studied BSC sequence from the Soltvadkert Trough.

Furthermore, there is evidence supporting resedimentation of BSC evaporites from the field of micropalaeontology. Sarmatian sediments regularly contain high percentages of reworked calcareous nannofossils from the Badenian (with *Helicosphaera waltrans* and *Sphenolithus heteromorphus*) indicating strong erosion and redeposition of the lower and middle Badenian sediments. Changes in the percentages of the reworked calcareous nannoplankton were successfully used for the reconstruction of the palaeoenvironment during the Karpathian and Badenian in the Central Paratethys (Ćorić & Rögl 2004). In many cases this reworking hinders the use of nannoplankton for the stratigraphical subdivision of the Sarmatian, but can serve as additional evidence for dissolution of Badenian evaporites.

The BSC evaporite formation took place not only in deep water settings, like the Soltvadkert Trough presented here, but there is a considerable amount of literature claiming that BSC depositional environments were shallow (Ghergari et al. 1991; Bąbel 2004, 2012; Bąbel & Becker 2006). Perhaps, some shallow water evaporites can avoid resedimentation depending on the particular geohistory of the salt basin. Models also exist of combining deep and shallow water formation of evaporites for the same basin, like in the Transylvanian Basin (Krézsek et al. 2010). Solving this puzzle is out of scope for the work presented here.

The reworking evaporite scenario B might have implications concerning the global cooling that takes place in the Middle Miocene. This climate transition (14.2 to 13.9 Ma) with its stepwise cooling and enhanced glaciation is not fully understood in many aspects (Holbourn et al. 2005, 2013; DeConto et al. 2008; Knorr & Lohmann 2014). According to scenario B, the BSC evaporite formation was not limited to the well known classical localities, but was much more widespread, perhaps in the entire deep water CP to be recycled later in the Badenian or Sarmatian. Taking into account possible coeval evaporites from the Middle East (Al-Husseini et al. 2010; Abu Seif 2014), the amount of locked-up salts during the BSC might have been underestimated. The correlation of the global cooling event Mi3b corresponding to the base of the Serravalian (Hilgen et al. 2012) with the BSC is rather well established (Karami et al. 2011; Gebhardt & Roetzel 2012; Peryt 2013; Hohenegger et al. 2014 among others) although according to many authors there was a cooling period preceding the evaporite deposition (Bicchi et al. 2003; Bukowski et al. 2010; de Leeuw et al. 2010; Peryt & Gedl 2010; Gonera 2013). This cooling, following an extreme climate optimum, did not change the hydrological budget keeping evaporation exceeding precipitation leading to anti-estuarine circulation (Báldi 2006; de Leeuw et al. 2010), thus making possible the formation of evaporites. The exact nature of the trigger to start BSC formation is not fully reconstructed, neither is the amount of evaporite formed during the BSC known. Thus, mass balance calculations concerning the extraction of NaCl from the World Ocean during BSC could be sensitive to the amount of evaporite precipitated and locked up in the Paratethys by reducing global salinity. A negative shift in salinity, even if it is just a slight change, might increase ice formation and global cooling by its positive albedo feedback. Hence, it seems worthwile to reconsider the role of the Paratethys during the BSC as a factor influencing global climate, as the amount of locked up evaporites may have been underestimated. The occasional modelling study taking into account the Paratethys (Karami et al. 2011), has a different focus, but perhaps future research can be justified to take into account the larger quantity of evaporites based on the presented work.

Conclusion

The newly-discovered massive evaporites from the Soltvadkert Trough in Hungary, 50 metres thick, are described and documented in the present work. They can be correlated with the classical evaporite occurrences of Wielician age formed during the salinity crises in the Badenian of the CFD based on calcareous nannoplankton and foraminifera biostratigraphy. The evaporites belong to the top of NN5 lowermost NN6, and the species *O. suturalis* has LO 15.1 Ma below the evaporitic horizon (Cicha et al. 1998; Hohenegger et al. 2014). Based on this evidence the studied evaporitic layers can be correlated to the classical CFD or Transylvanian deposits making its age undeniably Wielician.

Palaeoenvironmental reconstructions of the Soltvadkert Trough prior to evaporite formation, based on foraminifera, suggest deep water setting with highly stratified water column, oversaturated brine at the bottom, while surface water turned eutrophic. This high organic matter flux to the sea floor led to dysoxy at the bottom progressing into total anoxy during evaporite formation, and resulting in the formation of microlaminites in clay. This salt basin can be characterized by high sedimentation rates, also a prerequisite of preserving these evaporites.

The Soltvadkert Trough evaporites appearantly just one of many occurrences recently found in the CP, for example, NE from our locality in the East Slovakian Basin (Túnyi et al. 2005; Bukowski et al. 2007) or to the south, the Tuzla Basin (Ćorić et al. 2007), are all parts of the Pannonian Basin System. Also from Hungary there are some additional boreholes transecting evaporites NW of the study area in the Zsámbék Basin and nearby according to the data repository (Jámbor et al. 1976; Cserepes-Meszéna et al. 2000, 2004) and publications (Cornée et al. 2009; Tóth et al. 2010; Palotai & Csontos 2012).

Inspired by these new evaporite occurrences, different scenarios were developed to explain the presence or absence of evaporites in the geological record. It is presumed that during the salinity crises evaporites were forming in a much larger area than thought before, in the entire Central Paratethys. Concerning the further fate of the evaporite layer, two scenarios were developed:

- Scenario A: the presence of evaporites in the geological record is due to deposition in deep, rapidly sinking basins with high sedimentation rates, where the resedimentation-prone evaporites could remain under the protecting layer of covering sediments as in the Soltvadkert Trough (Figs. 2, 3). These are the salt basins where evaporites were preserved as the remnants of a widespread evaporitic layer formed during the salinity crisis.
- Scenario B: the evaporites deposited during the BSC were exposed later in the Badenian or Sarmatian to be recycled into the Sarmatian Sea, similarily to present day analogues (Camerlenghi 1990; De Lange et al. 1990). Salts and sulphates are both known to be easily recycled as observed at several places in the Paratethys (Kolasa & Slaczka 1985; Cendón et al. 2004; Bukowski et al. 2007; Głuszyński & Aleksandrowski 2016).

The new approach explaining the presence or absence of evaporites in the geological record inside the Carpathians sheds light on two scientific problems:

- Scenario B gives a hypothetical explanation for the recorded occurrence of Sarmatian hyper- or normal salinity by providing the source of salts from recycling the BSC evaporite. There has never been convincing evidence shown for excess evaporation due to aridity or reduced freshwater influx locally to support Sarmatian non-brackish salinity, while the confirming palaeontological and geological evidence is abundant (Harzhauser & Kowalke 2002; Piller & Harzhauser 2005; Cornée et al. 2009; Tóth et al. 2010; Bitner et al. 2014). Introducing the idea of reworking BSC salts, a Sarmatian Sea of variable salinity in both space and time from brackish to hypersaline becomes more conceivable. This way scenario B raises further doubts about the unified brackish nature of the Sarmatian (Piller & Harzhauser 2005; Tóth et al. 2010; Bitner et al. 2014).
- The scenarios presented here imply a much larger amount of evaporites being locked up in the Paratethys during the half-million years of the BSC, than was previously supposed. This draws attention to the relationship of the base Serravalian Mi3b global cooling event to the evaporite formation in the Badenian Paratethys. If we suppose, that basins were isolated by eustatic sealevel drop and ignore for the moment the possible tectonic causes, then the causality in the correlation of the two events might be reconsidered. According to the here presented scenarios BSC evaporites formed in a much larger area and quantity then previously supposed, and perhaps could have been of a magnitude to shift global salinity and enhance ice formation in the polar regions reversing the causality. Hopefully future research on modelling the mass balance of salts in the World Ocean will help us to understand better the relationship between the BSC event and the Miocene climate transition.

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