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The beginning, development and termination of the Middle Miocene Badenian salinity crisis in Central Paratethys

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Abstract

Middle Miocene Badenian evaporites of the Carpathian region are underlain and overlain by deep-water deposits, the onset of evaporite deposition was sudden but not synchronous in all facies zones and the deposition of evaporites was controlled by the evolution of Carpathian orogen. In the Carpathian Foredeep (and most probably in other basins) the Badenian evaporites represent the lower part of the NN6 zone. Halite and associated deposits in the central part of the Badenian evaporite basin show the same facies successions and marker beds can be traced across and between individual basins. Characteristic marker beds made it possible to correlate various facies zones of the marginal Ca-sulfate platform. These marker beds seem to reflect events that may be related to sudden and widespread changes in water chemistry, which in turn imply major changes in basin hydrology. The onset of the evaporitic deposition in the Carpathian Foredeep was clearly diachronous and the evaporites deposited in the basin centre preceded the beginning of evaporite sedimentation in the marginal basin, however, depositional history in the marginal basin and the basin centre was the same. A general transgressive sequence of evaporites found in the Carpathian Foredeep resulted from the migration of facies zones induced by the nappe movement.

Isotopic studies of Badenian foraminifers occurring below evaporites suggest that the interrupted communication of the Paratethys with the ocean was a consequence of eustatic sea-level fall, possibly related to climatic cooling, and it was coupled with a tectonic closure of connection with the Tethys. Thus both tectonics and eustacy have contributed to the origin of salinity crisis. Sedimentological and geochemical data indicate recycling of evaporites throughout most of the evaporite deposition. The recycling at the end of gypsum deposition in the marginal sulfate platform was accompanied by a change in the hydrology of the Central Paratethys that was tectonically-driven, and possibly related to the block tectonic phase manifested in the marginal part of the Carpathian Foredeep Basin. The change in hydrology implied the dilution of brines by inflowing marine water and this terminated the Middle Miocene Badenian salinity crisis. The onset of the Badenian salinity crisis shows great similarities to the onset of the Messinian salinity crisis and the terminations of both crises were different.

Keywords: Middle Miocene; Paratethys; Evaporites; Salinity crisis; Sedimentology; Ukraine; Poland

1. Introduction

The Messinian salinity crisis in the Mediterranean was preceded by the Middle Miocene salinity crisis in the Paratethys that resulted in deposition of evaporites in the Red Sea, Middle East and the Carpathian region (Fig. 1). The restriction that led to the origin of evaporites in the latter area was (1) tectonically driven due to the uplifts in the Carpathians that sealed off the foredeep, East Slovak Basin, Transcarpathian Basin, and Transylvanian Basin (Fig. 2), and only the area of the Pannonian Basin

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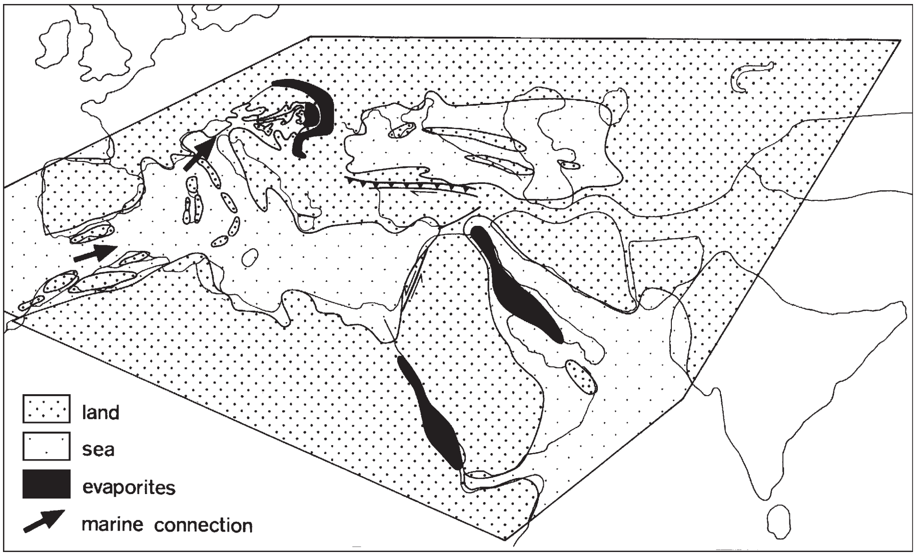

Fig. 1. Map of the Middle Miocene Badenian salinity crisis in the Paratethys (after Rögl, 1999).

retained a marine connection with the Mediterranean through a corridor in Slovenia (Rögl, 1999) (Fig. 1), and (2) eustatically-driven.

There are two regional stages of the Middle Miocene in the Paratethys area: Badenian (16.4–13.0 Ma; equivalent to the Langhian and a lower part of the Serravallian) and Sarmatian. Traditionally, it is accepted that the Badenian evaporites are related to Wielician, i.e. Middle Badenian (15.0–14.0 Ma). However, these evaporites occur in the lower part of the NN6 zone in the Carpathian Foredeep (Peryt, 1997, 1999; Mărunțeanu, 1999; Andreyeva-Grigorovich et al., 2003), the Transylvanian Basin (Chira, 2000) and possibly in East Slovak and Transcarpathian Basins; thus they are Late Badenian in age. This is supported by a recent dating of the tuff horizon (WT-3) occurring below the crystal salt in the Bochnia mine (southern Poland) that gave the age of 13.6 ± 0.2 Ma (Dudek et al., 2004).

The Badenian evaporites of Central Paratethys have been subject to studies for almost two centuries (for the research history, see Kwiatkowski, 1972; Korenevskiy et al., 1977; Garlicki, 1979; Stoica and Gherasie, 1981; Babel, 2004; with references therein). Those studies have yielded vast information on facies, sedimentology and geochemistry of the Badenian evaporite formations. During the last decade the research was focused on the Carpathian Foredeep Basin system (e.g. Cehlarov and Țibuleac, 1996; Peryt, 1996; Bukowski, 1997; Galamay et al., 1997; Garcia Veigas et al., 1997; Peryt et al., 1997; Petrichenko et al., 1997; Ślączka and Kolasa, 1997; Kasprzyk and Orti, 1998; Peryt et al., 1998a; Rosell et al., 1998; Babel, 1999; Kasprzyk, 1999; Turchinov, 1999a,b; Cehlarov, 1999; Peryt, 2000; Poberezhskyy, 2000; Toboła, 2000; Peryt, 2001; Babel, 2002; Peryt et al., 2002; Frunzescu, 2002a,b; Kasprzyk, 2003; Peryt et al., 2004a) and thus this basin that is the greatest Badenian evaporite basin (Fig. 2), has become the best studied, and known, evaporite basin of the Central Paratethys.

Despite a long history of research, many crucial problems focused on the onset and termination of evaporite deposition in the Badenian evaporite basins, including the history of evaporite deposition, the nature of evaporite-precipitating brines, the climate changes vs. evaporite deposition or the depth of brine body, remained controversial. The aim of this paper is to address these controversial problems using the information from the entire Carpathian Foredeep Basin system with a special emphasis on one particular area considered to be crucial for most of the above-listed questions. This area is located in the south-eastern part of the Ukrainian Carpathian Foredeep Basin (Fig. 2) lying half-way from the presumed entrance of seawater and half-way from its dead end (or perhaps another connection with the Tethys). The Badenian evaporite basin was particularly wide here since the basin includes both the foredeep element and the much wider foreland component (Figs. 3 and 4). Consequently, the facies changes are gradual and the facies zones are wide, making it possible to isolate the local factors influencing the evaporite deposition from regional ones.

2. Geological setting

The Carpathian Foredeep basin stretches for more than 1300 km from the environs of Vienna to the NW

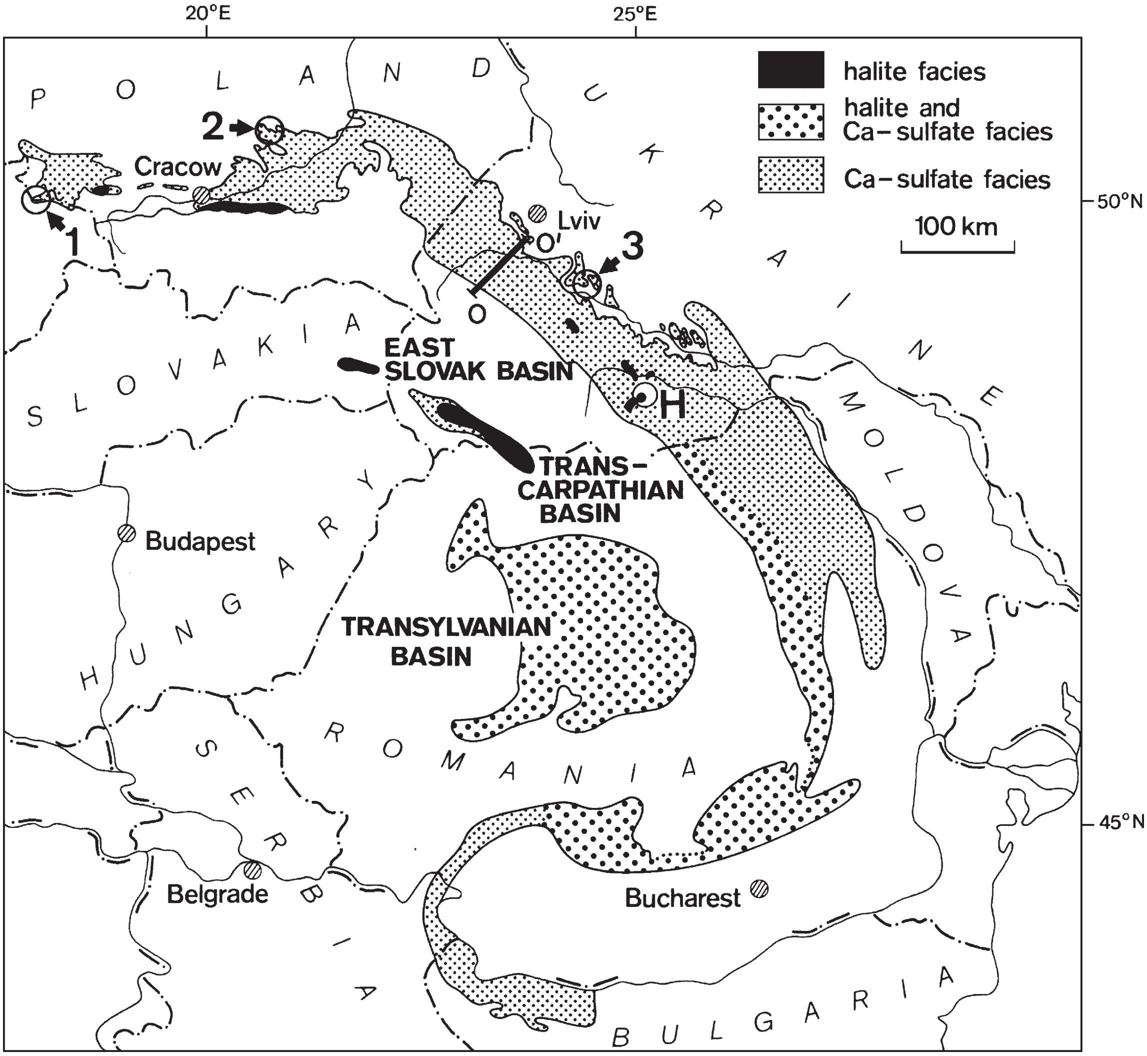

Fig. 2. Middle Miocene Badenian evaporite facies of the Carpathian region (based on Trashliev, 1969; Korenevskiy et al., 1977; Garlicki, 1979; Mărunţeanu, 1999; Peryt et al., 2004a). Numbers 1–3 refer to sections shown in Fig. 7; H shows the location of Hucuł 1 borehole described by Wyszyński (1939)); O–O′ shows the location of Fig. 4.

part of Bulgaria (Fig. 3). The Badenian evaporites are usually underlain by marine siliciclastics and carbonates (several tens to several hundreds of metres thick) although in the Carpathian foreland area (as well as in some parts of the Foredeep) gypsum deposits overlie the Mesozoic or Paleozoic rocks. The evaporites are overlain by thick marine to brackish siliciclastic deposits (Ney et al., 1974; Porębski et al., 2003) (Fig. 4) that attain up to 5 km in thickness (Kurovets et al., 2004).

In the Polish part of the Carpathian Foredeep Basin and its foreland, evaporite deposits overlie the deep-water Skawina Formation (Fig. 5). This locally contains a thin coquina bed (Ervilia Bed) in its uppermost part (e.g. Pawłowski et al., 1985). The evaporites are included into two formations: namely the Krzyżanowice Formation and the Wieliczka Formation (Alexandrowicz et al., 1982). The Krzyżanowice Formation comprises Ca-sulfate deposits with the associated siliciclastic deposits (mainly claystones) and barren and sulfur-bearing limestones that are lateral equivalents of Ca-sulfate deposits. The origin of gypsum-ghost limestones and sulfur is commonly attributed to metasomatic alteration of Ca-sulfates (see Kubica, 1997, for review) although Gąsiewicz (2000) stresses the differences between gypsum-ghosts limestones and selenitic gypsum facies on the basis of their sedimentological features and major element compositions, supposing that the both lithological units developed in coeval depositional domains.

The thickness of the Krzyżanowice Formation that occurs in the major part of the Carpathian Foredeep

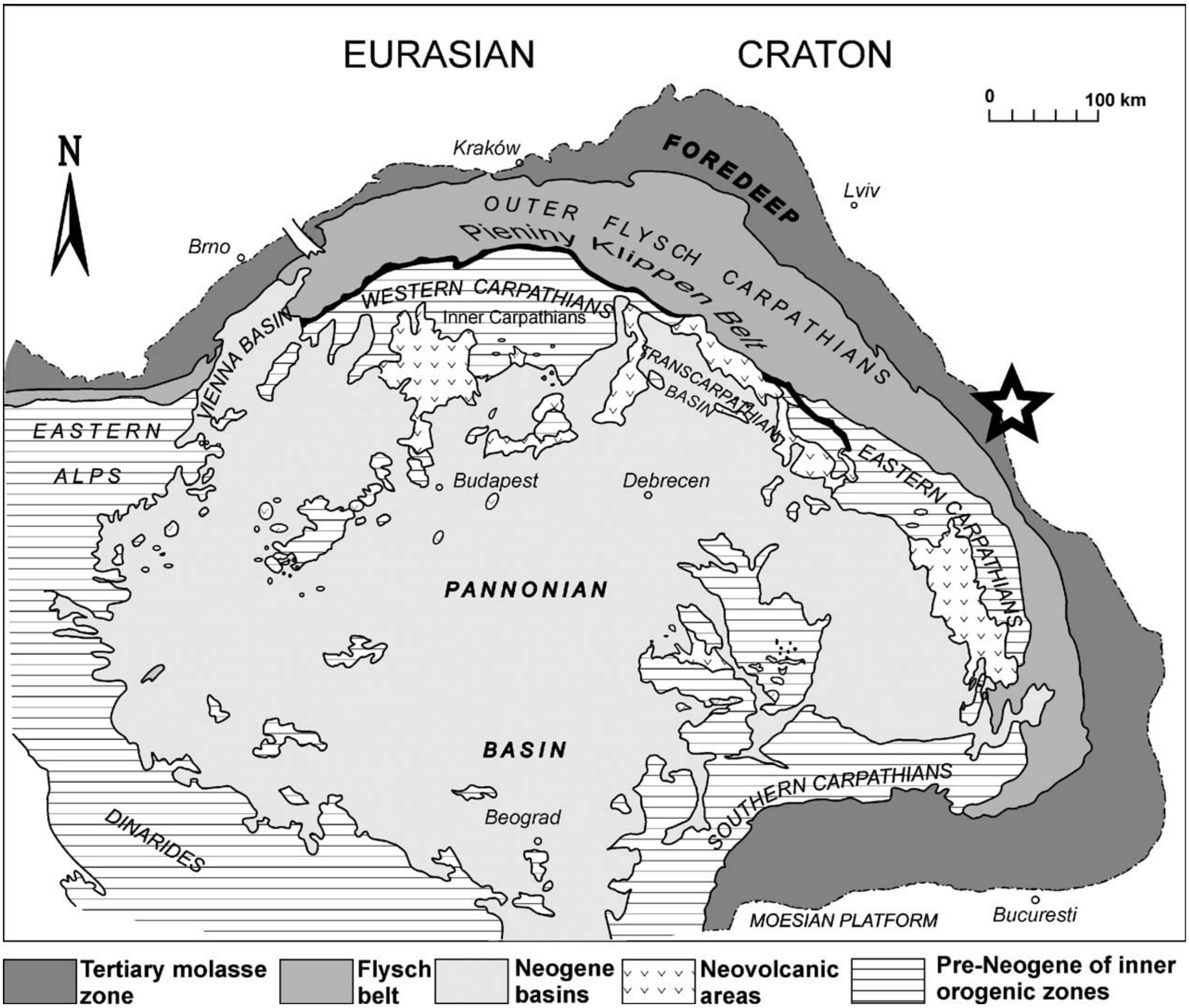

Fig. 3. Geological map of the Carpathian–Pannonian basin system (after Kovač et al., 1998) showing the location of Fig. 6 (asterisk).

(Fig. 2) is several tens of meters (up to 60 m) in the marginal part of the basin and 10–20 m in the central part. The Wieliczka Formation (Garlicki, 1994a) consists of rock salt with intercalations of claystones and minor Ca-sulfates of the total thickness 30–100 m. It occurs in Upper Silesia, then in the form of a narrow band extending along the Carpathian Overthrust from Cracow to Brzesko (Garlicki, 1979, 1994b), and further to the east where it occurs under the overthrusted Carpathian nappes (Połtowicz, 1993). The evaporites are overlain by the Machów Formation: Pecten Clay and Marl Member in the northern part of the Carpathian Foredeep, Spirialis Clay Member in its central and southern part, and Chodenice Member near Cracow (Fig. 5). Deposits of the Machów Formation (and its members), as well as the locally occurring (near Cracow) coeval Grabowiec Formation, originated in deep-marine environments as indicated by deep-water fauna and sedimentary characteristics of delta shelf to basin plain depositional systems (Dziadzio, 2000; Porębski et al., 2003). In the central part of the Polish Carpathian Foredeep Basin a regional angular unconformity developed between Badenian evaporites and overlying siliciclastics, and in the eastern part a gentle onlapping of evaporites by siliciclastics is recorded (Krzywiec, 2001).

In the Ukrainian Carpathian Foredeep Basin and its much wider foreland (Fig. 4), the evaporites and related deposits are included into the Tyras Suite (Formation) and the Kalush beds, although many authors consider that the Kalush beds belong to the Ottnangian Stebnyk Formation (see Wójtowicz et al., 2003, for discussion). Andreyeva-Grigorovich et al. (2003) concluded that the

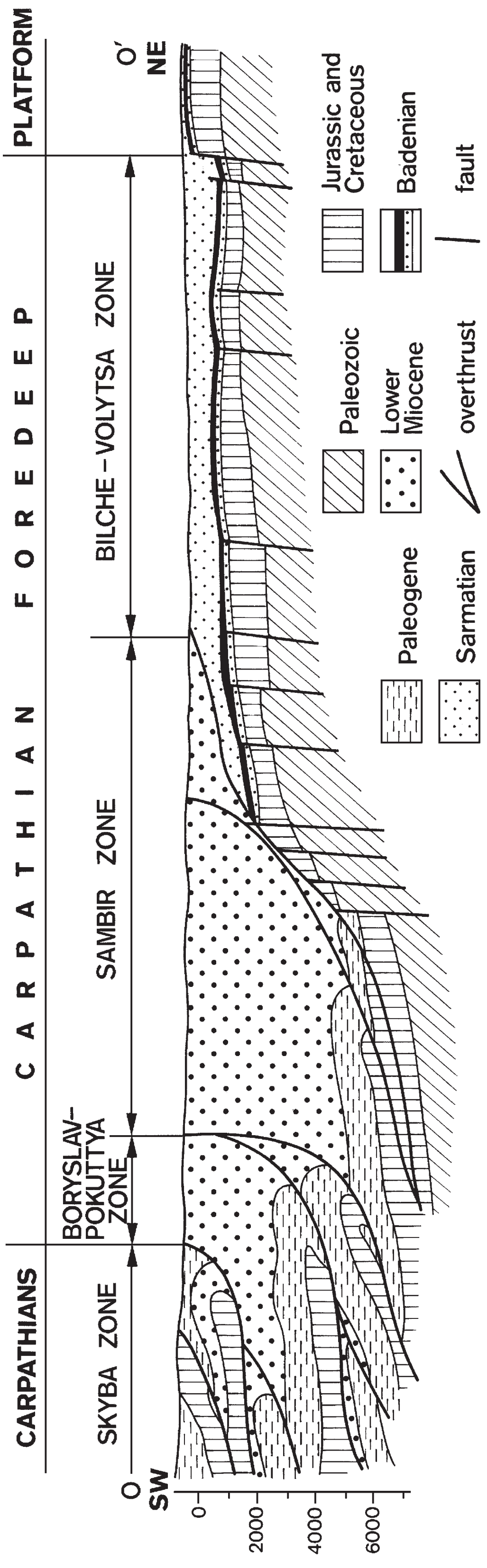

Fig. 4. Cross-section through the Ukrainian Carpathian Foredeep (after Dolenko et al., 1969). Line of profile (ca. 60 km long) in Fig. 2. Black band within the Badenian deposits indicates evaporites.

potash evaporites in Kalush (30 km NW of Ivano-Frankivsk — cf. Fig. 6) belong to the NN6 zone, but such an age assignment is in contrast to the K/Ar age of the langbeinite in Kalush (13.5–15.9 Ma — Wójtowicz et al., 2003) that suggests that potash evaporites in Kalush are older than the Tyras Formation and younger than the Vorotyshcha Formation (that is Ottnangian in age), although it should be recognized that in the Romanian part of the Carpathian Foredeep some potash evaporite deposits are considered to be Badenian in age (Stoica and Gherasie, 1981).

The Tyras Formation overlies the deep-water Bohorodchany Formation (occurring in the central, Sambir Zone of the Carpathian Foredeep), Zhuriv Formation (in the outer, Bilche-Volytsa Zone) and, in the craton area, sandy Rostochya bed (some cm thick) that overlies the thin (up to 10 cm thick) Kryvchytsi (Ervilia) Bed (Andreyeva-Grigorovich et al., 1997) (Fig. 5). The latter bed also overlies the littoral Naraiv Beds (Andreyeva-Grigorovich et al., 1997).

The Tyras Suite consists of Ca-sulfates with claystone intercalations in the basinal facies, and in local depressions Ca-sulfates occur with rock salt and claystone intercalations of considerably greater thickness (up to 275 m — Panow and Płotnikow, 1996: Table 1). In the Carpathian foreland, the suite consists of gypsum and, in places, sulfur-bearing limestones (Kudrin, 1955; Aleksenko, 1967). The Kalush beds of the Sambir Zone of the Carpathian Foredeep consist of interbedded salt claystones, potash salts, gypsum and anhydrite as well as sandstones. These beds have been subject to intensive folding making their present thickness range from 200 to 400 m (Petryczenko et al., 1994), although the depositional thickness was much less (cf. Koriń, 1994). The Tyras Formation is overlain by the deep-marine Kosiv Formation in the Carpathian Foredeep and the adjacent part of the foreland and by various marine facies in more marginal parts of the basin (Andreyeva-Grigorovich et al., 1997) (Fig. 5).

In the Romanian part of the Carpathian Foredeep, in the Tarcău Nappe, the Evaporitic Formation (salt with thin claystone–siltstone intercalations, salt breccias, and gypsum) is underlain by Slănic Tuff (composed of tuffs and tuffites interbedded with Globigerina marls) and overlain by Radiolarian Shales and Spirialis Marls, and in the Marginal Folds Nappe and Subcarpathian Nappe the Salt Formation (usually developed as collapse breccias — Cehlarov, 1999, and termed Cosmina Breccia — see Crihan, 1999) is underlain by Goru Mişina Formation and overlain by Condor Sandstone Formation (Mărunţeanu, 1999) (Fig. 5). Crihan (1999) recognized the presence of gypsum and microbial

	Sarmatian	POLAND	UKRAINE	ROMANIA
Serravalian	Badenian	Grabowiec Fm←→Machów Fm (Chodenice M.←→Spirialis Clay M. ←→Pecten Clay and Marl M.)	Kosiv Fm←→marginal marine facies	Radiolarian Shales & Spirialis Marls←→ Condor Sandstone Fm
		Krzyżanowice Fm←→Wieliczka Fm	Tyras Fm	Evaporite Fm←→Salt Fm (Cosmina Breccia)
		Ervilia Bed	Kryvchytsi (Ervilia) Bed←→Rostochya Bed	
Langhian		Skawina Fm	Bohorodchany Fm←→Zhuriv Fm←→ Naraiv, Mykolaiv, and Baraniv Beds	Slanic Tuff←→Goru Mişina Fm
Burdigalian	Karpatian			

Fig. 5. Stratigraphic scheme of Middle Miocene Badenian deposits in the Carpathian Foredeep of Poland, Ukraine and Romania.

stromatolites in the basal part of the Cosmina Breccia (see also Frunzescu, 2002a) although salt is also associated with breccia deposits, and thin pelagic intercalations contain rich in situ foraminiferal and calcareous nannoplankton assemblages (NN6 zone). The Slănic Prahova evaporitic sequence is ca. 120 m thick and is mostly halite with thin marl and anhydrite intercalations at the base and marl and clay intercalations at the top (Georgescu et al., 1994). In NW Bulgaria, Badenian Ca-sulfate evaporites (up to 40 m thick) occur (Trashliev, 1969; Fig. 1); they are mostly stromatolitic and laminated. These Ca-sulfates are underlain by Lower Badenian marls and overlain by Upper Badenian clays containing a chemical limestone (0.3–4.0 m thick) at the base. All these deposits are included into the Deleina Formation (Kojumdgieva and Popov, 1988). It is very probable that the same development characterizes the adjacent part of the Romanian Carpathian Foredeep. However, in most cases the data from literature do not allow for delimiting halite and Ca-sulfate areas in the Romanian Carpathian Foredeep or in the Transylvanian Basin, and therefore these zones are combined in Fig. 2. Consequently, the facies pattern of the Carpathian Foredeep basin discussed below refers to the Polish and Ukrainian parts of the basin.

3. Facies patterns in Badenian Carpathian Foredeep evaporite basin

Badenian evaporites in the Polish and Ukrainian parts of Carpathian Foredeep show a regular spacial facies pattern. Primary gypsum (several tens of meters thick) forming a wide (up to 100 km in Ukraine) marginal Ca-sulfate platform occurs in the most marginal, northern and northeastern parts of the Carpathian Foredeep (facies zones I–III; Fig. 6). It passes basinward into the Ca-sulfate basin (facies zone IV) where anhydrite deposits are 10–20 m thick. In the southern part of sedimentary basin in Poland, in the narrow axial part of the basin, halite deposits (rarely exceeding 100 m in thickness) occur in local salt basins (Fig. 2). Close to the halite facies field, halite and anhydrite intercalations of variable thickness and number are also present (Połtowicz, 1993).

The entire marginal Ca-sulfate platform of the Czech Republic and Poland and a part of this platform in the Ukraine are composed of giant gypsum intergrowths in the lower part, overlain successively by stromatolitic gypsum, sabre gypsum and clastic gypsum units (Fig. 7) that can be traced over the distance of 700 km; this is facies zone III. Kasprzyk (1993) recognized 18 units (units a–r) in the complete gypsum section south of the Holy Cross Mts (Poland), and many of them can be traced throughout the northern Carpathian Foredeep in Poland, the Czech Republic and the West Ukraine, although there are differences in the succession, thickness and component lithofacies of these gypsum units (Fig. 7; see Peryt, 1996; Peryt et al., 1998b; Babel, 1999; Kasprzyk, 1999). Also in the Ukraine other types of development of gypsum sections occur, and are discussed in the next chapter. In the deeper subsurface, gypsum is partly or completely replaced by anhydrite and associated secondary gypsum but it is possible to relate particular anhydrite lithofacies to their parent gypsum lithofacies (Kubica, 1992).

In general, the Ca-sulfate sections in the marginal Ca-sulfate platform can be divided into two parts: lower autochthonous (mostly crystalline and stromatolitic gypsum) and upper allochthonous (clastic), although in many cases, especially in West Ukraine, the upper part is absent, having been preserved (or deposited) only locally, in tectonically-controlled troughs (Peryt, 2001). Kasprzyk and Orti (1998) correlate this upper gypsum member of the marginal Ca-sulfate platform with the entire Ca-sulfate section in the sulfate basin area that consists mainly of interbedded laminated anhydrite and anhydrite breccia, often displaying features characteristic of redeposited sediments including distortions due to slumping, erosional boundaries, and graded–bedded laminae (Peryt, 2000). However, physical stratigraphic

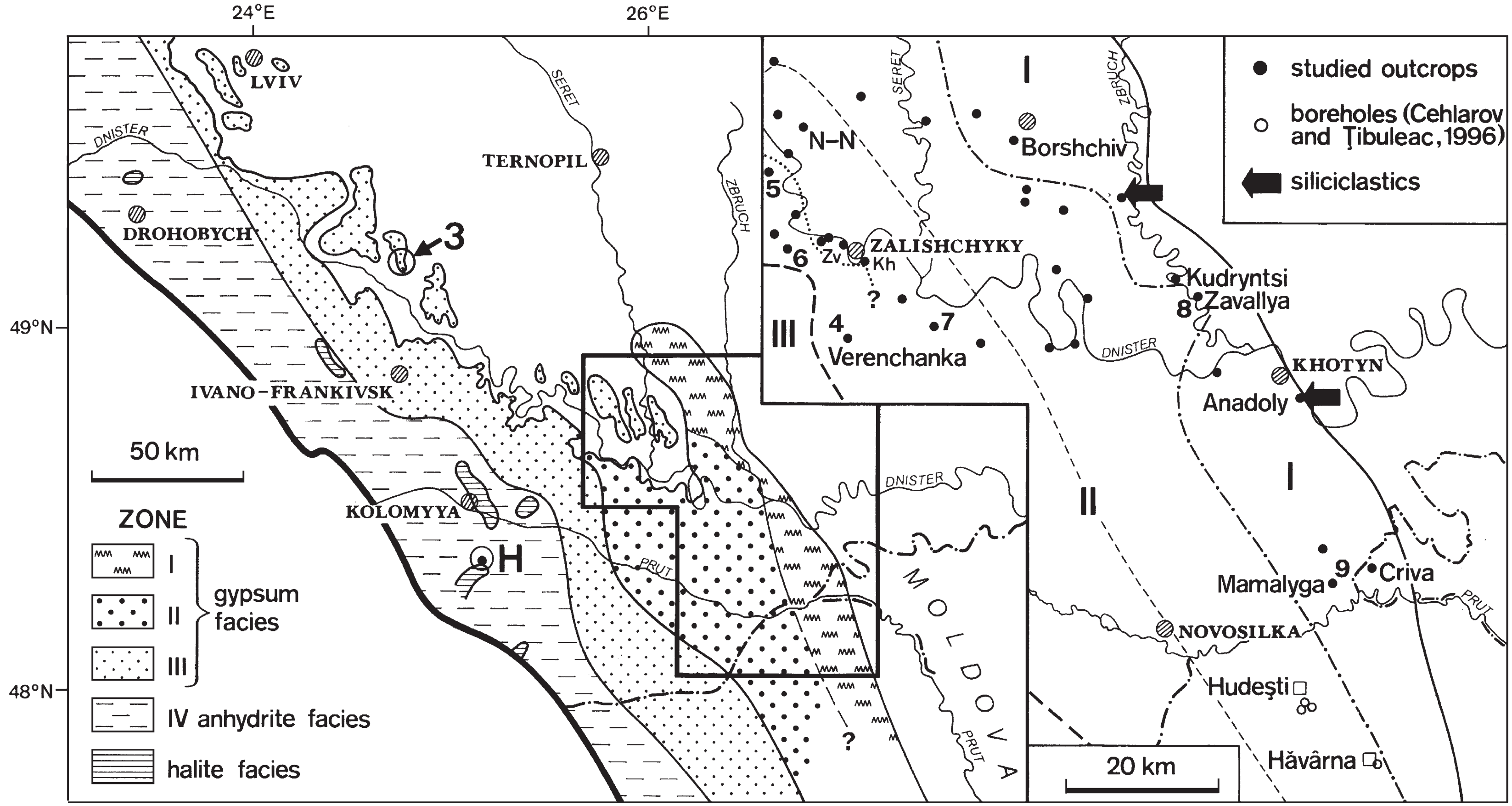

Fig. 6. Badenian evaporite facies in West Ukraine. The quadrangle on left map shows the location of the map shown to the right side. Numbers 4–9 on the right map refer to sections shown in Fig. 7; H shows the location of Hucuł 1 borehole; Kh — Khreshchatyk; N–N — Nyrkiv-Nagoryany; Zv — Zvenyachyn; I–III indicate corresponding gypsum facies zones; solid line is the present limit of gypsum facies (that probably does not differ significantly from the primary one as indicated by interfingering siliciclastic and gypsum facies — arrows); the boundary line between the gypsum zones I and II corresponds to the northeasternmost occurrence of sabre gypsum; the broken line within the gypsum facies zone II indicates the NE limit of the occurrence of marker bed 1; the dotted line within facies zone II shows the NE limit of occurrence of intercalation of crystalline gypsum within the basal stromatolitic gypsum unit; and the boundary line between the gypsum facies zones II and III corresponds to the NE limit of occurrence of giant gypsum intergrowths unit at the base of gypsum section. The interpretation of facies in Romania is based on Cehlarov and Ţibuleac (1996).

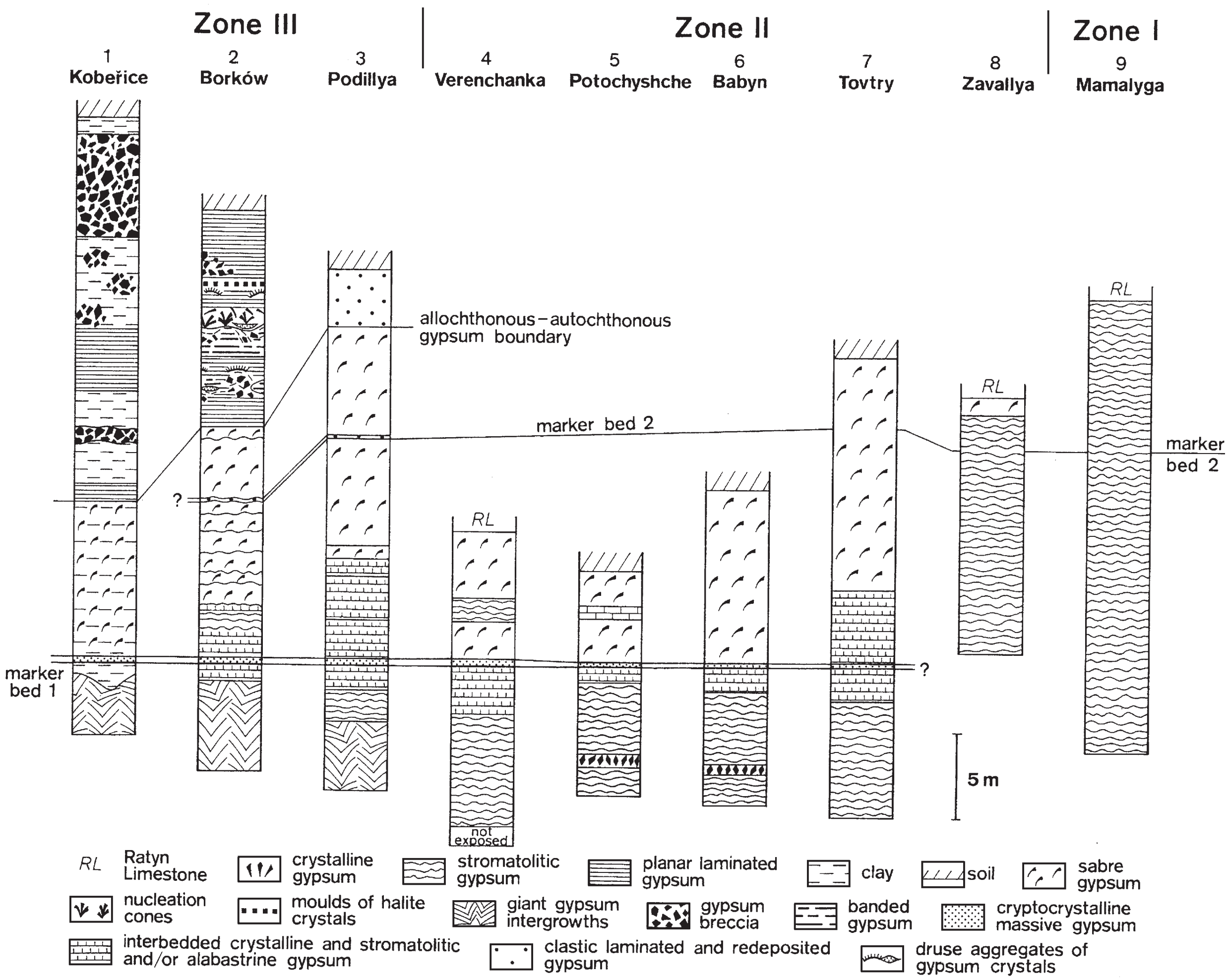

Fig. 7. Gypsum sections of the Carpathian Foredeep. See Figs. 2 and 6 for location of those sections. The older Badenian deposits occur at the base of those sections.

relationships between Ca-sulfates occurring in the marginal Ca-sulfate platform and Ca-sulfates from Ca-sulfate basin are uncertain, and this problem is discussed further in this paper.

Autochthonous gypsum facies (crystalline gypsum, stromatolitic and massive alabastrine gypsum) were deposited in two main environments (Peryt, 1996). One variety of crystalline gypsum (giant gypsum intergrowths) precipitated from highly concentrated brines in moderate water depths at the initial stage of gypsum precipitation. Other varieties of autochthonous gypsum facies (i.e. saber gypsum, "grass-like" gypsum, stromatolitic and massive alabastrine gypsum) represent very shallow subaqueous gypsum deposited in a vast brine pan characterized by a mosaic of facies. This facies mosaic reflected an interplay of concentrated brines from the central part of the evaporite basin, diluted brines resulting from the influx of continental meteoric waters, and local evaporation of a restricted shallow water body (Peryt, 2001; Cendón et al., 2004).

Halite and associated siliciclastic deposits in the central part of the evaporite basin in Poland show very similar facies successions (Garlicki, 1979, 1994b). The regional lithostratigraphical correlation based on sedimentary cyclothems and marker beds originally distinguished in the bedded part of the Wieliczka salt mine (located 11 km SE of Cracow — cf. Fig. 2), made it possible to distinguish five cyclothems (Garlicki, 1979, 1994b; Fig. 8). The first cyclothem was recorded only in area between Bochnia (located 34 km SEE of Cracow) and Tarnów (located 74 km E of Cracow) (Garlicki, 1979, 1994b). In cycle II, the salt sedimentation occurred in an area from Upper Silesia to Tarnów, and at that time the oldest salts of Wieliczka were deposited. The salts of

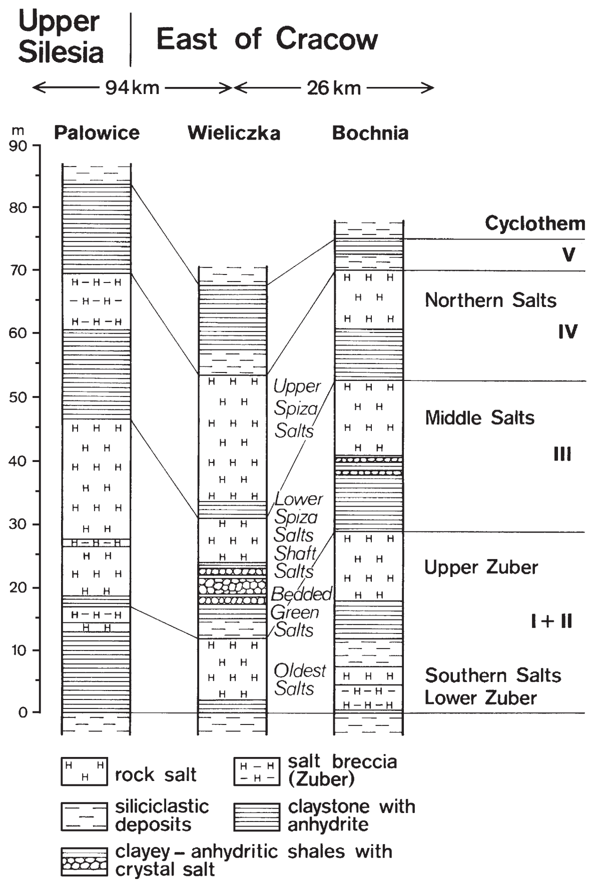

Fig. 8. Examples of sections from halite facies (after Garlicki, 1994b). Palowice borehole section is located in Upper Silesia 83 km WNW of Cracow (cf. Fig. 2), Wieliczka mine section is located 11 km SE of Cracow, and Bochnia mine section is located 34 km ESE of Cracow.

the cyclothem III have the widest extent — from Upper Silesia to the area east of Tarnów, and in the Wieliczka mine the cyclothem includes the varieties known as the green bedded salt, the shaft salt, and the lower spiza salt (see Garlicki, 1979; Hallett, 2002) (Fig. 8). The cyclothem IV in Wieliczka includes the upper spiza salt. The salts of the youngest cyclothem (V) are known only from some boreholes (cf. Fig. 8) (Garlicki, 1979, 1994b). It should be added that the best recognized facies changes of Badenian salts come from the historical Wieliczka salt mine where two units are distinguished (Gaweł, 1962): the lower unit (stratiform deposit-bedded part) and the upper unit (boulder deposit). The upper unit is developed as a coarse breccia composed mainly of salt clay with blocks (up to >150 m long) of coarse-grained salt. The stratiform unit deposits accumulated in the deeper and more distal part of the subbasin, and the salts forming boulder unit precipitated in a shallower evaporite basin situated closer to the Carpathian border (Bukowski, 1994). Both units exhibit sedimentary structures indicating that most of the halite layers have been formed from redeposition by gravity mass movements (e.g. Ślączka and Kolasa, 1997). In the Ukrainian part of Carpathian Foredeep evaporite basin halite deposits do not form a continual zone that occurs along the basin axis but instead there are some isolated halite basins (Fig. 6). There is no core material available that would make it possible to check if similar cyclothems to those recorded in the Polish part of the foredeep can be distinguished in the Ukrainian Carpathian Foredeep.

The relationship of the areas of halite and Ca-sulfate deposition remains enigmatic. In some boreholes in the inner zone of the Ukrainian part of Carpathian Foredeep (Wyszyński, 1939; Panow and Płotnikow, 1996) halite is underlain and overlain by Ca-sulfates. Petrichenko et al. (1997) suggested that at the beginning the terrigenous-Ca-sulfate and Ca-sulfate (mostly gypsum and minor anhydrite) deposition occurred in the zone adjacent to the Carpathians and subsequently it was changed by sodium chloride precipitation. The halite stage was followed by Ca-sulfate stage but Ca-sulfates were deposited only in the outer part of the Carpathian Foredeep basin in response to the migration of evaporite basin during the overthrusting of the Carpathian nappes. In the Polish part of Carpathian Foredeep similar relationships are observed in some borehole sections but in the others the evaporite succession is far more complex (Połtowicz, 1993: Fig. 7). If resedimented evaporites from the upper part of the Ca-sulfate sequence in the marginal Ca-sulfate platform correspond to the entire sequence from the Ca-sulfate basin, and the latter correspond to the entire halite sequence, the autochthonous gypsum deposits from the marginal Ca-sulfate platform would be represented in deeper-water settings only by the organic-rich shales underlying the redeposited evaporites (Oszczypko et al., 2005).

The evaporites are folded along the Carpathian overthrust, however, the southern margin of the basin is poorly known. In Poland, it is assumed that the original width of the axial part of the basin was not considerably larger than the present one (Garlicki, 1968; Oszczypko, 1981) except for two areas near Wieliczka where originally salts occupied a bigger area (Garlicki, 1968), up to 50 km wide (Połtowicz, 1993). The part of the Badenian evaporite basin adjacent to the Carpathians is poorly known because of the subsequent thrusting but near Wieliczka in Poland there are facies transitions of halite facies (in fact it is mixed siliciclastic-halite facies) to what is called Ca-sulfate facies (Garlicki, 1968) that consists of marly claystones, siltstones and sandstones (partly cemented by gypsum), and towards the south deposits are more coarse-grained or even conglomeratic. Thus the evaporite basin margin was near to that area (Garlicki, 1968) and such a conclusion is supported by interpretations of siliciclastic deposits associated with salts in Wieliczka (Bukowski, 1997).

4. Facies transitions in West Ukraine

4.1. Description

In the West Ukraine, in addition to facies zones III and IV, two other zones occur. The first one (facies zone I) consists entirely of stromatolitic gypsum, and is characteristic of the area (>15 km wide) bordering the nearshore Ca-sulfate facies limits and passes landwards into the siliciclastic facies as can be observed in Anadoly (Fig. 6). The stromatolitic gypsum exhibits a considerable variety of forms, although planar or slightly crenulated stromatolites prevail. The facies zone II is located basinward of the facies zone I and is characterized by the occurrence of stromatolitic gypsum in the lower part of the section and sabre gypsum (occasionally with a clastic gypsum unit above the sabre gypsum) in the upper part. The facies zone II is more than 40 km wide.

The correlation of zones III and II is possible because of the existence of two marker beds. The marker bed 1 (usually 20 – 40 cm thick) consists of cryptocrystalline massive gypsum with a distinctive finely crenulated lamination and a dome-like to cauliflower-like top. The marker bed occurs a few tens of centimeters to a few meters above the giant gypsum intergrowths unit in zone III and is usually underlain by a unit consisting of interbedded crystalline and stromatolitic and/or alabastrine gypsum, which is in turn underlain by stromatolitic gypsum (Fig. 7). In zone II the marker bed 1 occurs within a unit consisting of interbedded crystalline and stromatolitic and/or alabastrine gypsum (Fig. 7). The bed occurs only in the southwestern part of the facies zone II (Fig. 6). There is a clear trend of increase of thickness of giant gypsum intergrowth unit towards the southwest of the boundary between facies zones II and III and of decrease of the overlying stromatolitic gypsum unit below the marker bed 1.

Above marker bed 1, stromatolitic and selenitic facies occur, and in the upper part of the section sabre gypsum occurs. There are continual lateral facies changes between stromatolitic and selenitic gypsum, which can be observed within particular outcrops (Peryt, 1996), and thus the distance between the marker bed 1 and the sabre gypsum unit fluctuates.

Within the stromatolitic gypsum, in the facies zone II, in some sections located close to boundary between the facies zones III and II, an intercalation of crystalline gypsum in the lower part of the section occurs (Peryt, 2001). This intercalation is found 1.5–2.0 m above the base of the gypsum base in all outcrops located in the facies zone II southwest of the dotted line shown in Fig. 6 and is usually 0.5–1.0 m thick (although it is considerably thinner in two outcrops: Zvenyachyn and Khreshchatyk, near Zalishchyky — cf. Fig. 6).

The marker bed 2 is a thin (usually 20 cm) gypsarenitic unit (mostly laminated gypsum) which occurs within the sabre gypsum unit. In contrast to the facies zone III where this marker bed is very common, it is recorded only in a part of the facies zone II adjacent to the facies zone III. For example, in the borehole 119-D located 2.7 km ESE from Nyrkiv-Nagoryany (N–N in Fig. 6), the complex of sabre gypsum contains an intercalation (1.0 m thick) of aleurolite with a bed of tuff material (Peryt et al., 2004a). In some places the gypsarenitic zone is lacking and its place in the section is occupied by a distinct surface within sabre gypsum. In the facies zone II adjacent to facies zone I there is a clear channelized surface in the upper part of the stromatolitic gypsum sequence that in the Zavallya section is located ca. 3 m below the Ratyn Limestone. This surface was earlier regarded as the boundary between autochthonous and allochthonous units (Peryt, 1996) but a subsequent field study proved the presence of sabre gypsum (up to 2 m thick) in the uppermost part of gypsum sequence. Therefore, considering that the surface of the Zavallya section shows a remarkable similarity to the channelized surface within the gypsum and lying ca. 2.5 m below the Ratyn Limestone in the Kudryntsi section (4 km NW of the Zavallya section — see Fig. 6) it is regarded now as an equivalent of the surface in Kudryntsi. In Kudryntsi, the channelized surface is covered by lenticular limestones (up to 20 cm thick) showing mudstone and wackestone textures and bioclasts indicating their marine provenance (planktonic foraminifers, pteropods, ostracods, calcareous nannoplankton — Peryt, 2001).

A similar surface was recorded 8.3 m below the Ratyn Limestone in Mamalyga. It shows a clear relief of several centimeters, with some depressions filled by bioclastic and peloidal limestone (Peryt, 2001). In the Anadoly section, lenticular bodies occur (several tens of cm long and several cm thick) of peloidal and bioclastic limestone 2–8 m below the Ratyn Limestone. In addition, in Borshchiv section, a clear surface within the gypsum occurs ca. 5 m below the Ratyn Limestone.

In some sections of the facies zone II the boundary between autochthonous and clastic members is recorded. This facies boundary seems to reflect a major change in the basin history (see Peryt, 1996) and as such is considered to be essentially isochronous. In the facies zones II and I the clastic member occurs only. The Ratyn Limestone occurs on various stratigraphic levels of gypsum sequence (Peryt and Peryt, 1994).

4.2. Interpretation

Basin-marginal Badenian evaporites formed in a standing body of water, as well as in desiccated environments subject to floods (Peryt, 2001; Babel, 2004). The lateral persistence of thin marker beds over large areas with only minor changes in thickness and facies indicates that they formed on broad, very low relief areas which were affected by rapid transgressions that led to major changes in brine chemistry. Marine incursions were related to the extrabasinal factors. As the Badenian evaporite basin was located in a depression in which the brine top level occurred below the contemporaneous sea level, during sea-level rises new marine water could enter this depression and bring with it marine fauna and flora that were recorded from clays (and limestones) intercalated within the gypsum in the marginal gypsum facies as well as in the basinal facies, both Ca-sulfate (e.g. Peryt et al., 1998a; Peryt, 1999) and halite (e.g. Venglinskiy and Kopystyanskaya, 1979), in the West Ukraine and the adjacent part of Poland.

The correlations between the facies zones III, II and I are based on characteristic marker beds that strongly suggest that the deposition of giant gypsum intergrowth facies (in facies zone III) and stromatolitic gypsum facies (in facies zone II) as well as the deposition of sabre gypsum and stromatolitic gypsum were coeval. The marker bed 1 records a major phase of subaerial exposure of the entire marginal Ca-sulfate platform, and the lack of the marker bed 1 in the more marginal, northeastern parts of the platform (Fig. 7) is related to the lack of evaporite deposition preceding the origin of the marker bed 1. This in turn is related to the general transgressive trend (and at the same time brining-up trend) with evaporite deposition and migration of facies zones toward the northeast. Accordingly, the base of sabre gypsum facies in the facies zone II is strongly diachronous. Therefore, in the facies zone II adjacent to the facies zone I the equivalent of the marker bed 2 occurs within the stromatolitic complex and the sabre gypsum unit occurs higher up in the section (Zavallya). The correlation of zones II and I is more difficult since the marker zone 1 is lacking both in the facies zone II adjacent to the zone I and in the zone I itself. As the entire zone I is made up of stromatolitic gypsum, there is no marker bed 2 developed as gypsarenitic intercalation within sabre gypsum unit (as in facies zones III and II). However, there occurs a distinct surface within the gypsum sequence that can be correlated over great distance. Such a surface is sometimes accompanied by a limestone intercalation in the form of lenticular bodies (usually cm-thick) that contains marine fauna (Kudryntsi, Mamalyga). This surface and/or limestone intercalation occurs at approximately the same position in the gypsum section as the marker bed 2 does in the facies zone II and thus is regarded to be its equivalent.

The general transgressive trend finds its expression also during the deposition of the lower part of the gypsum sequence in the facies zone II adjacent to the facies zone III as indicated by the occurrence of the bed of crystalline gypsum within the stromatolitic unit (Peryt, 2001). This bed reflects the fluctuation of the boundary of two brine strata: the higher-density bottom brine that led to the origin of giant gypsum intergrowth facies and the lower-density upper bed that resulted in the deposition of stromatolitic gypsum.

The gypsum of the upper, clastic part of the section was deposited in a basin with bottom topography of at least a few tens of meters. In contrast, during the deposition of the lower part of the gypsum section the basin relief was minor, and the differences in water depth between facies zones I and III probably did not exceed ten meters. It is usually assumed that the depth of Badenian halite basins was a few hundred of meters (Garlicki, 1979). Such a conclusion seems to be supported by studies of fluid inclusions in halite that showed the high pressure implying great depths at deposition (Gaweł, 1965) and relatively stable brine content and concentration explained as due to stable conditions at the depth of at least several tens of meters (Kovalevich, 1997). However, the high pressure in fluid inclusions might result from pressure imposed during the Carpathian overthrusting, and thus the actual depths may have been less. Low bromine content (Garlicki and Wiewiórka, 1981; Galamay, 1997) indicates that halite is partly recycled in origin (cf. Garcia Veigas et al., 1997). Recently Cendón et al. (2004) concluded, based on geochemical modeling, that during halite precipitation there was recycling of previously formed evaporites with an important input of continental water. In addition, the δ^{37}Cl values higher than 0.4‰ recorded in halite from Wieliczka imply a measurable input of non-marine chloride leading to multiple cycles of dissolution and partial reprecipitation of halite (Eastoe and Peryt, 1999).

5. Onset of evaporite deposition

5.1. Description

Gypsum deposits overlie older Badenian deposits (e.g. Aleksenko, 1967; Pawłowski et al., 1985) and rarely the pre-Badenian strata both in the Carpathian Foredeep and its foreland. The local occurrences of mudstones overlying the Badenian sands and sandstones and the occurrence of boulders of likely redeposited red-algal limestone indicate local breaks in deposition prior to gypsum sedimentation (Pawłowski et al., 1985). In some places in the marginal sulfate platform area, a thin sandy or marly coquina layer (Ervilia Bed) occurs locally below the gypsum sequence. This layer, containing fauna almost exclusively composed of two mollusk species (*Modiola hoernesi* Reuss and *Ervilia pusilla* Philippi), is sometimes accompanied by individual shells of *Chlamys scissa* (Favre) (Pawłowski et al., 1985, p. 34) that are particularly adapted to an increased salinity and low oxygenation (Kowalewski, 1966). In some places the Ervilia Bed is covered by thin (<20 cm) black bituminous clays, barren marls or sandy Rostochya bed (some cm thick).

In the sulfate basin facies anhydrites are underlain by claystones that originated in outer shelf environments although immediately below the anhydrites there occur calcareous microbial laminites or fine-grained sandstones interpreted as storm deposits (Dziadzio, 2000). In the halite zone, 8–10 m of top claystones contain micronodular-laminated anhydrite often displaying enterolithic pattern (Gaweł, 1962); the anhydrite originated via displacive growth within laminated deposit (cf. Kasprzyk and Orti, 1998).

5.2. Interpretation

The scenario of events leading to the deposition of widespread evaporites in the Badenian has not been established in detail. Isotopic studies of Badenian foraminifers occurring below and above evaporites indicated the lowest temperatures in a part of the Badenian section where evaporites occur and thus it is assumed that the interrupted communication of the Paratethys with the ocean was a consequence of eustatic sea-level fall, possibly related to climatic cooling (Gonera et al., 2000). Quantitative reconstructions of the Middle to Late Miocene climate evolution in the southern Carpathian Foredeep Basin in NW Bulgaria (Ivanov et al., 2002) indicated the existence of a warm, subtropical climate during the Badenian, with a mean annual temperature between 16 and 18 °C and mean annual precipitation between 1100 and 1300 mm; however, small climate fluctuations existed as well and the precipitation rate could be thus considerably smaller during the period of evaporite deposition. The reconstruction based on paleobotanic study of the Transcarpathian basin showed that immediately before and after evaporite formation, warm temperate climate prevailed (Syabryay and Teslenko, 2000) but Böhme (2003) found that between 14.0 and 13.5 Ma the warm period ended abruptly, and the mean annual temperature dropped more than 7 °C to temperatures around 14.8–15.7 °C. A tectonic closure of

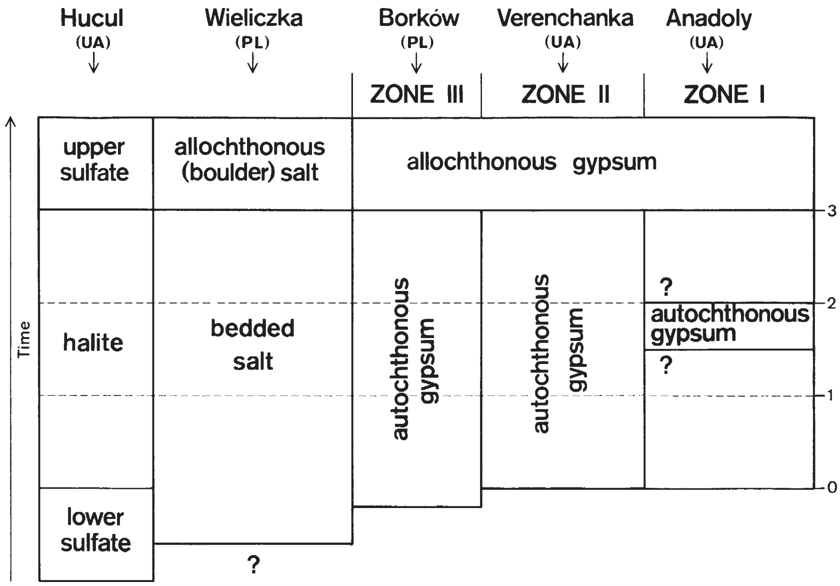

Fig. 9. Correlation of selected sections of Badenian evaporites (for actual thicknesses refer to Figs. 7 and 8; the Badenian evaporites in the Hucuł 1 borehole are 65 m thick: the lower Ca-sulfate unit is 15 m thick, the halite unit is 35 m thick, and the upper Ca-sulfate unit is 15 m thick — Wyszyński, 1939). Horizontal lines (dotted within the particular sections) are time lines: 0 is the onset of evaporite deposition in the gypsum facies zone III and the adjacent part of the gypsum facies zone II, 1 is the time of deposition of marker bed 1, 2 is the time of deposition of marker bed 2 (or its equivalent), 3 marks the beginning of deposition of allochthonous evaporites (considered to be roughly coeval).

connection with the Tethys could have contributed to the origin of a salinity crisis as well.

It is commonly accepted that the Badenian evaporite sedimentation was related to a sea-level fall (e.g. Kwiatkowski, 1972; Babel, 2004, with references). The Skawina Formation deposits have a deep-water character (Oszczypko, 1998) that is in contrast to the shallower water (to subaerial) settings in which the evaporites originated. The range of evaporite drawdown was estimated as a few tens of metres in the northern margin of the Carpathian Foredeep in Poland (Babel, 2004) and 50–100 m in its axial part (Oszczypko, 1998). Once the surface connection with the Tethys was broken, arid conditions developed, and the evaporite drawdown mechanism was initiated. The fall in water-level during evaporite drawdown was very fast and probably represented only a small fraction of the entire time interval of evaporite deposition.

The duration of the Badenian evaporite deposition in the Carpathian Foredeep was estimated, using the concept that the presence of laminae in Ca-sulfate and halite deposits are annual accumulations, to be 20,000–35,000 years (Garlicki, 1979; Niemczyk, 1995; Petrichenko et al., 1997). However, as discussed by Sonnenfeld (1984), each light–dark couplet alone represents a cyclicity covering several years, especially when couplets are storm derived, and this explains the lack of 11-year-cycles recorded in laminated gypsum in facies zone III (Słomka, 1979). The length of evaporite deposition could thus be one order of magnitude longer than the previous estimates.

As concluded by Pawlikowski (1982), the nature of crystal growths and the way of occurrence of impurities in gypsum suggest that giant gypsum intergrowth facies occurring at the base of gypsum section in the facies zone III originated from density-stratified brines. Babel (1999) presented more detailed interpretation of this facies assuming the existence of a relatively permanent pycnocline, with the salinity of the upper bed of brine that does not allow the gypsum precipitation.

This density stratification possibly started during the deposition of the Ervilia Bed. The lower-salinity brine bed resulted in the deposition of gypsified stromatolites in the facies zone II in the Ukraine. In Poland those facies zones were not developed since the inflow of continental water was probably too great to enable gypsum precipitation from the upper part of water body (cf. Babel, 1999, p. 431).

The density stratification of the brines means that in the deepest part of the basin where the heaviest brines occurred halite precipitation commenced. The salt cyclothem I was the oldest halite evaporite in the Carpathian Foredeep basin, and, as already indicated, it was preceded by deposition of the lower Ca-sulfate which is recorded in the Hucuł 1 borehole (cf. Fig. 9). However, the Ca-sulfate deposition in Hucuł 1 borehole may correspond to the syndepositional Ca-sulfate nodule growth in the uppermost part of the siliciclastics deposited prior to the onset of halite precipitation. The onset of evaporite deposition in the Carpathian Foredeep was thus clearly diachronous in particular facies zones as summarized in Fig. 9. The first step in the evaporite deposition was related to the basin centre (Fig. 9). This is in contrast to the Messinian basins of the western Mediterranean where the restriction affected the margins before the central areas (e.g. Butler et al., 1999; Riding et al., 1999; Bellanca et al., 2001; Matano et al., 2005) although both the Badenian and Messinian salinity crises resulted from a similar combination of tectonic and glacio-eustatic processes (see Hsü et al., 1973; Krijgsman et al., 1999; Duggen et al., 2003; for the discussion on the Messinian salinity crisis).

6. Termination of evaporite deposition

6.1. Description

In the halite and Ca-sulfate basin facies evaporites are overlain by claystones that originated on the shelf slope (Dziadzio, 2000). In most sections from the facies zone III, the clastic gypsum is covered by black laminated clays and marls with a local abundance of pelagic pteropods, planktonic foraminifers, pectens (mostly *Chlamys elini* Zhizhchenko) and tuff intercalations (Kowalewski, 1958; Pawłowski et al., 1985). Above the pteropod-rich, lowermost part of the Spirialis Clay Member, the section is rich in a planktonic fauna and then benthic foraminifers appear. The foraminifers are very abundant in the uppermost part of the Spirialis Clay Member where in turn pteropods are rare (Jurkiewicz and Karnkowski, 1961). In some sections in the Ukraine (Peryt and Peryt, 1994) and Poland (Peryt and Kasprzyk, 1992) the Ratyn Limestone deposits occur at the base of the gypsum-overlying strata. The gypsum sequence was clearly karstified prior to deposition of Pecten beds (Pawłowski et al., 1985).

Sabre gypsum and stromatolitic gypsum commonly occur at the top of the gypsum sequence of the facies zones II and I, although locally in the both zones clastic gypsum forms the upper portion of the gypsum sequence. In all cases gypsum deposits are overlain by the Ratyn Limestone. These rocks are peloidal wackestones, peloidal–intraclastic–bioclastic grainstones and packstones and peloidal–intraclastic–ooidal grainstones that accumulated in restricted environments (Peryt and Peryt, 1994) as indicated by pseudomorphs after lenticular gypsum crystals.

6.2. Interpretation

Pteropods are stenohaline organisms (see Krach, 1981) and their common occurrence in the lowermost part of the Spirialis Clay Member (Jurkiewicz and Karnkowski, 1961) are probably related to mass extinction caused by mixing of the upper water bed that was of normal salinity and of moderate temperature, with the warmer, lower water bed of high salinity. This conclusion is supported by a lack of bioturbation in clays as well as their bituminous-rich nature (e.g. Pawłowski et al., 1985, p. 72). In turn, the recorded foraminifer assemblages indicate an outer shelf setting where the water salinity was close to normal (Czepiec and Kotarba, 1998). The anoxic conditions inherited after evaporite deposition were accompanied by incomplete dilution of the dense bottom brines so preventing the further deposition of evaporite or the colonization of the bottom by marine fauna. At the same time, oxic conditions prevailed over the shallower parts of the basin where the Ratyn Limestone originated, although locally salinity of water was high enough to allow for displacive growth of lenticular gypsum crystals.

Although sedimentological and geochemical data indicate recycling of evaporites during most of the period of evaporite deposition, it became an especially important mechanism during the deposition of the upper part of evaporites, both in the halite and Ca-sulfate facies. Due to an increased rate of overthrusting movements within the Carpathian accretionary wedge and/or increased slab-pull processes within the Carpathian subduction zone (Oszczypko et al., 2005), this recycling was accompanied by the block tectonics that resulted in the creation of bathymetric differences, at least few tens of meters as evidenced by the occurrence of the Ratyn Limestone in the Ukraine (Peryt and Peryt, 1994) and the Pecten-Spirialis Beds in Poland (Pawłowski et al., 1985) on stratigraphically different parts of the gypsum section. The erosion preceding the deposition of the Ratyn Limestone and the Pecten-Spirialis Beds indicates the complete desiccation of the Badenian evaporite basin in its marginal part. The transgression that followed and led to the deposition of the Ratyn Limestone and Pecten-Spirialis Beds was a response to a change in the hydrology of the Central Paratethys that was tectonically-driven and associated with extension and then intensive subsidence (cf. Dziadzio, 2000; Krzywiec, 2001). This change in hydrology implied the dilution of brines by inflowing marine water, what terminated the Badenian salinity crisis, and in a relatively short time the basin water gained normal marine salinity.

A different general sequence of events was recorded in the whole Mediterranean where the Lago-Mare conditions, characterized by typically brackish and freshwater environments, developed at the end of the Messinian salinity crisis (Rouchy et al., 2001, 2003, with references therein). The causes of the environmental change from hypersaline to brackish conditions throughout the Mediterranean have been diversely interpreted (Rouchy et al., 2001). The rapid marine reflooding of the basin occurred at the beginning of the Pliocene.

7. Implications and conclusions

There are common features to the Middle Miocene Badenian evaporites of the Carpathian region. For instance they are underlain and overlain by deep-water marine deposits; the onset of evaporite deposition was sudden but not synchronous in all facies zones (as summarized in Fig. 9); and the deposition of evaporites was controlled by the evolution of Carpathian orogen. A general transgressive sequence of evaporites found in the Carpathian Foredeep (see Fig. 9) resulted from the migration of facies zones induced by nappe movement. In other Carpathian evaporite basins this transgressive sequence was not recorded, possibly because of their inner-basin position (cf. Fig. 2 and 3). In all the Carpathian basins the redeposition of evaporites was important, and although parent brines were marine in origin (Kovalevich and Petrichenko, 1997), they were subject to an important inflow of continental water (Cendón et al., 2004). This resulted in decreased Br content in the Badenian halites (e.g. Galamay, 1997) as well as their impurity. Another result of the influence of the Carpathian orogen for the evaporite deposition was the expulsion of buried brines from the orogen (Liszkowski, 1989; Eastoe and Peryt, 1999).

In the Messinian of the Mediterranean region, the diachronism of the restriction and onset of the evaporitic conditions first in the marginal areas and then in the basin centre are based on the study of the central Sicilian Basin (Bellanca et al., 2001, with references therein). On the other hand, in the Eastern Mediterranean, Krijgsman et al. (2002) concluded that the onset of evaporite deposition was synchronous and it was preceded by a progressive decrease in bathymetry (from approximately 500 m to very shallow-water conditions) accompanied by an approximately 60-kyr interval of deteriorating environmental conditions. Those two interpretations are not necessary mutually exclusive as the time difference of the onset of the evaporitic conditions in the Messinian could be negligible similarly as it was during the Badenian evaporite deposition (Fig. 9). It should be stressed that in the Badenian evaporite basin of the Carpathian Foredeep the onset of the evaporitic conditions in the basin centre preceded the onset in the marginal areas as shown in Fig. 9. The transgressive trend lead to an important increase of area of evaporite deposition and therefore the fact that in other evaporite basins evaporites cap marine platforms does not imply that the restriction occurred during relative high sea level (cf. Orszag-Sperber et al., 1993).

The history of Middle Miocene Badenian evaporite deposition is summarized in Fig. 9. It assumes the same depositional history in the marginal basin and the basin centre. There is no reason to assume that is unique in other Middle Miocene evaporite basins of the Paratethys. In the Red Sea, the basin was deep before the onset of the evaporitic sedimentation and the evaporitic succession is devoid of any features indicative of desiccation or shallow water conditions (Rouchy et al., 1995). The Red Sea evaporites originated in very shallow water with occasional subaerial exposures (Stoffers and Kühn, 1974). Fluids trapped between and among the evaporitic rocks entered the deposits during their formation in shallow pans or shortly thereafter, and they have a strong meteoric water component (Manheim, 1974). At the times of separation (partial or total) from the central Gulf of Suez, marginal closed basins would have become completely non-marine, as indicated by the fluid-inclusion study of gypsum (Attia et al., 1995). Accordingly, those characteristics are very similar to those recorded for the Badenian Carpathian Foredeep basin.

The Badenian evaporite basin was located in a depression below the contemporaneous sea level and thus an important sea-level rise resulted in quick flooding of this depression with seawater that stopped the evaporite deposition from mixed seawater–non-marine waters and led to the deposition of marine sediments. However, locally in marginal areas evaporitic conditions were maintained for some time as indicated by the occurrence of pseudomorphs after lenticular gypsum crystals in the Ratyn Limestone. Another situation occurred after local deposition of evaporites in Eastern Paratethys basins. In East Crimea, gypsum evaporites formed from mixed seawater–non-marine waters, and the brackish conditions prevailing during gypsum precipitation continued afterwards, although at the end of evaporite deposition the basin became desiccated and then it was rapidly reflooded by brackish water (Peryt et al., 2004b). A very similar scenario in terms of salinity conditions was earlier proposed by Rouchy et al. (2001) for the Messinian of eastern Mediterranean where, as indicated by study of the southern Cyprus basin, the oligohaline to mesohaline conditions typical of the Lago-Mare deposits in the eastern Mediterranean already existed during deposition of the upper gypsum sub-unit (Rouchy et al., 2001) when marine brines were diluted by massive inputs of meteoric water.

The Badenian and Messinian salinity crises show great similarities as far as their onsets are concerned but their terminations were different.

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