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Notes

The Badenian evaporite basin of the northern Carpathian Foredeep as a model of a meromictic selenite basin

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Abstract: The hydrography and brine flow patterns in the Middle Miocene (Badenian) evaporite basin of the northern Carpathian Foredeep (in Ukraine, Poland and the Czech Republic) are reconstructed based on studies of the peculiar, conformably oriented, bottom-grown gypsum crystals present in the selenite deposits along the basin margin. The crystal apices are turned in a similar horizontal direction that is interpreted as the product of consistent flow of the bottom brines during crystal formation. Similarly the regular millimetre-scale growth zoning in these crystals presumably reflects the annual stratification-mixing pattern in the brine column typical of monomictic basins. In the central, deeper parts of the basin deposition was dominated by Na-chloride, and the selenitic facies are lacking. These central areas are interpreted as being meromictic during the oriented selenite deposition. The permanent pycnocline separated a mixolimnion, at the surface, from an anoxic (euxinic) monimolimnion, at the bottom, where direct evaporative crystallization of gypsum was not possible. The mixolimnion, which extended far onto the shallow margin of the basin, showed only a seasonal (annual) pycnocline and monomictic hydrography. Oriented selenites grew just in this mixolimnetic marginal zone, under predominantly counterclockwise (cyclonic) flow.

In some models and palaeogeographical reconstructions of ancient evaporite basins (Warren 2006), and in a few modern basins (references in Bałbel 2004a), the selenite facies (i.e. large bottom-grown gypsum crystals) are distributed along the basin margins and are absent in the deeper basin centres. Such a depth-controlled distribution of selenite crystals is explained by the well-known fact that the shallow-water environment (strictly, some specific aspects of this environment) apparently favours the *in situ* growth of characteristic gypsum crystals. It is also known that the features of brine at the given depth change regularly following the annual hydrographical stratification-mixing cycle of the basin (Bałbel 2007). The crystallization of evaporite minerals and distribution of evaporite facies appear to be closely related to this changing hydrography of the brine column, as is proved by the modern evaporite deposition in some basins (e.g. Valero-Garcés & Kelts 1995; Last *et al.* 2002; Last & Ginn 2005; Warren 2006) and in the drying Dead Sea in particular (Neev & Emery 1967; Niemi *et al.* 1997; Herut *et al.* 1998). Ancient, giant, deep selenite basins have no modern analogs. However, certainly, as in the Dead Sea, some link between the hydrography of the deep brines and distribution of selenite facies in such basins can and should exist. So far the

hydrographical and hydrodynamical environment of such basins is poorly recognized and has not been reconstructed with the use of the modern limnological knowledge gained from saline lakes.

The Middle Miocene Badenian evaporite basin of the Carpathian Foredeep is one of such basins with the widespread marginal selenite facies. The main aim of this paper is to reconstruct the brine hydrography in this basin and, based on the actualistic limnological data as a model, to create a new comprehensive hydrographical model of a deep selenite basin to explain more clearly the specific marginal distribution of selenite facies and its lack in the deeper basinal centre. This model also may be valid for many other evaporite basins showing the same lateral differentiation of facies: the selenite or gypsum facies on the basin margin and Na-chloride (halite) facies in the basin centre, where the reason for this differentiation is poorly understood and thus remains controversial (Cohen 1993).

The reconstruction presented in this study is the result of the advanced investigation of the unique sedimentary structure present in some selenite deposits. Here, on the margin of the Badenian basin, there are large areas containing oriented gypsum crystals that grew on the bottom in a concordant manner under influence of an oriented flow of brines that

were calcium sulphate oversaturated (Pawlikowski 1982, p. 36; Dronkert 1985, p. 205). These oriented crystals were used as indicators for the brine flow paths and helped reconstruction of the hydrography in this marginal zone of the basin (Bąbel *et al.* 1999; Bąbel 2002; Bąbel & Becker 2006) while the hydrography in the remaining area remained unknown. This paper supplements these previous investigations. It demonstrates a methodology for brine palaeocurrent analysis and the validity of the previous hydrodynamical and hydrographical reconstruction in a small area of the basin chosen as a case study (located near Halych in Ukraine). This earlier reconstruction, valid for the marginal selenite zone of the basin, is integrated with a new concept concerning the brine hydrography of the adjacent deeper portion of the basin now represented by laminated Ca-sulphate and halite facies, where selenite deposits are lacking. The new model of the basin is developed, in which distribution of chemical facies is shown as a product of a specific stratification and hydrodynamic of the basinal brines.

Geology and palaeogeography of the Badenian evaporite basin

The Carpathian Foredeep basin is the largest evaporite basin developed during the Badenian salinity

crisis in the Central Paratethys area (Fig. 1). In the northern portion of this basin, in Ukraine, Poland and the Czech Republic, the Badenian evaporites crop out widely in the northern platform margin of the foredeep but are deeply buried in the foredeep (Fig. 2). The foredeep is mostly filled with the Miocene deposits and is subdivided into the autochthonous zone in the north and the allochthonous zone in the south, in front of the external flysch unit of the Carpathians. The Badenian evaporites are present in both these zones, however only in the autochthonous zone as *in situ* sediments. The evaporites form a relatively continuous horizon of gypsum, anhydrite and halite deposits, up to a few tens of metres thick, in places with thicker clay intercalations. The margin of the basin (i.e. mainly the platform zone) was dominated by gypsum deposition including extensive accumulations of selenites, particularly those selenites with the oriented crystals used for palaeocurrent analysis in this paper. The selenite facies was also deposited on the poorly preserved southern margin of the basin. The central areas of the basin (i.e. mostly the foredeep zone) were dominated by the laminated Ca-sulphate facies, clay and halite and in this presumably deeper zone of the basin the selenite deposition did not take place or is not preserved (Korenevskyi *et al.* 1977; Garlicki 1979; Połtowicz 1993; Smirnov *et al.* 1995; Petrichenko *et al.*

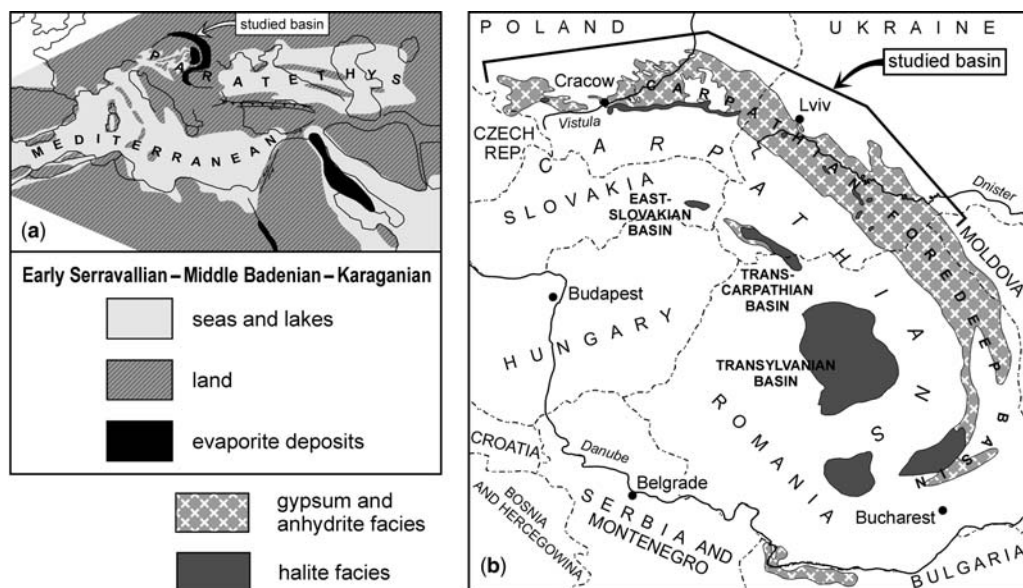


Fig. 1. Maps showing palaeogeography and distribution of Badenian evaporites. (a) Palaeogeography of Paratethys and Mediterranean in the Middle Miocene and location of the evaporite basin studied (after Rögl 1999); (b) present distribution of the Badenian evaporite basins in the Carpathian region and location of the basin studied (after Garlicki 1979; Khrushchov & Petrichenko 1979; modified).

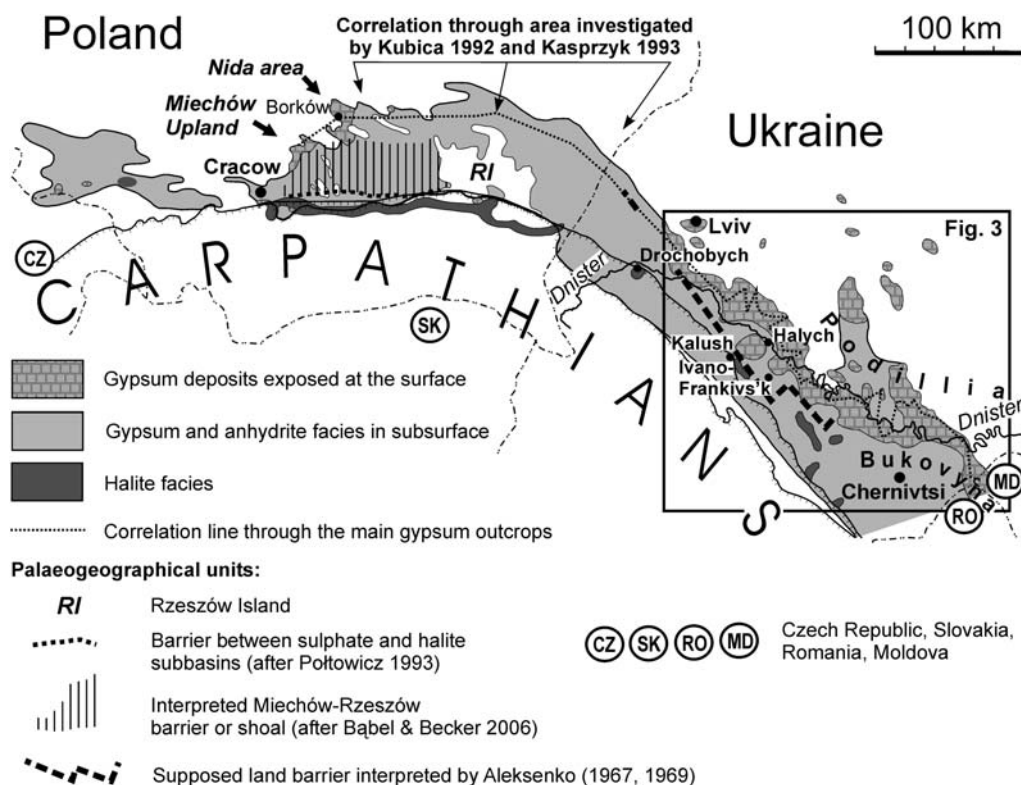


Fig. 2. Distribution of the Badenian (Middle Miocene) evaporites in the northern Carpathian Foredeep (after Atlas Geologiczny Galicyi 1885–1914; Garlicki 1979; Panow & Plotnikow 1996; and other sources).

1997; Kasprzyk & Ortí 1998; Peryt 2000, 2006; Kasprzyk 2003; Cendón *et al.* 2004; Bąbel & Becker 2006).

The evaporite basin comprised several more or less apparent subbasins. Two halite subbasins occurred along the axis of the foredeep in Poland (Figs 1 & 2; Garlicki 1979; Połtowicz 1993; Ślęczka & Oszczypko 2002). Several smaller halite subbasins also are recognized in Ukraine (Fig. 3; Klimov 1974; Petrichenko *et al.* 1974; Korenevskyi *et al.* 1977; Panow & Plotnikow 1996). The less pronounced gypsum subbasins were situated in the northern margin of the basin, commonly considered to be part of a giant sulphate platform or 'shelf' (Kasprzyk & Ortí 1998). Presumed shoals and islands apparently lay in between and within the subbasins, and their position could change with time. The largest central area, devoid of evaporite deposits, near Rzeszów (Poland), was interpreted as an island (Rzeszów Island), although evaporites could have been eroded from this area either during or soon after the evaporite deposition (Połtowicz 1993; Oszczypko 2006). The area extending from the

Miechów Upland to the Rzeszów Island was presumably a broad longitudinal uplift or barrier separating sulphate and halite subbasins during deposition of the selenite facies (Bąbel 2005b, p. 199; Bąbel & Becker 2006). A similar barrier might also separate the marginal gypsum 'platform' from the southern 'foredeep' subbasin in Ukraine (see Czarnocki 1935, pp. 114–115; Nowak 1938, p. 180). Aleksenko (1967, 1969) recognized a very narrow barrier, running roughly between the platform and the foredeep, based on absence of gypsum in drill cores (Figs 2 & 3). In this area it may be that the lack of gypsum is only an effect of the intersection of the cores taken in the drilled area by numerous oblique post-Badenian faults (Polkunov *et al.* 1979). The extension of the basin into the Romanian area is poorly recognized, although the evaporite shoal facies with gypsum microbialites are particularly widespread at the border of Ukraine, Moldova and Romania indicating extremely shallow water deposition in this area (Peryt 2001, 2006; Bąbel 2005b).

Stratigraphical correlation of the Badenian evaporites from the platform and particular

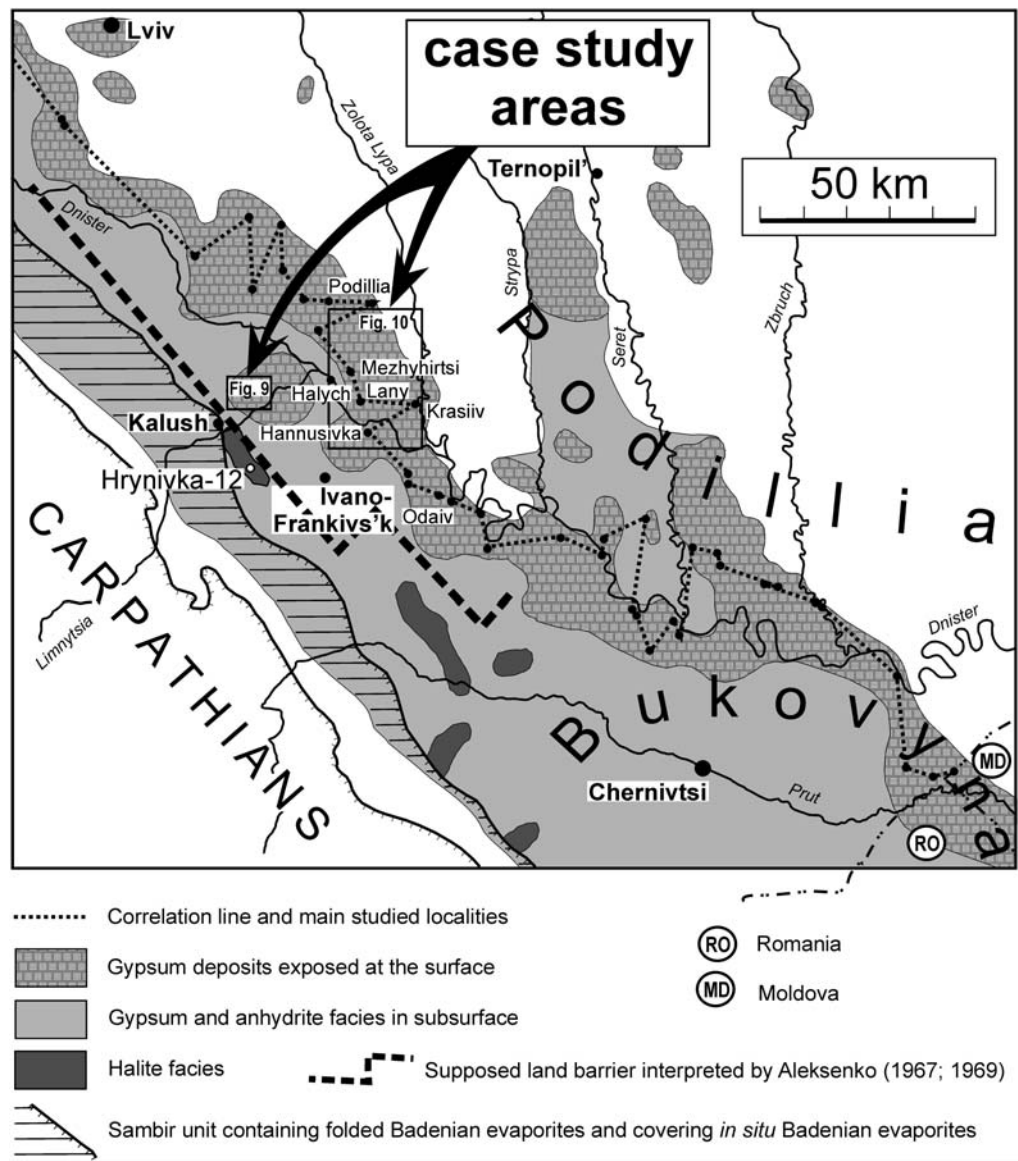


Fig. 3. Location and geology of the study area in the Ukrainian Carpathian Foredeep.

foredeep zones is unclear, although apparently they were deposited within a framework of the same evaporite basin. Event stratigraphical studies, based on a set of thin marker beds, proved that the gypsum deposits in the platform zone are coeval (Peryt 2001; Bałeł 2005a). However the time correlation of these selenite-dominated marginal deposits with the deposits of the remaining parts of the basin, where the facies are different, and selenites or their traces are absent, remains controversial.

The Badenian evaporite basin of the Carpathian Foredeep was probably a depression without open water connections with the sea and with the water level lowered below the sealevel (Peryt 2001, 2006; Cendón *et al.* 2004; Bałeł 2007). Such a basin can be compared with the modern saline lakes and its hydrography can be described by limnological terminology. Some evidence suggesting that the water level in the basin was below the sealevel can also be found in the studied oriented selenites (Bałeł 2004b, pp. 324–225).

Geology of the area selected for palaeocurrent studies

The area chosen for a case study is situated in Ukrainian Galicia (Halychyna), near Halych on the Dnister River (Fig. 3), the historical centre of Halychyna (from Greek 'hals' = salt). It occupies the basinal platform zone which borders the fore-deep zone along the regional Kalush fault. The area extends from the Kalush K-salt open pit mine (Hryniv *et al.* 2007a, b) on the west, to Zolota Lypa, the left tributary of Dnister, to the east. Kalush area belongs to the allochthonous Sambir zone or unit. This unit is overthrust to the northeast onto the deposits of the autochthonous foredeep and is in direct contact with the platform just at environs of Kalush, where the autochthonous foredeep deposits are completely overlain by it.

On the studied platform area the Miocene deposits lie horizontally, and with an erosional gap, upon the Cretaceous siliceous limestone. Gypsum deposits are underlain by marine clastic and carbonate deposits (most commonly glauconitic marls and sandstones) that are a few metres thick. Locally freshwater-limnic limestones are present at the base of Miocene sequence (e.g. at Lany). The Miocene (Badenian) strata below the gypsum are commonly much reduced in thickness and near Voinyliv (e.g. at Medynia), gypsum deposits lie almost directly on the eroded Cretaceous substrate. Just near Voinyliv and Medynia, Aleksenko (1967, figs 6 & 18; 1969, fig. 2) and Burov (1971) draw the mentioned morphological barrier: a narrow belt of emerged land running in a NW–SE direction in the Badenian evaporite basin (Fig. 3).

Gypsum sections in the studied area generally show the same sequence of lithostratigraphical units and arrangement of facies as in the whole northern margin of the Carpathian Foredeep basin (Kasprzyk 1995; Peryt 2001). The studied oriented selenites occupy the lithostratigraphical unit (or lithosome) C–D. The C–D unit is up to 15 m thick and is present in the entire northern margin of the basin except of its easternmost peripheries where it laterally passes into the other selenite and gypsum microbialite units (Figs 2–4). A thin layer of clastic gypsum–clay deposits in the middle part of unit C–D is traced across nearly the whole basin (e.g. at Ozeriany and Podillia, north of the study area, and at Palahychi and Odaiv, south and SE of the study area; Fig. 3; Babel 2005a, On-Line Appendix, fig. 17). This layer is apparently isochronous or nearly so, which suggests that the whole unit C–D was deposited roughly in the same time interval (Peryt 2001). This clastic marker bed was not found in the study area where mainly the lowermost part of unit C–D crops out.

Southwest of the study area, in the foredeep zone, the Badenian evaporites (mostly halite facies and thin-bedded calcium sulphates with clay intercalations) were recognized both within and below the allochthonous Sambir unit (Figs 2 & 3); however the precise time correlation of these evaporites with the gypsum sections from the platform zone is controversial. Available data indicate that no traces of the selenite facies were found in this zone (e.g. Smirnov *et al.* 1995), although core sections from sulphate evaporites in the vicinity of the halite field near Drohobych show traces of oriented selenite crystals and lithostratigraphical sequence the

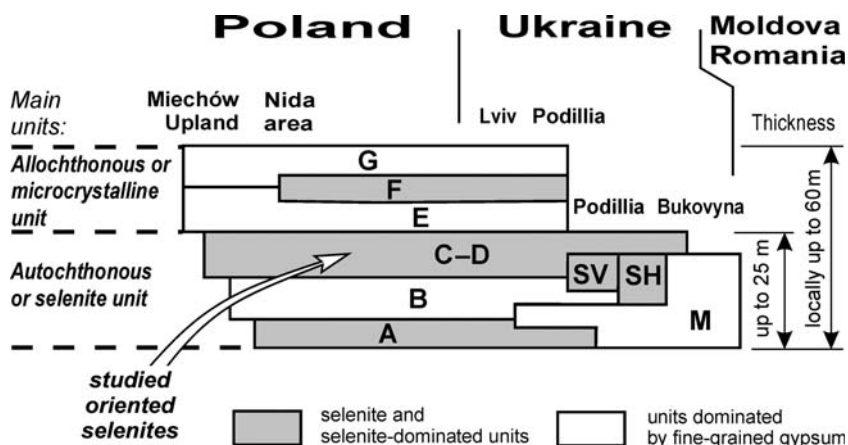


Fig. 4. Lithostratigraphy of the Badenian gypsum evaporites in the northern margin of the Carpathian Foredeep along the correlation line from the Miechów Upland in Poland to Bukovyna in Moldova and Rumania; see Figures 2 & 3 (after Kubica 1992; Babel 2005a).

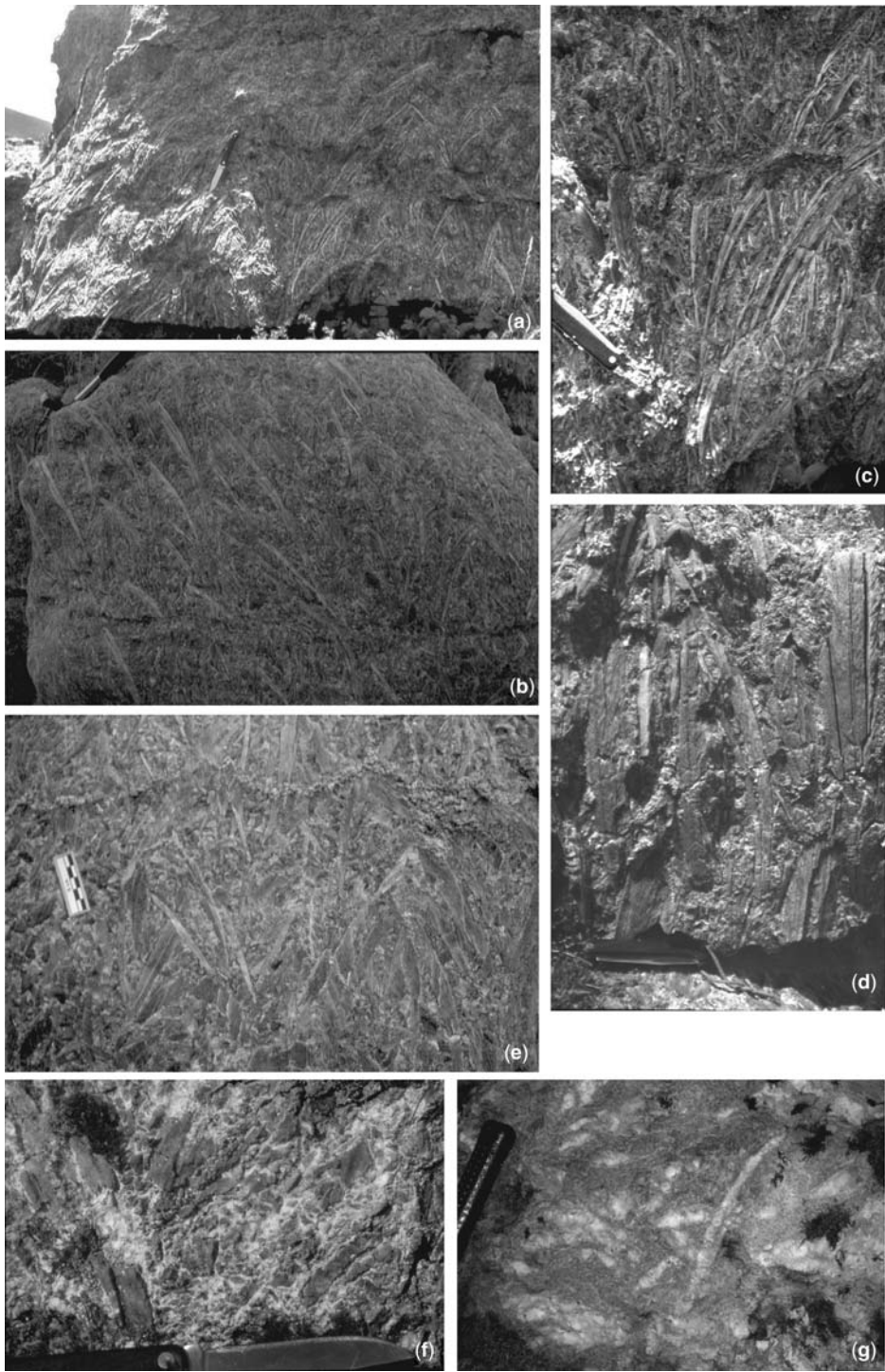


Fig. 5. *Continued.*

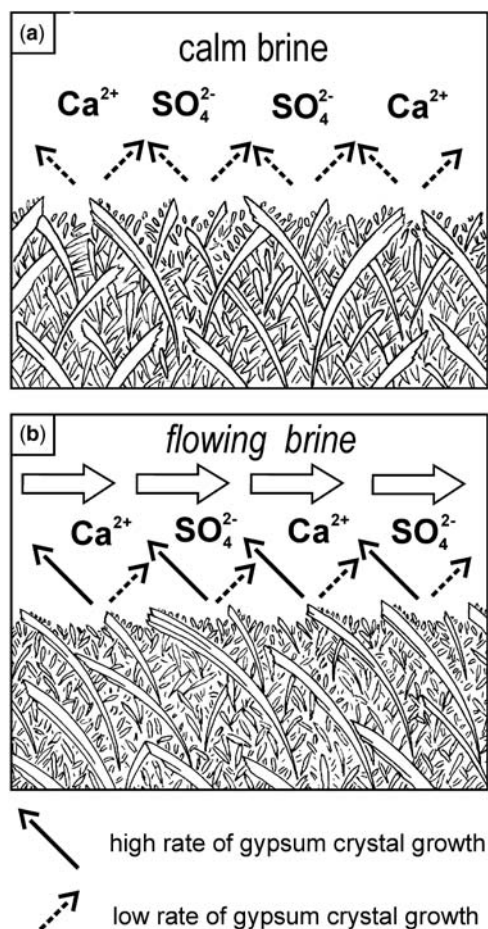


Fig. 6. Scheme showing competitive growth of gypsum crystals at the bottom of evaporite basin: (a) in calm brine; (b) in flowing brine.

same as in the platform area (Fig. 2; Kasprzyk 1995; Kasprzyk & Ortí 1998, fig. 3).

Closer to the study area, c. 20 km SSE of Kalush, the halite evaporites were found at about 1.5 km depth in the foredeep area and were recognized as Badenian in age (Korenevskiy *et al.* 1977, fig. 69). The evaporite section from Hrynivka-12 borehole (Fig. 3), apparently not corrected for dip, comprised (from the bottom to the top): a 12 m

thick layer of anhydrite, a 18 m thick layer of rock salt, a 6 m thick layer of anhydrite, a 66 m thick layer of rock salt and a 16 m thick layer of anhydrite (Panow & Plotnikow 1996). This section is similar to the core sections from the five other halite facies fields in the autochthonous foredeep zone in Ukraine, which are recognized as Badenian in age, although most probably only the upper parts of these thick evaporite sequences are age equivalents of the Badenian gypsum on the platform zone (see Figs 2 & 3; Ladyzhenskiy & Antipov 1961, p. 225; Burov *et al.* 1971, fig. 12; Petrychenko *et al.* 1994, fig. 2; Petrichenko *et al.* 1997, fig. 9; Peryt 2006).

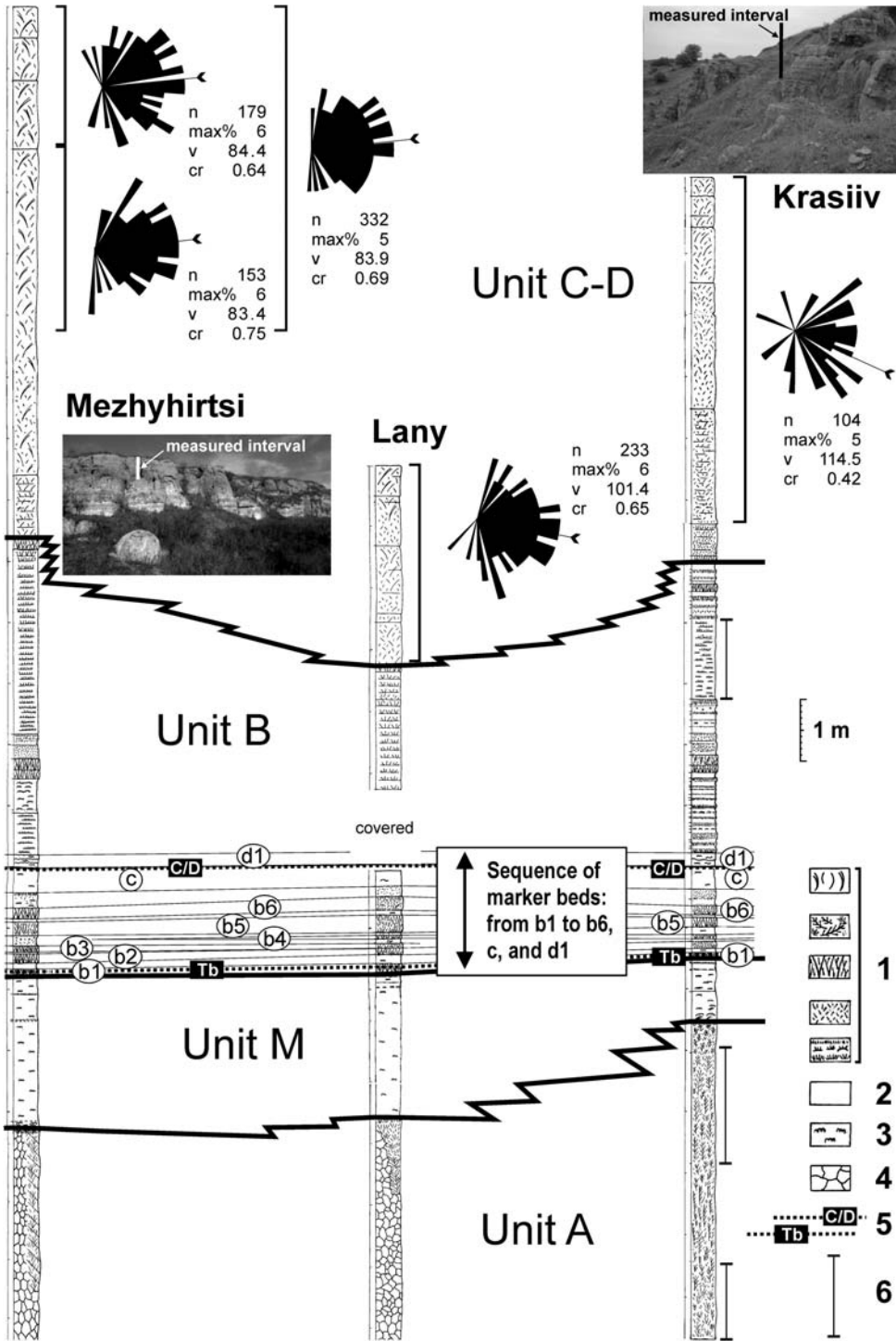
Summarizing, the available data suggest that selenite deposition, abundant at the studied edge of the platform zone, did not take place in the adjacent foredeep zone where the halite deposition was commonly associated with clay and took place in some deeper depressions or subbasins.

Method and results of measurements in the environs of Halych

The palaeocurrent analysis in this area of the Carpathian Foredeep basin is based on the directional structures occurring in the whole of unit C-D and formed by selenite crystals with the apices directed in a similar horizontal direction (Fig. 5; Babel *et al.* 1999; Babel & Becker 2006, with references). The asymmetric crystal fabric was interpreted as the product of competitive growth of gypsum crystals on the bottom, modified by their more rapid growth in one horizontal direction, towards the inflowing brine (Fig. 6; Dronkert 1977, 1985, p. 205; Pawlikowski 1982; B. C. Schreiber 1982 in Folk *et al.* 1985; Babel 2002; Babel & Becker 2006, with references). The largest crystals, with their apices turned horizontally in the same direction (upstream), representing the winners in the competitive growth, are palaeocurrent indicators.

The measurements were collected from intervals of the section usually 2 m thick. In three localities measurements were made separately in the lower and upper part of the strata to reveal the possible change of the brine flow in time (Figs 7 & 8). The azimuths of the apices of the large oriented crystals were measured statistically not only in outcrops of

Fig. 5. (Continued) Studied oriented selenite deposits: (a, b) selenite beds showing upstream oriented crystals at Lany (a), and Krasiv (b), Ukraine, compare with Figure 6b; (c) detail of (a) showing aggregates of splited crystals; (d) selenite crystal seen from its side view (at centre), with {010} cleavage surfaces parallel to the picture, and the crystals seen from the side of the curved surface, with {010} cleavage surfaces normal to the picture (at left and right); Lany, Ukraine; (e) variable oriented crystals presumably growing in a calm brine (see a); the wavy bedding surface (at top) is a dissolution surface; Krasiv, Ukraine; (f) relics of the primary selenite crystals in secondary alabaster deposits, Hannusivka, Ukraine; (g) ghosts of the primary selenite crystals in secondary alabaster deposits, Voynivliv, Ukraine.



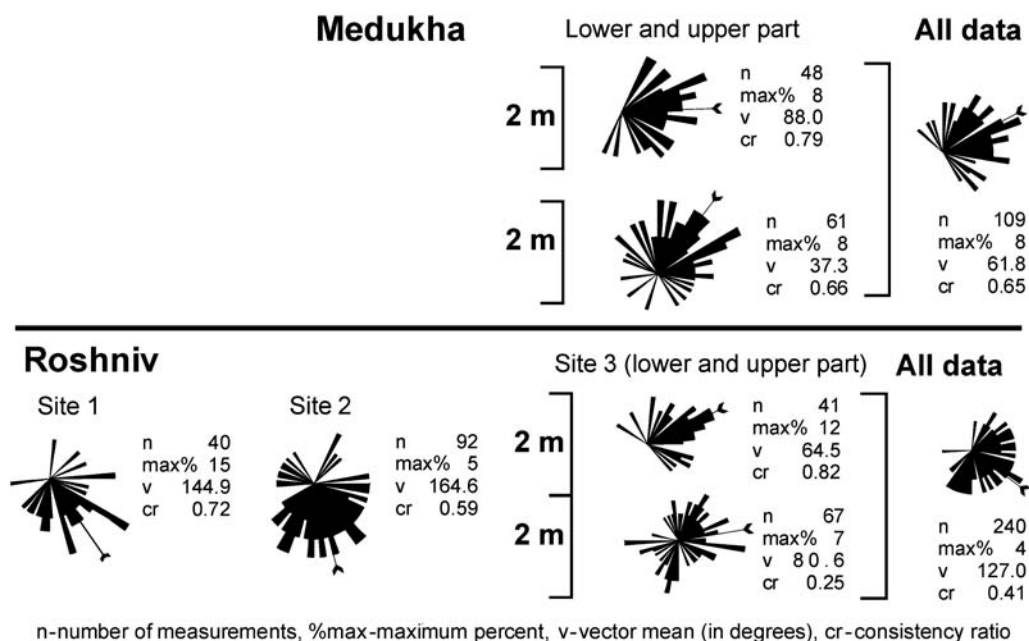


Fig. 8. Rose diagrams showing orientation of apices of curved selenite crystals, unit C-D, at Medukha, Ukraine, and from four different sites at Roshniv, Ukraine (at Roshniv the measurements include relics and ghosts of primary crystals).

primary gypsum facies but also in outcrops of secondary alabaster facies (at Voinyliv, Hannusivka and Roshniv; Fig. 5f & g). In the latter outcrops both relics and ghosts of crystals were measured.

Measurements were subjected to classical statistical analysis used in palaeocurrent studies (Potter & Pettijohn 1977). The statistical data are documented in Figures 7–10, and can be interpreted in the same manner as in the earlier studies (Babel *et al.* 1999; Babel 2002; Babel & Becker 2006). Mean vectors were recognized for particular groups of measurements and for grouped data and they were interpreted as parallel to the average brine flow.

The measurements made in the lower and upper gypsum layer at Mezhyhirsy showed nearly the same mean vectors, although the shapes of the rose diagrams and consistency ratio values were slightly different (Fig. 7). The upper layer showed broader span of the azimuths than the lower one. The results suggest that the average flow direction did not change during deposition of the oriented selenites

at Mezhyhirsy although brine flow could be more dispersed in the later stage of gypsum crystallization.

The measurements made in the lower and upper layer at Medukha showed a different orientation of mean vectors, suggesting that the average flow direction changed with time (Fig. 8), and shifted clockwise about 50°. Shapes of rose diagrams and consistency ratio values suggest that the flow directions were more uniform during deposition of the upper layer.

The measurements in the lower and upper layer at Roshniv suggest a similar brine flow direction (Fig. 8). However because of the poor preservation of the primary gypsum crystals, systematic data collection throughout the whole bed was not possible; thus at this site the results are not conclusive.

Palaeocurrents at the environs of Halych

The measurements revealed great uniformity of the orientation of the gypsum crystals within the

Fig. 7. (Continued) Correlation of studied gypsum sections at Mezhyhirsy, Lany, and Krasiv, Ukraine (compare Figs 3 & 4), with location of measured intervals and rose diagrams showing azimuths of selenite crystal apices; top of marker bed c as datum. 1, Bottom-grown gypsum crystals creating variable grass-like structures; hachure reflects arrangement of crystals (for details see Babel 2005a, On-Line Appendix); 2, fine-grained homogeneous gypsum; 3, fine-grained gypsum with traces of gypsified crenulated microbial mats; 4, secondary alabaster with homogeneous or nodular structure; 5, isochronous surfaces (after Babel 2005a); 6, poorly exposed part of the section. Other explanations: see Figures 8 & 10.

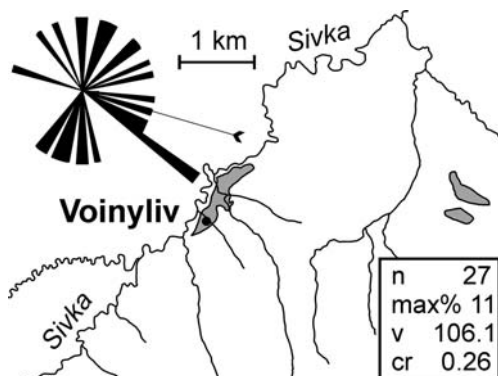


Fig. 9. Rose diagram showing orientation of ghosts of primary curved selenite crystals at Voinyliv, Ukraine (Fig. 3). Badenian gypsum deposits exposed at the surface are shadowed; after Atlas Geologiczny Galicyi (1885–1914). Further explanations see Figures 8 & 10.

studied area. This indicates that the brine in the environs of Halych flowed very uniformly from east to west (Figs 9 & 10). At Hnil'tse, however, the brine flowed from the north to the south apparently because of the presence of some local islands, peninsulas or shoals which disturbed the uniform flow.

The results suggest that during crystallization of the selenite unit C-D the brine flowed *en mass* from east to west in the study area. It apparently formed a broad stream a few tens of kilometres wide moving to the west. The results from Voinyliv (Fig. 9), a few kilometres north of the Kalush fault zone coinciding with the supposed land barrier separating the north from south area of the basin drawn by Aleksenko (1967, 1969), suggests that the brine flowed further west, sub-parallel to this hypothetical barrier (Figs 2 & 3). However the number of measurements is too small and consistency ratio too low for any sure determination of the brine flow direction. If the result is correct the presence of such a barrier in the environs of Kalush cannot be excluded.

The mean vectors from localities east of Halych indicate a swirl or rotary pattern as if the real brine streamlines were arcuate (Fig. 10). Such a pattern is very similar to the large-scale water swirls observed in the modern basins particularly to water swirls formed within separate subbasins where the water tends to flow parallel to the isobaths and shoals (e.g. Csanady 1978). This swirl pattern suggests that the brine, on average, flowed into the study area from SE and then gradually changed the direction of flow into east–west. At Hannusivka the brine flow direction again turned WSW, directly toward the central basin areas (Figs 2 & 10). This

brine could flow further into the zone of halite deposition in the environs of Hrynivka (Fig. 3; Korenevskiy *et al.* 1977, fig. 69; Panow & Plotnikow 1996), apparently not being disturbed by any land barrier crossing the basin in this area as proposed by Aleksenko (1967, 1969). The results from Hannusivka are exceptional; it is the only place in the whole basin where the direct brine flow towards the halite facies was detected (see Bąbel *et al.* 1999).

Problem of brine flow into the halite zone

The results from Hannusivka suggest that the calcium sulphate saturated brine flowed over the selenite bottom toward some presumably deeper area in the basin centre where selenite deposition was not recorded. Such deposition should, however, took place there at least from time to time, assuming the downslope flow of brine evidently capable of selenite crystallization.

The nature of the recorded brine currents and hydrography of the selenite area of the basin were originally interpreted by Bąbel & Becker (2006). Their interpretation omitted, however, the transitional zone between the selenite and deeper halite part of the basin and, in particular, the reasons for the disappearance of selenite deposition towards the central halite facies areas, and this requires explanation.

To explain the absence of the selenite facies in the halite areas of the Badenian basin we suggest that these areas were permanently stratified, i.e. they were meromictic subbasins during the time of the oriented selenite crystallization. They were deep enough so that persistent bodies of brine existed, separated from the upper moving and mixing water masses by a permanent pycnocline, at the bottom. These bottom brines remained unmixed with the surface water and the pycnocline acted as a 'virtual bottom'.

During the unit C-D deposition the brine inflowing from the marginal sulphate zone into the halite area was thus moving over the permanent pycnocline (cf. Ahrensbrak 1974). Inflowing into the halite area these waters lose contact with the bottom and being deflected from it they flowed further, along the pycnocline, in a way similar as the so-called mesopycnal flows known from the studies of turbidity currents (see Last & Schweyen 1983, p. 259; Rimoldi *et al.* 1996; Mulder & Alexander 2001). The inflowing brine could mix partly with the brine below similarly conditions known in the Dead Sea (Stiller *et al.* 1997). In spite of being oversaturated with calcium sulphate, the horizontally flowing brine was not able to promote the growth of selenites simply because it was not in contact with the basin floor.

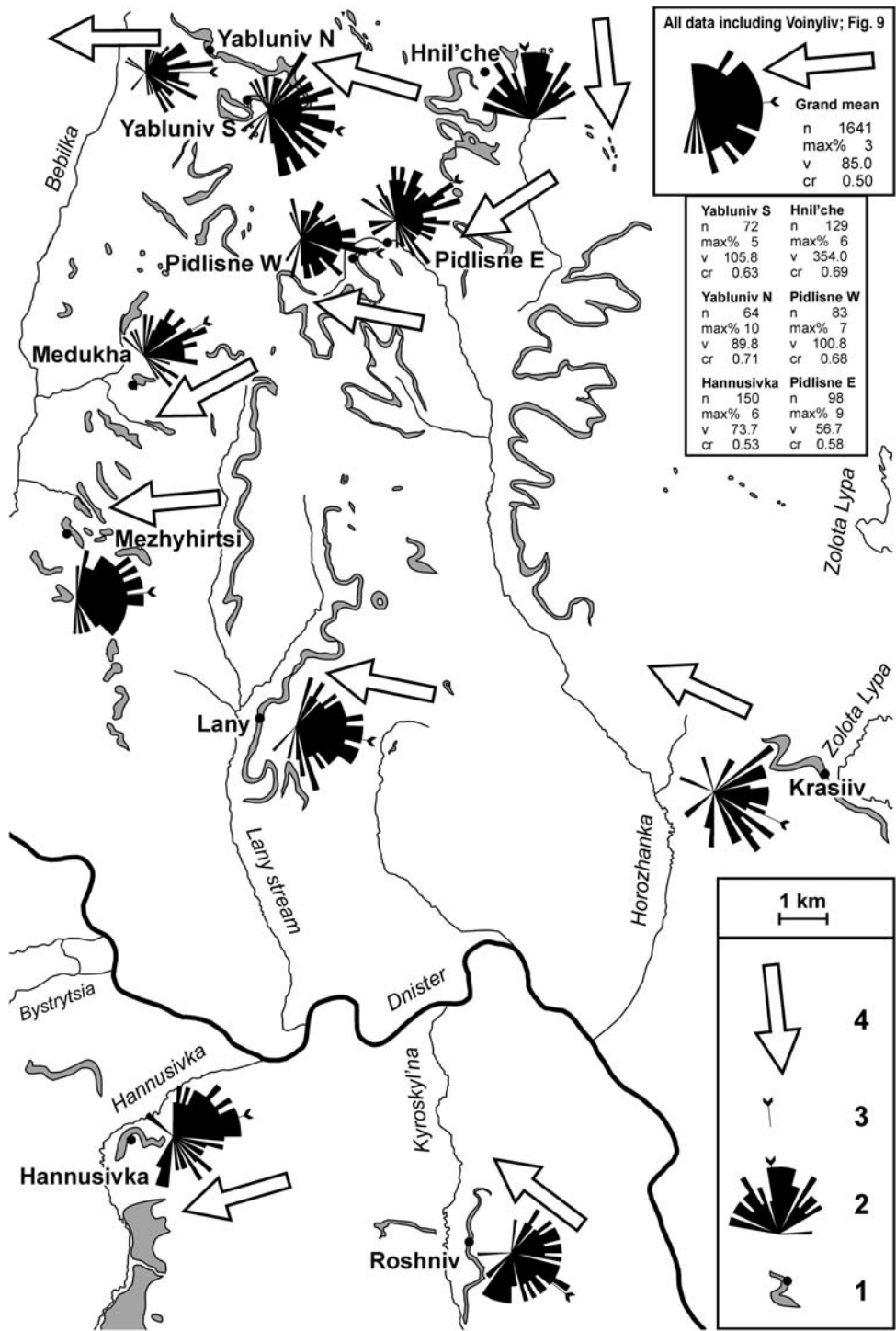
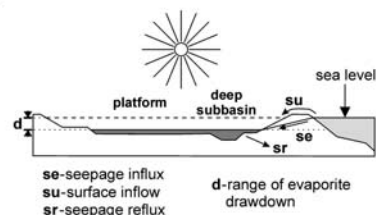


Fig. 10. Palaeocurrents indicated by oriented selenite crystals from unit C-D in area west of Zolota Lipa in Ukraine (Fig. 3); measurements at Hannusivka and Roshniv include relics and ghosts of primary crystals. 1, Badenian gypsum deposits exposed at the surface (shaded; after Atlas Geologiczny Galicyi 1885–1914) and locality studied (pointed); 2, rose diagram of the azimuth of the gypsum crystal apices; 3, mean vector of the measured azimuths; 4, interpreted brine flow direction; further explanations in Figure 8.

(a) Salina-type basin with marginal platform



(b) stratification

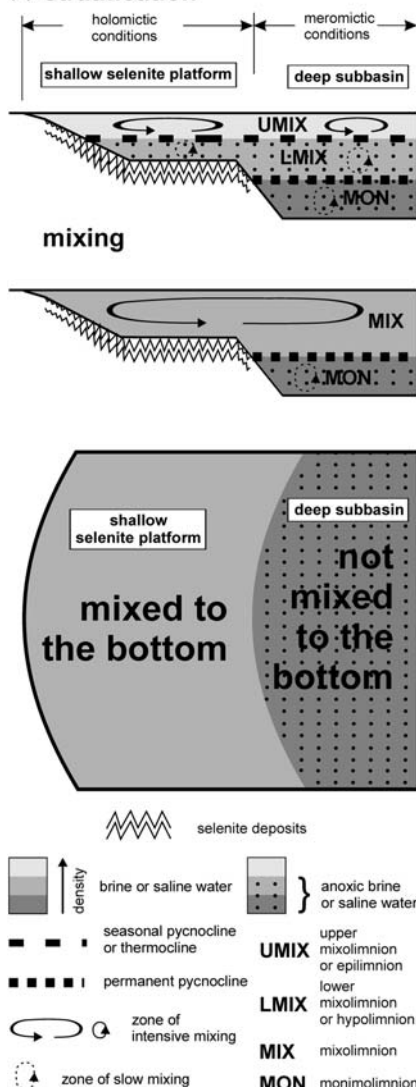


Fig. 11. Model of the Badenian evaporite basin. (a) Scheme showing basic features of the basin; (b) hydrographical features of the meromictic (selenite) evaporite basin during stratification-mixing cycle (scheme is showing the northern part of the Badenian basin; further explanations in the text).

The concept outlined above is developed below into a more universal hydrographical model of the deep permanently stratified (i.e. meromictic) evaporite basin. The model is presented first, and then it is applied to the geology of the Badenian basin and discussed.

Hydrographical model of the meromictic evaporite basin

To construct an applicable model, and reconstruct the hydrography of the Badenian basin, actualistic data from hydrography of the modern meromictic freshwater and saline lakes were used. They were integrated with the fossil record from the Badenian basin, as well as with the previous hydrographical interpretation of the marginal selenite zone of the basin (Babel & Becker 2006). The model is similar to the meromictic selenite basins discussed by Babel (2004a, pp. 242–243) and mentioned by Warren (2006, p. 350). A related model was described by Valero-Garcés & Kelts (1995).

According to limnological terminology (Hutchinson 1975; Lewis 1983) in the meromictic basins the deepest water body or zone which is not affected by seasonal vertical mixing is called monimolimnion (Fig. 11). Owing to high concentrations of dissolved ions (or, in some cases, dispersed solids) this deep water is denser than the overlying mixolimnion, defined by the greatest depth reached by mixing of surface waters. The transition zone between mixo- and monimolimnion is defined by a gradient in dissolved solids and is called a chemocline (see Hutchinson 1975, p. 480; Ludlam 1996, p. 116). Because the model concerns evaporite basins with the stratified brine bodies showing pronounced vertical density gradients a chemocline is here described as a permanent pycnocline (as in the Dead Sea and some other basins; Neev & Emery 1967; Miller *et al.* 1993). As recommended by Hutchinson (1975, p. 537) and Lewis (1983), the mixolimnion can be described according to the terminology of holomictic basins, i.e. basins completely mixed down to the bottom at least once a year. Mixolimnion can be subdivided into the upper warmer epilimnion, metalimnion with the seasonal thermocline, and the lower colder hypolimnion. The terms epi-, meta- and hypolimnion, as originally defined in lakes of temperate zone, in many cases do not fit to the evaporite basins and saline lakes in the arid and tropical zones. In such basins the surface waters are commonly colder than the waters below the seasonal thermocline which shows the temperature gradient reverse than in temperate zone. Therefore the mixolimnion is here described differently than suggested by Hutchinson (1975). The average, relatively thin

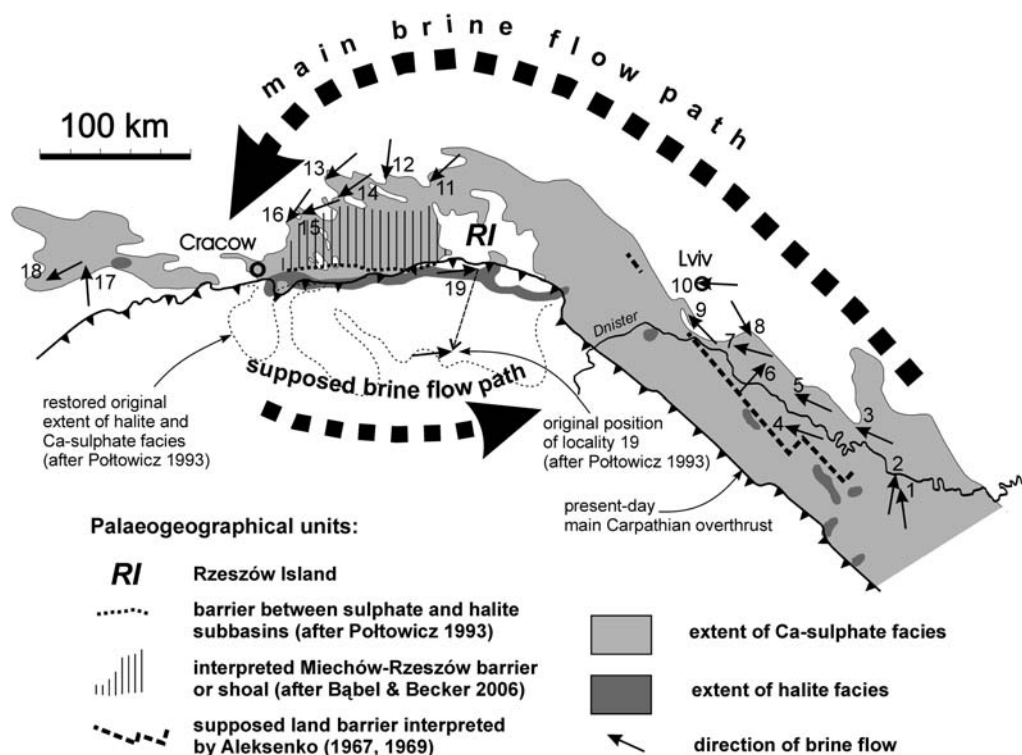


Fig. 12. Mixolimnetic brine palaeocurrents recorded in the Badenian (Middle Miocene) evaporite basin of the northern Carpathian Foredeep reconstructed from orientation of bottom-grown gypsum crystals (after Bąbel & Becker 2006). Localities: 1, Verenchanka; 2, Kostryzhivka; 3, Holovchyntsi; 4, Oleshiv; 5, Krasiiv (see Figs 7 & 10); 6, Podillia; 7, Zahirochko; 8, Pidkamin'; 9, Schyrets'-Pisky; 10, Lviv; 11, Piaseczno; 12, Staszów; 13, Chwałowice; 14, Siesławice; 15, Działoszyce; 16, Koscejów; 17, Czernica; 18, Kobeřice; 19, Broniakówka.

mixed layer, being an equivalent of epilimnion in temperate lakes, which tends to follow the annual regional temperature changes, is called the upper mixolimnion, the layer below it, defined by the maximum depth of mixing, the lower mixolimnion (Fig. 11). The intermediate zone between the upper and the lower mixolimnion can be described by a seasonal thermocline because temperature is most commonly responsible for seasonal stratification. For simplicity it is assumed that this thermocline roughly coincides with the seasonal pycnocline. In many basins the stratification of mixolimnion is more complex and the upper and the lower mixolimnion can be distinguished only arbitrary or the mixolimnion subdivided into the other pattern of zones.

The model basin contains stratified brines forming three distinct zones which can be described as follows (from the bottom to the top; see the simplified scheme in Fig. 11): (1) monimolimnion enclosing the densest brines showing constant temperature and salinity; (2) pycnocline

(chemocline) which shows density gradually decreasing up; and (3) mixolimnion where density, salinity, and, in particular, temperature change seasonally, as well as in smaller time periods. The mixolimnion is subdivided into lower and upper zone and the average seasonal thermocline (or some average seasonal pycnocline) is the boundary between these zones. The mixolimnion is mixed down to the permanent pycnocline at least once a year and then mixolimnetic waters are fully homogenized.

Modern analogues for the basin model and its mixolimnion

Assumed seasonal stratification-mixing pattern of the mixolimnion (Fig. 11), driven mostly by annual cycle of air temperature changes, is common and characteristic feature of all the modern meromictic basins, both freshwater and saline ones (Table 1). Also in the permanently

Table 1. Exemplary meromictic basins showing seasonal stratification of mixolimnion (with a few exceptions where the data were lacking) and comparative data for thickness of water zones

Name and location of the basin	Salinity	Mixolimnion, mixing character	Mixolimnion, structure, depth (m)	Chemocline-pycnocline, depth (m)	Monimolimnion, depth (m)	References	Notes no.
Berkeley pit lake, Montana, USA	FS	Supposedly dimictic	EPI (0–10), THER (10–15), HYP (15–60)	40–60	60 to >250	Gammons & Duaime 2006; references in Boehrer & Schultze 2006	
Big Soda Lake, Nevada, USA	S	Monomictic	For 1933: EPI (0 to 5–19), THER (5–19), HYP (5–19 to 20). For 1980s: HYP (5–19 to 34.5)	1933: <i>c.</i> 20; In 1980s : <i>c.</i> 34.5	1933: 20–60; In 1980s : 34.5–60	Kimmel <i>et al.</i> 1978; Cloern <i>et al.</i> 1983 <i>a, b</i> ; Zehr <i>et al.</i> 1987	1
Crawford Lake, Ontario, Canada	FS	Dimictic	EPI (0–4), THER (4–8), HYP (8 to 13–16)	13–16	16–24	Dickman 1985	
Deadmoose Lake, Saskatchewan, Canada	S		MIX (0–8)	8	8–48.10	Last & Slezak 1986; Last 1994; Last & Ginn 2005	2
Dead Sea, Israel–Jordan–Autonomous Territory of Palestine	S	Monomictic	UMIX (0 to 15–20), THER (15–25), LMIX (15–25 to 40)	40–100	100 to >350	Neev & Emery 1967; Oren & Shilo 1982; Gertman <i>et al.</i> 2003	3
Faetteville Green Lake, New York, USA	FS	Dimictic	EPI (0–2), THER (2–6), HYP (6–29)	29–40	40–51	Anderson <i>et al.</i> 1985; Thompson <i>et al.</i> 1997; Suits & Wilkin 1998	4
Freefight Lake, Saskatchewan, Canada	S		UMIX (0–3), THER (3), LMIX (3–6)	<i>c.</i> 6	6–24.92	Last 1993, 1994; Last & Ginn 2005	5
Isabela Crater-Lake, Mexico	S	Supposedly monomictic	UMIX (0–2.5), UPYC (2.5–4.5), LMIX (4.5–12)	LPYC (12–13)	13–17.5	Alcocer <i>et al.</i> 1998	6
Lac Pavin, France	FS	Dimictic	EPI (0–10), THER (10–20), HYP (20–60)	60–70	70–92	Aeschbach-Hertig <i>et al.</i> 2002	
Lake Bogoria, Kenya	FS		MIX (0–6)	<i>c.</i> 6	6–11.5	Renaut & Tiercelin 1994	17
Lake Cadagno, Switzerland	FS	Dimictic	UMIX (0 to 7–8), THER or UPYC (6–8); LMIX (7–8 to 10–12)	8–15.5	15.5–21	Del Don <i>et al.</i> 2001; Tonolla <i>et al.</i> 2004	
Lake Goitsche (mine pit lake), Germany	FS	Dimictic	EPI (0–11), THER (<i>c.</i> 11), HYP (11–27)	<i>c.</i> 27	27–31	Boehrer & Schultze 2006	
Lake Fouthiaux (mine pit lake), France	FS		EPI (0–5), THER (5–10), HYP (10 to 20)	20–25	25–37	Denimal <i>et al.</i> 2005	

Lake Kauhako, Moloka'i, Hawaii, USA	S		UMIX (0–1), THER (1–2), LMIX (2 to 3–5)	4–4.5	4.5–248	Donachie <i>et al.</i> 2004	17
Lake La Cruz, Spain	FS	Monomictic	For 1987–1988: EPI (0 to 5–10), THER (5–10 to 10–15), HYP (10–15 to 18–19)	18–19 to 21	21–24	Rodrigo <i>et al.</i> 2001, fig. 1; Romero <i>et al.</i> 2006	
Lake Malawi (Nyassa), Tanzania–Mozambique–Malawi	FS	Monomictic	UMIX (0 to <40) THER (<40 to >80), LMIX (220–230 to >250–300)	c. 250–300	300–706	Eccles 1974; Reynolds <i>et al.</i> 2000; Branchu <i>et al.</i> 2005; Fillippi & Talbot 2005	18
Lake Mary, Wisconsin, USA	S	Dimictic	EPI (0 to 1–4), THER (1–4), HYP (1–4 to 5–9)	5–9 to 11	11–21.5	Weimer & Lee 1973	7
Lake Sonachi, Kenya	S		UMIX (0–1), THER (1–2), LMIX (2 to 3–5)	3–5	5 to c. 8	MacIntyre & Melack 1982; Njugund 1988; Verschuren 1999	8
Lake St Louis (mine pit lake), France	FS		EPI (0–5), THER (5–15), HYP (15 to 20–22)	20–22 to 28	28–60	Denimal <i>et al.</i> 2005	
Lake Tanganyika, Tanzania–Zambia–Zair–Burundi	FS	Presumably monomictic	UMIX (0 to 40–50), THER (40–50), LMIX (40–50 to 100–250)	100–250	250–1471	Reynolds <i>et al.</i> 2000	18
Lake Vähä-Pitkusta, Finland	FS		MIX (0 to 17–23)	17–25	25–35	Hakala <i>et al.</i> 2004; Hakala 2005	17
Lake Zige Tangco, Amdo Caunty, Xizang Autonomous Region, China	S		UMIX (0–8), LMIX (8–22)	21–22	22 to c. 38	Li & Li 2004	9
Mahoney Lake, British Columbia, Canada	S		UMIX (0–1), UPHYC (1–2), LMIX (2 to 6–7)	6–10	10–18.3	Northcote & Hall 1983; Overmann <i>et al.</i> 1996; Lowe <i>et al.</i> 1997	10
Medicine Lake, South Dakota, USA	S		MIX (0 to 3.5–4.5)	3.5–4.5	4.5–9	Valero-Garcés & Kelts 1995, table 2; Valero-Garcés <i>et al.</i> 1995	11
Mono Lake, California, USA	S	Monomictic	EPI (0 to 10–20), THER (10–20), HYP (10–20 to 14–28)	14–28	28 to c. 45	Jellison & Melack 1993; Miller <i>et al.</i> 1993, p. 1044	12
Pao-Cachinche reservoir, Venezuela	FS	Monomictic	EPI (0 to 2–4), THER (2–7), HYP (7–10)	PHYC and MON (10–20)	PHYC and MON (10–20)	González <i>et al.</i> 2004	13
Piaseczno reservoir (mine pit lake), Poland	FS	Dimictic	EPI (0–4.5), THER (4.5–7.5), HYP (7.5–15)	c. 15	15–21.8	Wilk-Woźniak & Żurek 2006	

(Continued)

Table 1. *Continued*

Name and location of the basin	Salinity	Mixolimnion, mixing character	Mixolimnion, structure, depth (m)	Chemocline-pycnocline, depth (m)	Monimolimnion, depth (m)	References	Notes no.
Pretoria Salt Pan, South Africa	S		MIX (0–0.55)	c. 0.55–1.00	1.00–2.85	Ashton & Schoeman 1988; Ashton 1991	14
Soap Lake, Grant County, Washington, USA	S		EPI (0 to 6–8), THER (c. 6–8), HYP (6–8 to 17)	c. 17	17–25	Edmondson & Anderson 1965; Walker 1974	
Waldsea Lake, Saskatchewan, Canada	S	Dimictic	UMIX (0–2), THER (2–3), LMIX (2–3 to 6–8)	6–8	6–8 to 14.8	Swanson & Hammer 1983, p. 155; Last <i>et al.</i> 2002	15
West Basin Lake, Victoria, Australia	S		MIX (0 to 4–11)	4 to 10–11	10–11 to 13	Timms 1972; Last & De Deckker 1990	16

S, saline basin; FS, freshwater or slightly saline basin; EPI, epilimnion; THER, thermocline (or metalimnion); HYP, hypolimnion; MIX, mixolimnion; UMI, upper mixolimnion; LMI, lower mixolimnion; CHEM, chemocline; PYC, pycnocline; UPYC, upper pycnocline; LPYC, lower pycnocline; MON, monimolimnion.

Notes: 1. 'The mixolimnion has an annual cycle of mixing comparable to a cold monomictic lake, with thermal stratification from spring through autumn and near-complete turnover in winter' (Zehr *et al.* 1987, p. 783).

2. The mixolimnion exhibits seasonal thermal stratification (Last & Slezak 1986, p. 7).

3. Meromictic before 1979, in 1980–1982 and 1992–1995. Brine zones interpreted from figure 32 in Neev & Emery (1967).

4. Interpreted from summer profile (Anderson *et al.* 1985, fig. 9).

5. 'The mixolimnion is thermally stratified during the ice-free season with a thermocline located at about 3 m depth' (Last 1993, pp. 435–436).

6. Thin 'epilimnion' is produced by rain. Water zones interpreted from description by Alcocer *et al.* (1998).

7. Thermocline position interpreted from figure 2 in Weimer & Lee (1973).

8. Meromictic during high lake level in 1969–1979; at that period the mixolimnion showed the seasonal thermocline at depth 1–2 m (in January–February 1979; Njuguna 1988, fig. 4); 'the low lake level ($Z_{\max} = 5$ m) prevailing since 1985 currently prevents chemical stratification from persisting year-round, with deep wind-driven mixing most likely to occur during the dry-season lowstand in February–March' (Verschuren 1999, p. 115). A shallow daily thermocline is present within mixolimnion.

9. Water zones interpreted from description by Li & Li (2004).

10. Arbitrary interpretation based on spring stratification (Northcote & Hall 1983, p. 192). Depth after Overmann *et al.* (1996). Mixolimnion shows complex stratification and bias from 'normal' dimictic pattern of mixing due to influence of ice cover.

11. 'Although Medicine Lake possesses a permanent chemocline, the bacterial plate forms in a temporary chemocline at the lower part of the mixolimnion, which evolves during the year in response to changes in amount of rainfall and temperature' (Valero-Garcés *et al.* 1995, p. 257).

12. Meromictic in 1983–1988 and after 1995.

13. Water zones interpreted from figure 2 in González *et al.* (2004).

14. Note possibly one of the thinnest natural mixolimnions.

15. Position of the thermocline in spring. Mixolimnion shows complex stratification due to influence of ice cover (see Northcote & Hall 1983, p. 192).

16. 'The mixolimnion stratified during summer and as it cooled in autumn the lake became mesothermal and finally by winter the temperature profile was inverted' (Timms 1972, p. 918).

17. Lack of data on seasonal stratification pattern in mixolimnion.

18. In large lakes (like Malawi, Tanganyika) 'the depth and thickness of seasonal thermoclines are often difficult to determine from temperature profiles alone: solute content (including gases) is generally more reliable guide to vertical integration or to the lack of it' (Reynolds *et al.* 2000, p. 5).

stratified Black Sea, the shallow seasonal (summer) thermo-, halo- and pycnoclines develop under influence of cyclically (annually) changing air temperature, river flow, precipitation, evaporation, over the permanent deeper thermo-, halo- and pycnoclines, the position of which depends on the intensity of the general cyclonic circulation of surface waters (Titov 2005). Among the saline lakes, the monomictic stratification-mixing pattern of mixolimnion was observed by Neev & Emery (1967) in 1959–1960 in the Dead Sea which showed meromictic hydrography at that time. Neev & Emery (1967) used their own terminology for description of the lake hydrography. According to the terminology accepted in this paper, and by Steinhorn *et al.* (1979), and Steinhorn (1985), in the Dead Sea in 1959–1960 a permanent pycnocline was at depth 40–100 m (and was less sharp towards the bottom) over deep monimolimnion extending down to over 350 m. Mixolimnion was fully mixed in early winter (December–January) and stratified in the rest of the year, with the most pronounced seasonal thermocline showing gradually lowering tendency with time (from April to September) at depth of 15–25 m (Neev & Emery 1967, fig. 32). Such monomictic pattern of mixing was also recorded in 1980–1981 within much thinner mixolimnion at that time (Oren & Shilo 1982; Anati & Stiller 1991; Anati 1997). Many other meromictic saline lakes show the monomictic mixolimnion, stratified mostly on the temperature basis (Table 1). Because monomixis is typical of the tropical warm zone (Lewis 1983), it is very likely that the mixolimnion of ancient meromictic evaporite basins in the warm and arid zones was also monomictic (as in the Dead Sea). Saline meromictic lakes situated in a temperate and cold zone commonly show dimictic mixolimnion (Table 1).

In some cases and particularly in temperature zone stratification-mixing pattern in the mixolimnion of saline lakes is more complex. Saline lakes seasonally covered with ice commonly show temporary multiple stratification patterns in the mixolimnion (Northcote & Hall 1983; Ludlam 1996; Overmann *et al.* 1996). Small meromictic saline lakes with a shallow permanent pycnocline (a maximum of a few metres from the surface) appear to not show the seasonal stratification-mixing cycle in the mixolimnion (Kirkland *et al.* 1983; Ashton & Schoeman 1988), although certainly their mixolimnion exhibits some temporary or daily stratification (MacIntyre & Melack 1982). Any saline lake can develop such a temporary stratification after rain, due to inflow of the fresh waters covering the lake surface.

A stratification pattern similar to those from stratified stage in the model basin (Fig. 11) exists

persistently in some deep fiords separated from the sea by a bottom barrier (Ross *et al.* 1993, fig. 1).

Features of mixolimnion in the Badanian basin

The hydrography of mixolimnion in the Badanian basin was characterized by Babel & Becker (2006, figs 8 & 9). The brine was maximum of a few metres deep and the observed regular millimetre-scale growth-zoning of the selenite crystals suggests that such a shallow basin was monomictic (Babel & Becker 2006, figs 3f, 9 & 11). The mixolimnion was thus stratified in one, presumably wet, period of the year and fully mixed down to the bottom during the dry period (Fig. 11). It was further assumed that the enhanced crystal growth could take place at the bottom of mixolimnetic zone only during the period of mixing, because only during this period could the bottom brine be fully oxygenated (due to mixing) and highly oversaturated with calcium sulphate (due to increased evaporation). Just at that time the growing selenites obtained the oriented fabric which reflected the *en masse* flow of brine on the whole margin zone of the basin. During the stratification period the growth of selenites was slowed or arrested because the bottom brines were separated from the atmosphere by some seasonal pycnocline and were not subjected to evaporation that is considered as the main driving force of the gypsum crystal growth. Moreover, during and particularly at the end of stratification period, the lower mixolimnion could develop seasonal anoxia (Fig. 11; hypolimnetic anoxia; Horne & Goldman 1994; Babel & Becker 2006, fig. 10), and hence the brines could be temporarily stripped of sulphate due to the activity of sulphate-reducing bacteria. The concentration of SO_4^{2-} ions could be too low for the crystallization of gypsum at that time.

As in many modern basins, the stratification of mixolimnion was presumably caused by annually changing environmental factors influencing the surface brines, such as air temperature, precipitation, rate of evaporation or even marine brine inflow to the basin, like in the Solar Lake on Sinai, where the inflow is dictated by the annually fluctuating mean water level of the Red Sea (Cohen *et al.* 1977). All these factors acting separately or together could influence the surface waters producing a seasonal thermocline and/or pycnocline in the mixolimnion.

Most probably the mixolimnion was seasonally stratified on a thermal basis (Neev & Emery 1967) and in the summer its upper layer was warmer (and lighter) than its lower layer. During winter this stratification could disappear and the whole

mixolimnion could show uniform temperature, salinity and density, down to the permanent pycnocline.

The other possibility is that mixolimnion was stratified in the wet season due to increased inflow of some less saline water into the basin (from run-off, rain or rivers) associated with lowered evaporation rate, when the layer of less saline water could appear floating at the more saline brine below. During the dry season the surface layer could partly evaporate and could be fully mix with the underlying brine (more precisely, at the end of the dry and the beginning of the wet season, because of some lag time necessary for generating the full mixing of the brine).

Modern analogues for the Badenian basin and its palaeocurrents

Babel & Becker (2006) inferred that the Badenian oriented selenites recorded the mean direction of the brine flow in a given place (Figs 5 & 6), apparently some average value from a relatively long period of time necessary for the growth of gypsum crystals (possibly hundreds of years for a gypsum stratum 1 m thick). The pattern of mean vectors was compared with the average flow pattern observed in lakes which is called the circulation or mean drift, although these terms were commonly attributed to the surface flow (see references in Babel & Becker 2006). The mean vectors represent only the flow pattern from the periods of the Ca-sulphate saturation of the bottom brine, because only during such periods could the gypsum crystals grow and could be influenced by the brine current.

Results of all the measurements throughout the entire basin margin, including the study area, strongly suggest counterclockwise (cyclonic) brine flow around the basin shoreline (Fig. 12; Babel *et al.* 1999; Babel & Becker 2006). This general reconstruction is in agreement with the observed pattern of water flow (circulation or mean drift) in nearly all the closed and semi-closed basins of the northern hemisphere (Emery & Csanady 1973; references in Babel & Becker 2006). The cyclonic circulation was present only in the surface mixolimnetic zone of the basin, down to the permanent pycnocline (Fig. 11). The monimolimnion could show the other unknown pattern of flows and presumably was more stagnant.

Among modern meromictic lakes showing the same circulation pattern as the Badenian basin, the best analogue is the Great Salt Lake (Utah). It is remarkably large and shallow (a water depth fluctuated and attained *c.* 12.5 m in 1873, and *c.* 8.5 m in 1963; Cohenour 1968). The lake brine

composition is very similar to that of the seawater and approaches salinity over 300‰. Brine density ranges between 1.104 and 1.221. The Great Salt Lake from 1959 to 1991 was meromictic (Great Salt Lake Planning Team 2007, <http://www.ffsl.utah.gov/sovlands/GreatSaltLake/resource-fal.PDF> Lin 1976). The deepest central parts of the lake, in the southern basin, below about 7–8 m depth, remained unmixed, while above the permanent pycnocline periodic mixing still occurred. The bottom brines below 7–8 m (monimolimnion) remained unmixed even during winter storms (Stephens & Gillespie 1976) when the wind waves can be over 2.7 m high and seiche waves 0.5–1 m high can flood the shores (Cohenour 1968; Lin & Wang 1978). The pattern of beach spits and bars in the Great Salt Lake indicates that the surface waters circulated along the shores predominantly counterclockwise, exactly as the case of the Badenian evaporite basin (Figs 10–12; Cohenour 1968; Butts 1980).

A similar meromixis and circulation as in the Badenian basin was recently documented in the southern Aral Sea. The water in the 25 m deep Chebotarev Bay below 8 m remained unmixed during annual cycle (Friedrich & Oberhänsli 2004). The mixolimnion showed predominantly cyclonic circulation (Zavialov *et al.* 2003).

The persistent cyclonic circulation of the slightly saline surface waters over the more stagnant and saltier bottom waters is known also from semi-closed basins connected with the ocean like the 34 m-deep Lake Maracaibo, Venezuela (Laval *et al.* 2005), or the Black Sea (Titov 2005).

The other partial analogue of the Badenian basin is a 4 m deep meromictic salt pond, Lago Pueblo in Venezuela (Sonnenfeld 1984; and references in Babel 2004a), where thin gypsum crusts are deposited exclusively in the uppermost 0–1 m deep mixolimnion and gypsum deposits are absent in the anoxic monimolimnion below. Medicine Lake in USA is the next example (Table 1). Thin gypsum crusts, equivalents of selenites, were found there in the littoral zone and gypsum laminites produced by precipitation within the water column in the whole deeper zone (Valero-Garcés & Kelts 1995). Finally, wind-driven cyclonic flow of mixolimnetic brines over the unmixed monimolimnion was recorded in the Pretoria Salt Pan (Table 1; Ashton 1991).

Modelled basin and the Badenian monimolimnion

The monimolimnion of deep meromictic basins is typically anoxic (Fig. 11) and its brine properties are constant or, strictly speaking, change extremely slowly with time (e.g. Anderson *et al.*

1985). Crystallization of evaporite salts in the monimolimnion is difficult and very complex because the crystallization cannot be directly driven by evaporation (but can be driven by some temperature changes or by salting-out mechanisms; Last & Ginn 2005). In particular, crystallization of calcium sulphate (gypsum and anhydrite) within the monimolimnion is very difficult when it is anoxic. The monimolimnion of sulphate basins is commonly euxinic (showing sulfidic anoxia). It accumulates large amounts of hydrogen sulfide by bacterial reduction of SO_4^{2-} ions if sufficient organic material is available. Crystallization of gypsum in such an environment, showing the lowered concentration or lack of SO_4^{2-} ions, is not or is barely possible (it was recorded, e.g. in Freefight Lake, Canada; Table 1). Gypsum can, however, precipitate in the brine column over the euxinic monimolimnion for several reasons, such as (1) direct evaporation and concentration rise in the surface mixolimnetic brine, (2) 'salting-out' effect during mixing of brines showing different composition and (3) temperature changes of the saturated solution. Such precipitation within the brine column can produce suspension clouds of tiny gypsum crystals and these crystals can be periodically deposited as a rain of particles settling through a brine column and producing laminated deposits (cumulates) at the bottom in the monimolimnion zone, similarly to the meromictic Dead Sea (Neev & Emery 1967; Heim *et al.* 1997) and many other lakes listed by Valero-Garcés & Kelts (1995, p. 141) including Medicine Lake studied by them (Table 1).

The model suggests that the selenite deposition (*in situ* growth of large gypsum crystals at the bottom) is restricted to the better oxygenated mixolimnion zone, where the concentration of SO_4^{2-} ions is high at least seasonally (Fig. 11). The depth limit for selenite deposition coincides with the maximum depth of the surface brine mixing. Some authors suggested that the gypsum crystallization in evaporite basins is limited to the photic zone where the photosynthetic activity of cyanobacteria supply the oxygen and thus support the existence of SO_4^{2-} ions (Sonnenfeld 1984). This model relates the limit for selenite deposition to a depth and intensity of physical mixing of surface waters which are oxygenated both by photosynthesis and direct diffusion from the air (see Babel 2004a). Thus it is rather related to the external environmental and climatic factors, like wind, fetch, etc., which influence the thickness of mixed layer.

A typical feature of monimolimnion is that it contains a fossil water or brine which is older in age than the water in the mixolimnion above (e.g. Walker 1974, p. 215; Steinhorn *et al.* 1979). The monimolimnetic water is commonly a product of

evaporation pre-dating the present stage of the basin, sometimes even the events not directly related to the evaporation (like the brines from dissolution of the Messinian evaporites filling up the deep depressions of the Mediterranean; Cita 2006). It is possible that such fossil monimolimnetic brines can show substantial differences in the chemical composition in comparison with the mixolimnion above (as in the Mediterranean; references in Cita 2006).

The meromictic basin model clearly explains the lack of selenite deposits in the deep central areas of the Badanian basin (Fig. 11). They could not be deposited in the monimolimnion zone because of two main reasons: (1) sulfidic anoxia and associated low concentration or lack of SO_4^{2-} ions (in similar fashion to the model outlined by Parea & Ricci-Lucchi 1972, fig. 5b); and (2) separation from atmosphere and the environment of evaporation – a necessary condition and main reason for the concentration and rise in salinity required for the rapid crystal growth.

Geological data from the Badanian basin can support this interpretation. Laminated, organic, clay and fine-grained clastic deposits typical of the monimolimnion zone (e.g. Anderson *et al.* 1985) occur in the central zone of the Badanian basin (Kasprzyk & Orti 1998). Anoxia in the halite depositional zone was suggested by Garlicki (1979). Laminated calcium sulphate deposits are very common in the basin centre. They could be deposited by settling from the water column from some suspended clouds of fine sediment generated by slumps, storms or low-density turbidity currents (Peryt 2000; Kasprzyk 2003). They are mostly clastic deposits derived both from basin margin or slope and from *in situ* redeposition, as evidenced by common washout surfaces and slump folds. These structures, as well as numerous soft-sediment deformations, indicate that the laminated calcium sulphate deposits remained loose and unlithified at the bottom, although in places they could be partly consolidated or cemented (Peryt 2000). They were rarely subjected to syndepositional cementation by gypsum or anhydrite, which can mean that the bottom was rarely in the long-term contact with the calcium sulphate saturated to oversaturated brine. The brine over the bottom could become undersaturated with calcium sulphate because it was impoverished in SO_4^{2-} ions due to anoxia. There are evidences of the syndepositional and early diagenetic *in situ* growth of calcium sulphate nodules directly at the bottom and within some laminae (Kasprzyk & Orti 1998; Kasprzyk 2003), which can suggest that some oxygenated sulphate brines from the surface layers reached the bottom promoting the growth of gypsum or anhydrite crystals (cf. Beyth 1980).

Concepts of brine transport in evaporite basins; a discussion

The concept of the meromictic basin and the data gained from palaeocurrent studies throw some new light into the hydrodynamics of brine both in the Badenian and other similar evaporite basins. This application of hydrodynamics has been commonly understood and described by traditional concepts omitting or ignoring the possibility of persistent brine stratification. Some of these concepts are discussed below and addressed with the new approach.

Coriolis effect and cyclonic flow

The reconstruction presented here is similar to the model of lagoonal evaporite basin considered by Sonnenfeld (1974, 1975, 1984 and other papers) who assumed that Coriolis force influences the stream of marine water inflowing through the narrow strait to the basin and forces the cyclonic flow along the shores of basin. In his evaporite lagoon the marine water makes only one open circle within the basin. It evaporates on its way along the shores and gradually becomes a marine brine that finally flows out of the basin as the bottom current through the same strait (in the similar way as the bottom brine current once flowed the Lynch Strait in the Dead Sea; Neev & Emery 1967, fig. 35).

The brine circulation in the Badenian basin is interpreted differently than in Sonnenfeld's model. In particular, the detected brine flow directions do not reflect the inflow path of the marine water or marine brine to the Badenian evaporite basin (Fig. 1). The brine circulation was similar to those present in most lakes which means that the brine made not an open but a closed circle, flowing more or less continuously along the basin shores and above the permanent pycnocline in the deep basin centre (Figs 11 & 12).

The presented view, if correct, strongly suggests that the oriented selenite facies should be present along the entire path of brine flow and thus, consequently, that such selenites also crystallized on the hypothetic southern Carpathian margin of the basin destroyed by erosion after tectonism (Fig. 12). The presence of such a facies continuity, however, is documented only in one place in Poland (locality 19, Fig. 12) and is unrecognized in Ukraine.

'Saturation shelf' concept

Sonnenfeld (1974, 1975, 1984, 1992) adopted the concept of 'saturation shelf' proposed by Richter-Bernburg (1955) to his evaporite lagoon model

and assumed that the flat marginal platforms covered by flowing marine water were such a shelf ('gypsum shelves'; Sonnenfeld 1984, p. 41). 'Flowing over the shallow coastal shelves, the surface waters are warmer and evaporate faster as they encounter dry winds from land and receive more radiation per unit of depth' (Sonnenfeld 1984, p. 41). These 'sunlit shelves act as preconcentrators, as preferred sites of gypsum precipitation' (Sonnenfeld 1992, p. 263). When the flowing waters are 'sufficiently concentrated', they 'veer toward the deeper parts' of the basin (Sonnenfeld 1984, p. 41), commonly being rapidly subsiding grabens (Sonnenfeld 1992). Halite deposition eventually takes place in these depressions, in centre of the basin. The 'saturation shelf' concept was applied for the Messinian and Badenian evaporite basins (Garlicki 1979; Cohen 1993; Połtowicz 1993).

The palaeocurrent analysis in the Badenian basin does not exactly support this concept. Although the brine flow through the shallow marginal sulphate platforms is documented (Fig. 12), any evident traces of the current flowing directly downslope to the halite depositional areas were not detected (Babel *et al.* 1999). Only the data from Hannusivka, documented in this paper, indicate the presence of such a current. Babel & Becker (2006) speculated that perhaps such downflowing brine currents were sporadic and too short events to be recorded by the growing gypsum crystals. They also assumed that the downflow of brines was partly blocked by some shoals or islands at the basinward edge of selenite platforms (Fig. 12); however, it is difficult to accept that such a continuous barrier was present around the whole basin.

Downslope brine transport

Downslope flow of brine was not documented by the palaeocurrent studies in the Badenian basin. This is in contrast with many theoretical concepts concerning the brine transport in evaporite basins which assume that density underflows (downflowing) are very common. The brine transport to the basinal depressions is commonly described as a process exclusively driven by evaporation; when produced by evaporation, increasingly dense surface water sinks down and 'displaces' the less dense bottom water (e.g. Schmalz 1969). It is believed that the dense water, which is produced by evaporation on shoals ('saturation shelves'), flows basinwards as a permanent bottom current accompanied by a surface compensation counter-current flowing towards the shoals and carrying the lighter waters displaced upward by the downflowing brine (Richter-Bernburg 1955, fig. 2).

These concepts are oversimplified and appear to be unrealistic when compared with the real patterns of brine and water transport in the modern basins.

The physical, 'volume by volume' displacement of bottom water by sinking or inflowing surface brine appears to be nearly impossible in deep evaporite basins. Most if not all the modern saline basins show a nearly permanent pycnocline zone existing and separating the bottom dense brines from the surface lighter waters and this does not permit the surface waters to reach the bottom directly. In the Dead Sea the very dense brine produced in saltworks pans operating in the southern shallow subbasin outflowed as a bottom current through the Lynch Strait to the deep permanently stratified (meromictic) northern basin (Neev & Emery 1967; Steinhorn *et al.* 1979). This brine did not reach the deepest zone of the basin. It spread along the pycnocline, or along the deep water layers having the same density as the inflowing brine (see Ahrensbrak 1974), possibly contributing to increased halite crystallization at a depth of 170 m (Stiller *et al.* 1997). This brine continued its flow northward but not downslope. It flowed along the eastern shore in the typical cyclonic way (Neev & Emery 1967).

A persistent, downslope-flowing bottom current accompanied by a surface countercurrent (Richter-Bernburg 1955) is possible in the case of semi-closed shoals connected with the deep basin through some relatively deep strait, like the mentioned Lynch Strait in the Dead Sea (Neev & Emery 1967); however, this is less probable in case of open-type shoals or platforms. It seems that evaporation which produces highly saline and dense water on the open shoals is too slow a process to generate any rapid, permanent downslope density flow because water movements on the shoals are rather generated, and controlled nearly all the time, by much more effective and stronger wind forces (Walker 1982). Certainly evaporation contributes to the pattern of water movements in every evaporite basins; however in nature many forces act on the shallow water and commonly deflect the flow direction rather parallel to the isobaths and shorelines (e.g. Csanady 1978).

Besides the wind, the downslope outflow of brines from the shoals can also be controlled by inclination of the slope, temperature of brine and horizontal temperature gradients in particular. Cornée *et al.* (1992) investigated shallow saltwork pans and found that the more saline and warmer gypsum saturated brine was formed on shoals (0–20 cm deep) and stayed there nearly permanently. Its flow down into the depressions (30–40 cm deep) occupied by less saline and cooler brine was absent or very sluggish. Apparently the horizontal salinity gradient persisted because the density

difference, caused by salinity difference, was compensated by difference in brine temperature (Sonnenfeld 1984, p. 73; Anati 1998). The density difference was too low to cause the rapid downflow of brine on a very gently inclined slope. Similar persistent horizontal salinity and temperature gradients exist in the so-called compensation fronts, from 10 m to 100 km wide (typically 3–4 km), in the 100 m thick mixed layer of the open oceans (Rudnick & Ferrari 1999; Rudnick & Martin 2002). Such fronts persist because seawater mixing dissipate the density gradient in the front without obliteration of the coinciding salinity and temperature gradients which compensate each other exactly. Thus it seems that some sufficient temperature difference between the warmer and more saline waters occupying the basin margin, and cooler and less saline water in the basin centre (as in the saltwork pans; Cornée *et al.* 1992), can indeed inhibit any basinward density flow when the density difference related to salinity difference between such water masses is compensated by this temperature difference. However there is no any data to prove that such a 'compensation' barrier or front was present in the Badanian basin, and on the other hand such a hypothetical front, if ever possible, appears to be only a temporary phenomenon, and downflow of brine to the basinal depressions should take place at least from time to time.

Brine accumulation in meromictic basins

The model presented here suggests a more complex mechanism of brine accumulation in the deep Badanian halite subbasins than formerly assumed (Garlicki 1979; Połtowicz 1993). It was not caused by a downslope flow of dense brine directly to the bottom but rather by its flow into the permanent pycnocline. The brine accumulation could be realized by a series of mixing events at the boundary between mixolimnion and monimolimnion associated with the vertical fluctuations of the permanent pycnocline.

As in the Dead Sea the effective salinity rise in the halite subbasins was probably connected with deeper mixing and thickening of their mixolimnion. Such a deeper mixing in the meromictic Dead Sea was associated with the shallowing which caused the gradual rise in the salinity and density of the mixolimnion up to the level approaching the density of monimolimnion. This destabilizes the permanent pycnocline and permits the deeper mixing of the mixolimnion. The gradual thickening of the more saline and denser mixolimnion was associated with 'erosion' of the monimolimnion which took place rapidly during succeeding five annual mixing periods and culminated with the

complete mixing of the entire water column in 1979 (Steinhorn *et al.* 1979; Steinhorn 1985). The thicker mixolimnion was formed at the expense of monimolimnion. The salinity and density of the thicker mixolimnion rose mainly due to the mixing with the monimolimnion and additionally due to the evaporite concentration (Jellison & Melack 1993). It is thought that such deep mixing events, sporadically culminating in short holomictic (monomictic) periods, took place in the previous history of the meromictic Dead Sea but they have been stopped. A new thinner mixolimnion and a new shallower permanent pycnocline were developed during some years due to extensive inflow of meteoric waters (Oren & Shilo 1982; Steinhorn 1985; Jellison & Melack 1993, p. 1012). Owing to such flooding the monimolimnion contained, after many years of development, 'fossil' layers of various 'ages' recording some past deep mixing events (Steinhorn 1985, p. 460). The deepest layers contained the oldest, saltiest and densest brine.

Halite crystallization in the Badenian subbasins

The effective salinity rise at the bottom of the Badenian halite subbasins, which could eventually initiate the halite crystallization there, presumably required complete mixing, i.e. temporary or permanent transition of the meromictic hydrography into holomixis. One of the reasons for such a transition is shallowing or evaporite drawdown. The shallowing of the meromictic saline basin can change its hydrography into monomixis, as recently it has happened in Mono Lake (Melack & Jellison 1998) and the Dead Sea (Gertman *et al.* 2003). Rapid, massive, halite crystallization at the entire bottom of the Dead Sea started with the monomixis in 1979 and continues with the water level drop and gradual salinity rise in this drying lake (Niemi *et al.* 1997; Herut *et al.* 1998).

If such a scenario for halite deposition in the deep Badenian subbasins is true it means that the halite deposits in the basin centre could be associated with the shallowing or emersion events on the basin margin and the halite deposition should be preceded by salinity rise of the mixolimnetic brines. Some geological data support such an interpretation for the period connected with the oriented selenite deposition. Indeed, some geochemical evidence (rise in Sr content in selenite crystals; Babel 2007, with references) suggests a gradual salinity increase during deposition of unit C-D, and hence in the presumed mixolimnion in the Badenian basin. However this salinity increase is associated with the deepening rather than shallowing, although gypsum microbialites and traces

of erosion are common at the top surface of unit C-D and suggest such a shallowing (Babel 2005b, pp. 199–200). Traces of dissolved halite were found directly above unit C-D (Fig. 4; Babel 2005b, On-Line Appendix, figs 12a, 13a, 14a & 15b), suggesting the possible halite deposition also in the basin centre just after deposition of unit C-D. This fits to the scenario proposed previously and is in accordance with the former interpretation that the brines from which the halite on the basin margin was crystallized could partly derive from the central subbasins (Babel 2005b, p. 202). As in the drying Dead Sea and Mono Lake, where the beginning of the meromictic–holomictic transition was associated with the deepening of the permanent pycnocline (Steinhorn *et al.* 1979; Anati & Stiller 1991; Jellison & Melack 1993), the Badenian mixolimnion (Fig. 11) could become thicker at the expense of the monimolimnetic brines and hence enriched in NaCl, necessary for halite crystallization, by mixing with these brines, presumably containing a large amount of NaCl.

Implication for stratigraphy of the Badenian chemical facies

The model presented in Figure 11 is appropriate for the conditions of crystallization of selenite unit C-D, when the gypsum and halite subbasins were well connected, but not necessary for the other units. In particular selenite unit A was deposited when the large morphological barriers present in the basin (see Babel 2005b, p. 199; Babel & Becker 2006) could make its hydrography different from the model. According to the model, it is unlikely that during unit C-D deposition on the basin margin the halite could crystallize in the monimolimnion zone in the basin centre (but it could be deposited there after crystallization of that selenite unit). If the interpretation is correct then the oriented selenites correlate with some non-halite deposits in the halite facies areas, most probably with some laminated clay or laminated Ca-sulphate deposits. Such laminated deposits are found directly below, over and within the halite evaporites; however, which of these deposits are the age equivalent of the investigated unit C-D is unknown.

It is likely that during unit C-D deposition the monimolimnion contained some fossil brines from some earlier evaporite events or even from dissolution of some older halite deposits (see Cendón *et al.* 2004; Peryt 2006). Such a view fits the interpretations which assume that the halite deposition at the basin central areas pre-dated the gypsum deposition on the northern margin of the basin (Ladyzhenskyi & Antipov 1961, p. 225;

Burov *et al.* 1971, fig. 12; Petryczenko *et al.* 1994, fig. 2; Petrichenko *et al.* 1997, fig. 9; Peryt 2006).

Conclusions

The distribution of selenite facies along the margin of the Badenian evaporite basin in the northern Carpathian Foredeep, and the lack of selenites in the deeper center of the basin occupied by halite, laminated Ca-sulphate and clay facies, is interpreted as a result of the meromictic hydrography of the basin. Because the basin was presumably isolated from the sea, its hydrography can be compared with the modern meromictic and saline lakes and described by limnological terminology. There were two main brine bodies separated by a permanent pycnocline in the basin: monimolimnion, in the deepest halite areas, and mixolimnion at the surface, extending onto the selenite basin margin. The monimolimnion was or tended to be euxinic and direct evaporative precipitation of salts in it, and selenite crystallization, in particular, was not possible (because of the complete separation from the atmosphere and scarcity of SO_4^{2-} ions which were mostly decomposed by bacterial reduction). Some clastic calcium sulphate was deposited in the monimolimnion zone, mostly by settling from the brine column. The mixolimnion contained calcium sulphate saturated brine. It was seasonally stratified and mixed down to the permanent pycnocline once a year (i.e. it was monomictic as suggested by regular millimetre-scale growth zoning in the selenite crystals presumably reflecting such stratification-mixing cycle in the brine column typical of monomictic basins). During seasonal stratification of mixolimnion the selenite growth at the bottom was slowed or arrested because the bottom brine was not able to evaporate and presumably developed temporary anoxia. Only during the mixing periods was the brine in the entire mixolimnion zone fully oversaturated with calcium sulphate due to direct evaporation. At that time the selenites could grow rapidly but only in the marginal zone of the basin, not in the deeper halite facies zone below the mixolimnion. Currents were common in the mixolimnion whereas monimolimnion was relatively stagnant because it was separated from the flowing surface waters above by a permanent pycnocline. As in the modern basins, the surface mixolimnetic brines showed a dominantly cyclonic pattern of circulation along the basin shores. This average circulation was recorded on the Badenian basin margin by the selenite crystals growing at the bottom. These crystals show the apices turned in the similar horizontal direction which is interpreted as a result of upstream growth in the moving calcium sulphate oversaturated brine.

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