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Evaporites Through Space and Time

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Depositional environments of a salina-type evaporite basin recorded in the Badenian gypsum facies in the northern Carpathian Foredeep

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Abstract: An integrated group of conceptual models for evaporite deposition is presented for a shallow salina-type basin, supplied both with marine and non-marine water, and with a water level separated from and drawn down below world sea-level. Knowledge of, and terminology for, modern limnology is used in these models in order to build a new and more comprehensive link between the hydrography and hydrochemistry of brines and the depositional and stratigraphical record anticipated in such basins. In these modelled basins it is assumed that (as in saline lakes): (1) the evaporite deposition reflects the stratification-mixing cycles in the brine column; (2) the evaporative crystallization of salts culminates during the mixing periods; and (3) the evaporite facies are linked to the position of water zones separated by a horizontal pycnocline. The models are prepared especially for interpretation of subaqueous coarsely crystalline gypsum (selenite) deposition in perennial-to-ephemeral saline pans, and also for fine-grained gypsum deposition (clastic, microbialite and pedogenic) on specific, flat, semi-emerged shoals (majanna-type shoals), commonly flooded by wind-driven brine sheets, in between them. Coarse, crystalline selenites appear to form below the pycnocline and the crystallization of particular well-developed grass-like selenite beds is thought to be connected with the pycnocline highstands. Such beds are both marker beds and ideal datum surfaces. The models presented are used for sedimentological interpretation of the various gypsum facies of the Badenian (Middle Miocene) evaporite basin in the northern Carpathian Foredeep. The observed architecture of these facies suggests that the margin of the basin was occupied by a system of variable saline pans (dominated by selenite deposition) and evaporite shoals (dominated by gypsum microbialite deposition); some of these shoals were majanna-type. Many features of the studied facies can be clearly explained by the models presented, particularly by the rapid and variable fluctuations in water and pycnocline levels incomparable in time scale and size with any global sea-level changes. All these features together consistently suggest that the Badenian gypsum basin was a salina-type basin with a water level below global sea-level, although salts in the basin are/were basically marine in origin.

Evaporite deposition in a shallow salina-type basin (a basin with the water level below world sea-level and supplied by seawater by occasional inflows and/or seepage) is specific. It is controlled by very rapid and large-scale water level changes. The hydrography of brine bodies is comparable to saline lakes. The water and brine chemistry commonly are of seawater composition but some features may become drastically different from it, depending on place in the basin and stage of its evolution.

An integrated group of conceptual models for evaporite deposition in a salina-type basin was introduced in Bąbel (2004a) employing modern limnological knowledge and terminology, building a new and comprehensive link between the hydrography and hydrochemistry of brines and the depositional and stratigraphical record of the formative basin. The basic ideas are the following: (1) the evaporite deposition reflects the stratification-mixing cycles in the brine column; (2) the evaporative crystallization of various salts

culminates during the mixing periods in the basin; and (3) the evaporite facies are linked to the particular stratified water zones, separated by a pycnocline.

These models have been applied for sedimentological interpretation of the various gypsum and selenite facies of the Badenian (Middle Miocene) evaporite basin in the northern Carpathian Foredeep (Bąbel 2004b, 2005a, b). Many features of these observed facies are clearly explained by these models and particularly by the rapid and variable water and pycnocline level fluctuations and by different water levels between subbasins.

This paper partly reviews earlier ideas, but also refines them, adding new concepts supplementing previous interpretations. The functional concepts are outlined and then they are applied to sedimentological interpretation of the Badenian evaporite deposits. These hypotheses, naturally, are open for future corrections, modification or withdrawal whenever the new data does not fit.

Geology of the Badenian evaporite basin in the Carpathian Foredeep

The Carpathian Foredeep Basin is the largest of the several evaporite basins formed in the Carpathian area as a result of the separation of the Central Paratethys from the Mediterranean during the Badenian time (in the Middle Miocene) about 6–8 million years before the well-known Messinian salinity crisis (Figs 1 & 2). The Paratethyan Badenian is a rough equivalent of Langhian–Serravallian and the Badenian salinity crisis took place in Serravallian rather than Langhian (e.g. Oszczyk 2006a; Peryt 2006). The Badenian evaporites comprise mainly calcium sulphate and sodium chloride facies and the most widespread evaporite facies in the northern Carpathian Foredeep are primary gypsum deposits such as bottom-grown gypsum crystals (selenite), gypsum microbialites and clastic gypsum. They crop out along the northern margin of the basin but to the south they are in the subsurface and are commonly transformed into anhydrite (Fig. 2). Halite deposits intercalated with laminated anhydrite and clay occupy the central and southern area of the basin. They are univocally interpreted as deeper facies (Kwiatkowski 1972; Garlicki 1979; Petrichenko *et al.* 1997; Kasprzyk & Ortí 1998; Kasprzyk 2005) in relation to the more shallow marginal sulphate facies (zero to several metres of water). These deposits are largely in the subsurface and the transition between the two facies is not visible. Additionally many details have been obliterated by the processes of calcium sulphate hydration/dehydration (Kasprzyk 2005). Depending of the stage of basin evolution the marginal sulphate area was a platform in relation to the halite basin (Garlicki 1979; Kasprzyk & Ortí 1998), or a shallow subbasin (or chain of subbasins) separated from the deeper halite subbasin by semi-emerged shoals or islands (Bąbel 2005b). These shoals were periodically inundated

and finally entirely covered with gypsum sediments in the later phase of evaporite deposition.

Following some earlier suggestions, it seems that the Badenian gypsum evaporite basin in the Carpathian Foredeep was a depression affected by water-level drawdown below sea-level (Peryt 1996, 2001; Bąbel 2004b). This concept fits, more fully, to the observed geochemical data (Cendón *et al.* 2004) and works well for the event stratigraphic and facies analysis of the evaporite basin (Bąbel 2005a, b). The Badenian gypsum facies are very similar to those recorded in some modern coastal marine salinas (Kasprzyk 1993b). However the Badenian facies show greater differentiation because the basin was larger than any Recent evaporite basin. The understanding and interpretation of these facies over such an extended area require an application of new, comprehensive models.

Concepts for evaporite and selenite deposition in a salina-type basin

The concepts explaining evaporite and gypsum deposition in the basin with the water level drawdown below sea-level are developed below, step-by-step, beginning with the basic features of the model basin and of its hydrography. They are the background for definitive characteristics of the two main sub-environments of the basin: saline pans and evaporite shoals.

Definition of a salina-type basin

Grabau (1920, p. 123) defined a marine salina as 'salt lake or salina near the sea, the water of which is supplied from the sea, not by overwash or canals, as in the case of salt pan, but by underground passages such as seepage through the sand or other material which separates it from the sea'.

The basin model considered for the Carpathian Foredeep basin is that of a salina or salina-type

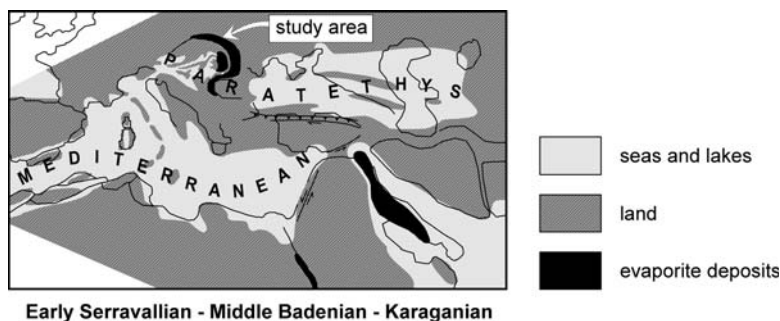


Fig. 1. Palaeogeography of Paratethys and Mediterranean in the Middle Miocene and location of the evaporite basin studied (after Rögl 1998).



Fig. 2. Present distribution of the Badenian evaporite basins in the Carpathian region (after Garlicki 1979; Khrushchov & Petrichenko 1979, modified).

basin (Băbel 2004a, b) because its principal features fit to the marine salina defined by Grabau (1920), avoiding the mixture of definitions employed in many later studies. The basin model employed here is devoted mainly to shallow water subaqueous deposition. The most important factor in this model salina basin is that its water level is drawdown below world sea-level – as in typical coastal salinas (Fig. 3). The model belongs to the wide group of related models known under various names (for reviews see Sonnenfeld 1984; Dronkert 1985; Băbel 2004b). Specific features are extracted from these previous models to define the basin.

The salina basin model assumes that: (1) the evaporite basin is a depression separated from the ocean by some topographical barriers which eliminate the open water connections between the basin and the sea; (2) evaporation is the main reason for water deficit, and for the depressed basinal water level lowering (known as evaporite drawdown), and for its chemical sedimentation; (3) the sea water enters the basin mainly by subsurface seepage, although surface inflows are also possible.

Additionally, it can be assumed that (4) the salina basin is a system of interconnected or temporarily disconnected subbasins or saline pans.

There are many possible variants of a salina basin depending on various parameters, like the shape of the basin, stage of its evolution, and even the chemistry of seawater supplied to the basin, all of which could change through time. The model considered in this paper is applied to the basin at the stage of gypsum deposition from seawater, the same in composition or not too much different from the recent seawater.

Main features of a salina-type basin

The main feature in the basin is its lowered water level, which determines the development of high accommodation and a possibility of the rapid and large water level fluctuations within the basin. The accommodation is limited by mean sea-level which is the upper limit for generating any evaporites from seawater brines ('equilibrium level' of Logan 1987). The resultant spatial accommodation

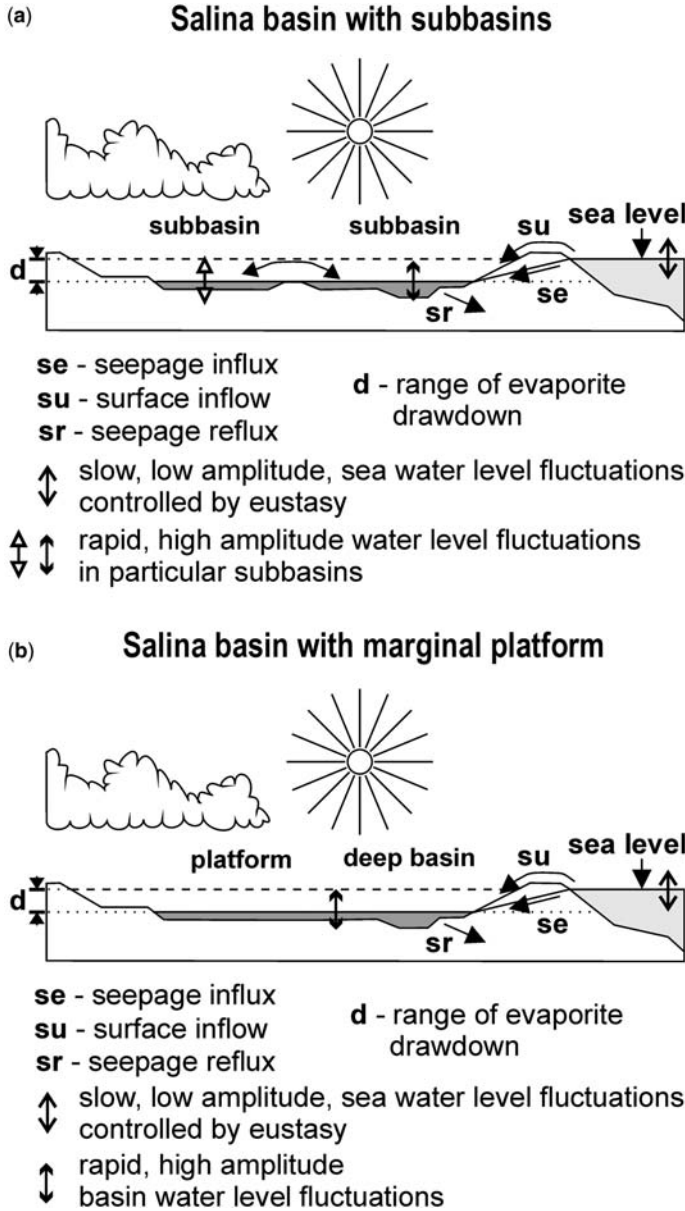


Fig. 3. Schemes showing basic features of a salina-type evaporite basin. Both types of the basin (a and b) can be considered as evolving one into the other in time. Type (b) corresponds to basinal highstand, type (a) to lowstand (see Babel 2004a, fig. 3).

makes deposition of thick sequences pedogenically formed evaporites in the salina basin possible (see Lowenstein *et al.* 2003). The water level fluctuations are the most important for the depositional dynamics, sequences and architecture within the basin. In a salina basin they are dependent on particular local parameters, like regional climate,

seepage inflow and outflow rates, tectonics and sediment supply (see Logan 1987; Strecker *et al.* 1999; Ilgar & Nemec 2005). As in modern coastal salinas, the water level fluctuations are similar to those observed in saline lakes. The intrinsic feature of all the salina-type and salt lake basins is that their water level is unstable and always

fluctuates, rising and falling over various time periods that are commonly irregular (Langbein 1961; Jauzein & Hubert 1984; Williams 1996; Comín *et al.* 1999). Additionally, a salina-type basin can be rapidly flooded by marine water, and pass through an abrupt evaporite drawdown after disconnection from the sea.

In most recent salt lakes the annual rise and fall of the water level is variable (Anati 1997) and always fluctuates seasonally, annually, and over longer time periods. This fluctuation is dictated mainly by climatic changes (Comín *et al.* 1999). Such dramatic fluctuations are not observed in freshwater lakes that usually show relatively stable water levels (Langbein 1961; Scholz *et al.* 1998). The depositional environment of a salina-type basin is very similar to those of salt lakes or closed basins, although some specific differences are also present. The architecture of depositional sequences in a shallow-water salina basin is similar to the so-called underfilled lake basins (Caroll & Bohacs 1999; Bohacs *et al.* 2000). Variable water level fluctuations can produce both shallowing- and deepening-upwards sequences, as

well as deepening- and brining-upwards sequences. The latter sequences appear to be barely possible in lagoonal evaporite basins with the water level coinciding with the sea-level (Babel 2004b).

Among many possible environments of the salina basin, two main ones are discussed below: perennial and ephemeral saline pans (or subbasins), and evaporite shoals (as defined in Babel 2004a), which are particularly important for analysis of the Badenian evaporites (Fig. 4).

Hydrographical classification of saline pans

Saline pans are, for practical purposes, lakes showing more or less persistent water stratification which can be permanent, seasonal or temporary depending on many parameters like climate, size and shape of the pan (fetch), depth and salinity. Following limnological and hydrographical terminology the pans can be subdivided on the basis of the frequency of the periods of complete mixing per year (Fig. 5; Lewis 1983) into: (1) meromictic

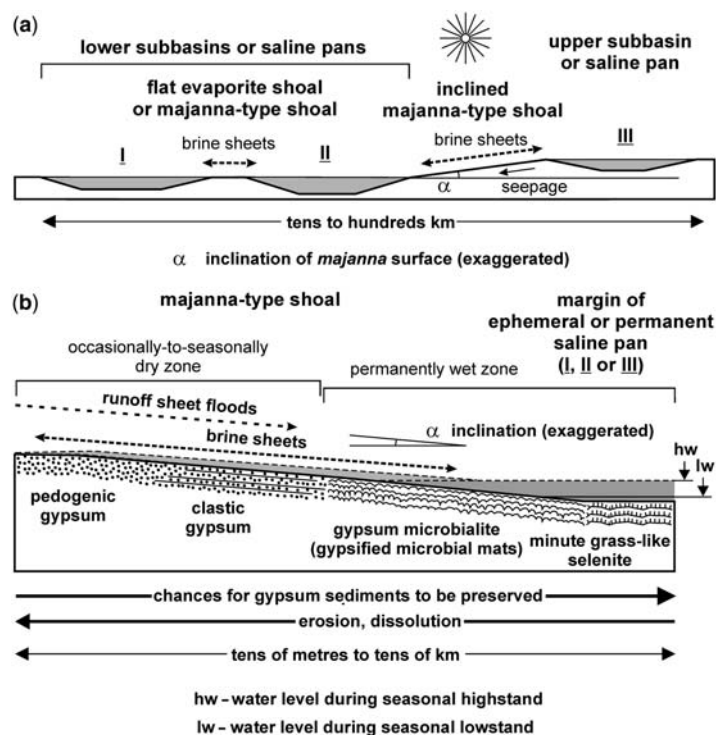


Fig. 4. Schemes showing basic shallow-water depositional environments in a salina-type basin (Fig. 3; partly after Friedman & Krumbein 1985; Logan & Brown 1986; Logan 1987). (a) Saline pans or subbasins and majanna-type evaporite shoals; (b) depositional environment of the majanna-type shoal (a). Vertical sizes and angles exaggerated. Detailed explanations in the text.

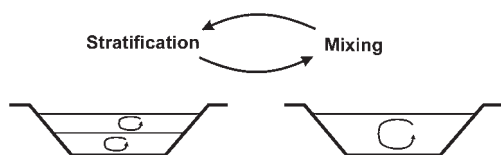


Fig. 5. Simplified scheme showing basic stratification-mixing cycle in a closed basin.

pan, which are permanently stratified (see Babel & Bogucki 2007, for more details); and (2) holomictic pans, which undergo complete mixing up to the bottom during the annual cycle (Hutchinson 1975). The latter ones can be subdivided into subordinate types depending on the frequency of complete mixing periods per year; from monomictic pans which show alternately stratification and mixing once a year, through discontinuous polymictic pans which mix more than once a year at intervals of days to weeks, to continuous polymictic pans which mix daily or without interruption (Lewis 1983, 2000).

The limnological classifications adopted here are mainly applied to freshwater lakes and are based on the seasonal thermal variations observed in lakes, namely on the frequency of periods per year when conditions of isothermia are reached in the whole water column due to complete vertical mixing of waters during circulation or de-stratification period (e.g. Ambrosetti *et al.* 2003). In the saline lakes or pans only the homogenization of all the water properties (temperature, salinity and density, where the first two parameters basically determine the third one, e.g. Anati 1997; and the water chemistry) is indicative of the full mixing (Anati & Stiller 1991), and the mixing processes are more complex than in freshwater systems. Therefore the classification adopted here is a further simplification of classification by Lewis (1983), set up for the purpose of closed saline basin modelling and study. The term 'pycnocline' is used to designate the interface of the two water bodies density stratified on the basis of salinity and/or temperature (similar to the approach adopted by Del Don *et al.* 2001).

Stratification-mixing phenomena and their cyclicity are crucial for evaporite deposition in the saline pans. It is known from study of many saline lakes and coastal salinas that precipitation of evaporite minerals is strictly linked to particular zones within stratified water masses separated by a pycnocline and to particular periods during the stratification-mixing cycle (Krumbein & Cohen 1977; Niemi *et al.* 1997; Kirkland 2003; Torfstein *et al.* 2005; and references in Babel & Bogucki 2007). In this outline the author focuses his consideration of evaporite deposition in saline pans

on the large bottom-grown crystals which are one of the most characteristic subaqueous Ca-sulphate evaporite facies.

Selenite deposition in saline pans

Of the many varieties of subaqueous precipitates, one of the most common are crusts or layers of *in situ* grown crystals. It is well known that they grow from well-mixed supersaturated brines and, most commonly, in very shallow brine, up to a few metres deep (e.g. Smoot & Lowenstein 1991). Such deposits are typically composed of vertically elongated, large crystals, which in a case of gypsum are known as 'selenite'. The <5 m depth limit for such selenite deposition was suggested by Schreiber (1978), based on observations of many recent environments and ancient deposits, and it was later tentatively extended down to 10–20 m, but without any firm example from the geological record (Schröder *et al.* 2003, p. 884; Babel 2004a) (perhaps gypsum crusts crystallizing at depth of 18 m in the hypersaline Gotomeer basin, island of Bonaire, Netherlands Antilles, can be such an example; Kobluk & Crawford 1990). The reasons for such a depth limit are largely related to the hydrography of stratified brines.

Complete brine mixing (i.e. de-stratification) associated with evaporite concentration of calcium sulphate is the most effective for the accelerated growth of selenite crusts at the bottom of saline pans (Fig. 6, centre; Warren 2006). During stratification periods the selenite growth at the bottom, below the pycnocline (see Fig. 6, top), cannot be promoted directly by evaporation. The waters below the pycnocline cannot evaporate because they are separated from the atmosphere (Sloss 1969). In the deep brine below the pycnocline anoxia can develop, because oxygen is utilized by decomposition of settling dead plankton and other organic debris, and consequently sulphate ions necessary for gypsum precipitation can be removed by sulphate-reducing bacteria. Therefore the selenite crystal growth is hardly possible at the bottom of saline pans during long-term stratification periods, although the crystals can grow below the pycnocline due to temperature changes in the saturated solution or some other effects, like the 'remnant supersaturation' of Stiller *et al.* (1997, p. 182).

The bottom-growth selenites cannot grow by evaporation of surface brines at the bottom of the permanently stratified meromictic basins (commonly deep and highly saline) although they can grow in the upper water mass over the permanent pycnocline (see Babel 2004a; Babel & Bogucki 2007). The selenites grow at the bottom of shallow to moderately deep holomictic saline

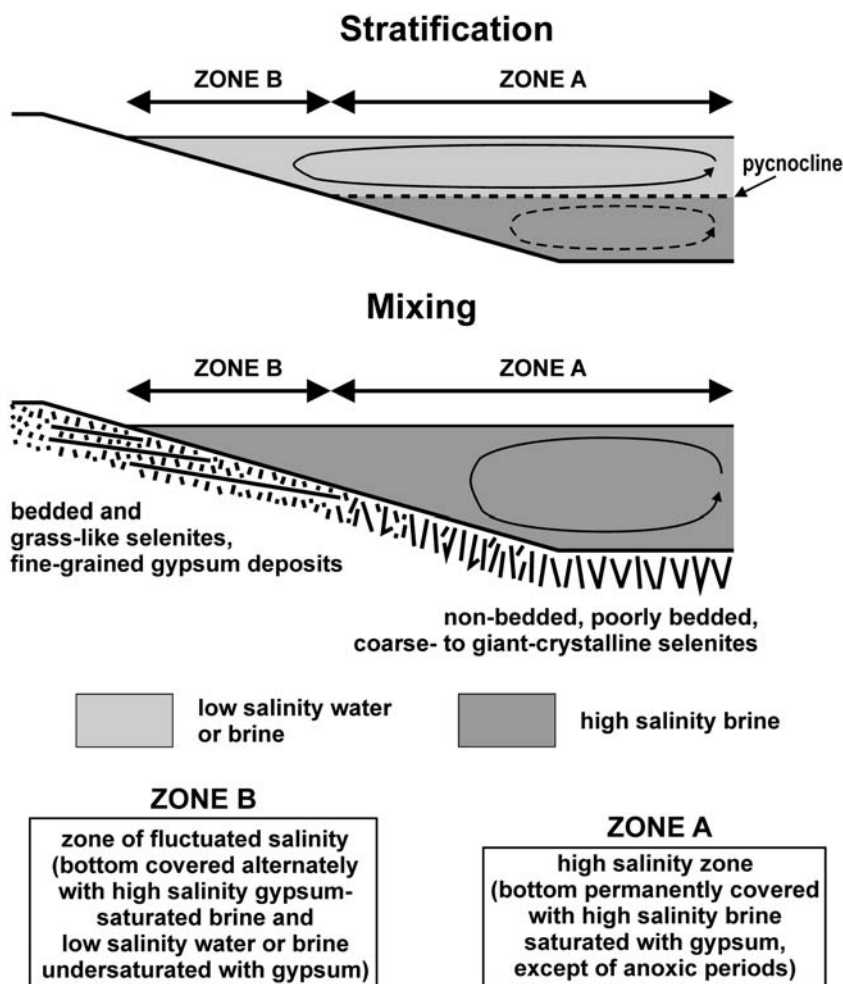


Fig. 6. Depositional model for selenite deposition in a saline pan (Fig. 4a) within a salina-type basin (Fig. 3). Detailed explanations in the text.

pan: monomictic or polymictic, depending on frequency of mixing periods per year, and particularly in those which do not develop the intensive anoxia during stratification periods. Such pans should be well oxygenated and calcium sulphate-saturated during mixing. The deep brine is oxygenated not only by diffusion from air and mixing but by photosynthetic activity of cyanobacteria as well (Horne & Goldman 1994). This activity however decreases with the water depth and the water transparency (e.g. Cloern *et al.* 1983). The transparency of brines is commonly very low due to planktonic blooms shading the bottom and limiting the growth of phototrophic benthic cyanobacteria.

The more frequently the holomictic pan is mixed the more favourable is its bottom for the growth of the gypsum crystals (assuming that the brine is

saturated with calcium sulphate at least during the mixing periods). Consequently polymictic, calcium sulphate-saturated pans appear to be the most favourable for abundant selenite deposition. It is usual that the shallower the pan the more likely is its polymictic state; the shallowest pans are always easily, nearly continuously, mixed by wind, down to the bottom.

The shallowness of polymictic pans implies frequent emersions and associated processes, and hence the interruptions in the crystal growth and destruction of the crystal beds. Indeed the selenite deposits in most modern shallow polymictic basins are composed of small crystals, a maximum of several centimetres long, and commonly contain clastic gypsum as well. The larger, well-developed selenite crystals, decimetres in

size, composing thicker selenite crusts, are found only in a few sub-fossil settings where they grew under more permanent cover of relatively deep brine (Warren 1982*b*). Just such coarse- and giant-crystalline selenite beds are very common in some ancient evaporites. Also in these ancient selenite deposits the larger sizes of crystals appear to coincide with rarity or lack of any evident dissolution or abrasion features. The ancient coarse crystalline selenites apparently grew upwards from the bottom in crystallographic continuity, i.e. syntaxially, for periods of time long enough for creation of decimetres-to-metres thick palisade-like or grass-like beds, without traces of any nucleation or settling of new gypsum crystal seeds on the depositional surface. It seems that the growth of such selenites requires somewhat deeper brine. The environment of coarse-crystalline selenites is interpreted in the following paragraphs.

The optimal place for coarse-crystalline selenite growth is below the seasonal (temporary) pycnocline of monomictic (to polymictic) saline pans in a salina-type basin, at a depth of no more than a few metres (zone A in Fig. 6; Babel 2004*a*). In this zone the brine can be calcium sulphate-saturated nearly all the time, during both stratification and mixing. This practically eliminates crystal dissolution and creates a very stable environment favouring the growth of large crystals. Many conditions in this zone appear to be optimal for the growth of large crystals. These conditions include long-term, persistent and relatively low supersaturation staying within the metastable zone, which eliminates any spontaneous nucleation (Mersmann 1996; Ulrich & Strege 2002). The rises in Ca-sulphate concentration are not so rapid and large as they potentially are in the zone of upper brine mass above the pycnocline (Fig. 6, top), and hence they are not able to promote spontaneous nucleation and to produce a great quantity of new gypsum crystal seeds. On the other hand drops in concentration are too small to promote abundant gypsum dissolution. The crystals at the bottom are nearly always in contact with the gypsum saturated brine. Such crystals can grow syntaxially by deposition of the new portions of gypsum in crystallographic continuity on the pre-existing gypsum crystal faces. Long-term, continuous, syntaxial growth leads to creation of extremely large crystals. Such a growth is not substantially disturbed (mechanically) by deposition of clastic particles or growth of thick microbial mats which could cover the crystal surfaces. Clastic deposition and erosion is uncommon at the bottom of monomictic pans during stratification periods because their bottom is below the seasonal pycnocline and therefore is below the wave base (Sonnenfeld 1984). Because of the greater depth, a higher salinity

level (staying within gypsum saturation field in marine brine) and very low illumination caused by possible shading by phytoplankton during eutrophication events, any thick cohesive and impermeable cyanobacterial mats are not developed there (Babel 2004*a*). Such mats commonly cover the gypsum deposits in the shallower and better-illuminated zones above the pycnocline (zone B in Fig. 6) and are a very effective barrier for the syntaxial gypsum growth (Geisler-Cussey 1997, p. 23). Below the pycnocline crystal apices are in contact with basinal brine, even when covered by some biofilms, because the biofilms are very permeable (see Gerdes *et al.* 2000, p. 204).

It is very likely that in the monomictic saline pans, in the model salina basin, the mixing period coincides with the seasonal lowstand of water level. This is true for many shallow (less than 6 m deep) coastal salinas and salt lakes such as Solar Lake (Eckstein 1970; Cohen *et al.* 1977), Lake Hayward (Coshell & Rosen 1994; Rosen *et al.* 1996), salinas of the York Peninsula (Warren 2006), and even for about 2 m deep Red Pond and Green Pond in Arizona (Cole *et al.* 1967). The beginning of the mixing usually starts in late summer or autumn, being slowed in relation to the climatic cycle. In all these basins (except of those in Arizona) precipitation of evaporite salts (gypsum) coincides with the period of mixing. In some deep saline monomictic basins like the Dead Sea (c. 320 m deep) and Mono Lake (45 m deep) the mixing also starts in late autumn, at the beginning of the highstand, but continues during the advancing winter highstand (Anati 1997; Melack & Jellison 1998). In these deep basins evaporite precipitation mechanisms are more complex and salts can be deposited both during mixing and stratification periods.

The main requirement for the gypsum deposition in this model is that the bottom brines (in zone A in Fig. 6) must be saturated with gypsum both during stratification and mixing. The pans thus should be in their 'Ca-sulphate productive' stage (similar to 'self-precipitating basins' distinguished by Valyashko 1952, 1972; see also Borchert & Muir 1964, pp. 65–67). In reality great disturbances in gypsum productivity can take place which depends on the levels of gypsum concentration within the lower and upper water bodies which influence the level of concentration during mixing. In some lakes containing gypsum saturated brine, after mixing, development of undersaturation of the whole water body with respect to gypsum is possible (depending on temperature, oxygenation etc.; see Last & Schweyen 1983, table 4).

The model presented here for selenite deposition in a saline pan is in agreement with the interpretation by Warren (1982*b*, 2006), who suggested a

monomictic salina for coarse-crystalline selenite growth basing on the Holocene and modern examples from some Australian coastal salinas. Warren indicted two of them, the Deep Lake and Lake Innes (Marion Lake complex, York Peninsula) where such a growth is currently taking place. However study of these lakes is not complete, but apparently is very similar to the Solar Lake, which is the best hydrographical analog for the model presented (Cohen *et al.* 1977). The ancient coarse-crystalline selenites commonly show millimetre-scale regular growth zoning which was interpreted as the reflection of an annual, i.e. monomictic, cycle of precipitation (Warren 1982b, 2006; Petrichenko *et al.* 1997).

Evaporite shoals in a salina-type basin

Gentle, flat-bottomed topography and shallowness of some salina-type basins imply that, between the drying saline pans containing ephemeral or permanent brine bodies, vast semi-emerged shoals will develop (Fig. 4a). Features of these shoals can be to some extent represented in the modern coastal salinas and the best example of such shoals are the flats described under the name 'majanna' (a term introduced by Logan in 1984, see Logan & Brown 1986, p. 6) from the MacLeod basin in Australia (Logan 1987). The evaporite shoals in the model basin are described as majanna-type shoals, although their predicted features come from many salina settings.

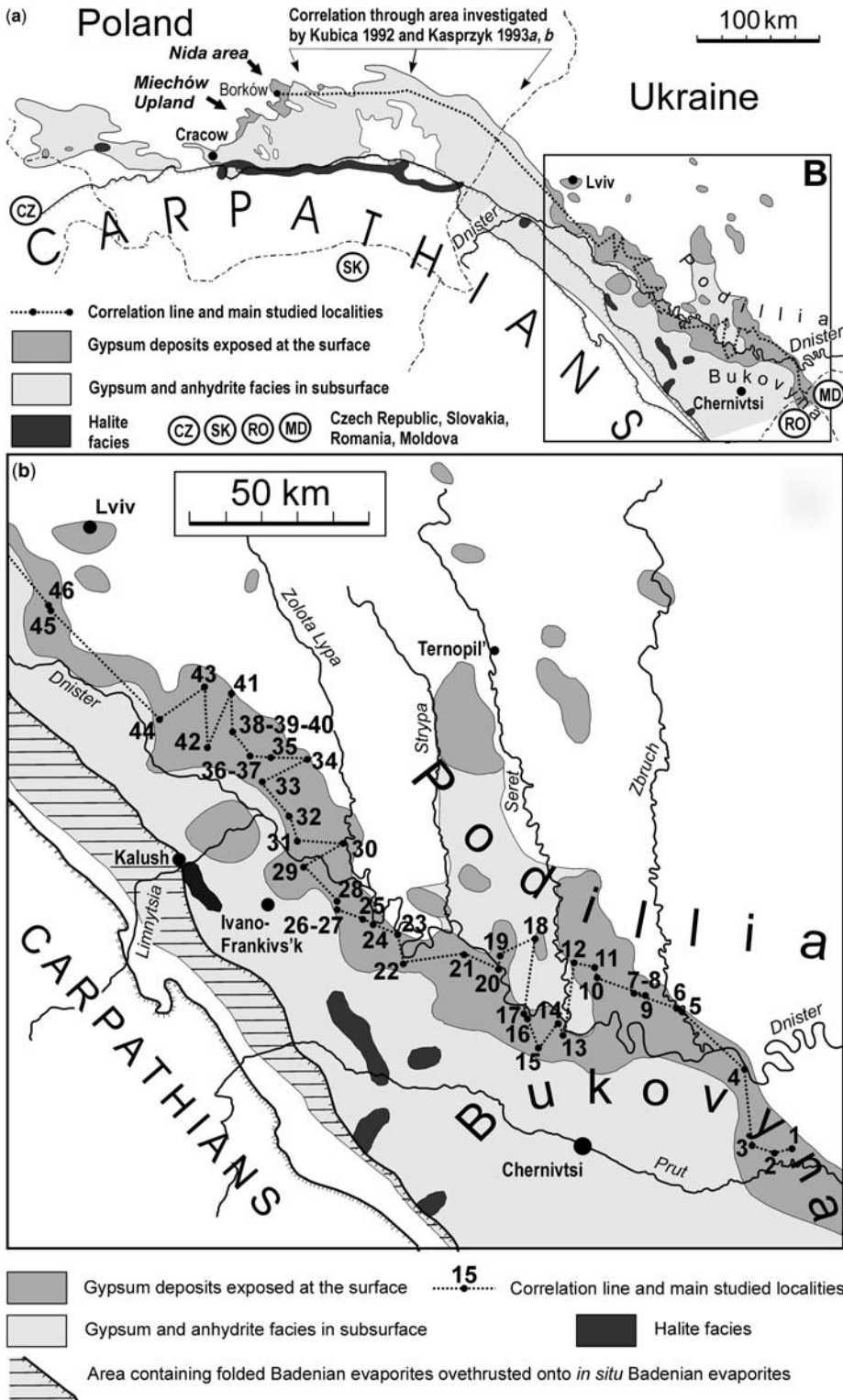
The specific feature of shoals in a salina basin appears to be the flow of 'brine sheets' (Last & Schweyzen 1983), defined by Logan & Brown (1986, p. 143) as 'bodies of free brine, a few centimetres deep, that are not topographically confined' (Fig. 4a & b). Brine sheets can form as an outflow from seep areas on the slopes of saline pans or as returning outflow from saline pans when the brine level is rising. The former brine sheets, as known from MacLeod basin, are commonly permanent, and the latter ones temporary. Brine sheets are commonly driven by wind in a similar way as 'roving' freshwater sheets in some playa lakes (Torgersen 1984). Sometimes, pushed by wind, they actually can flow upslope as detached migratory brine bodies over large distances attaining a level 2 m higher than the original site, as recorded in Lake Tyrrel in Australia (Teller *et al.* 1982, p. 169). In the MacLeod basin brine sheets, pushed by persistent, winds are held upslope for days to weeks (Logan 1987, p. 64). Such migratory brine sheets were observed on the drying Chott el Djerid flat in Tunisia (Bryant *et al.* 1994) and in the drying Kara-Bogaz-Gol in Turkmenistan (Lepeshkov *et al.* 1981, pp. 186–187; Levine 1998).

The majanna from the MacLeod salina is an evaporite flat, lying below sea-level, controlled by seepage inflow and evaporite outflow, with a suppressed brine table and common migratory brine sheets outflowing from saline pans and permanent brine sheets inflowing into them (Logan 1987). The surfaces of majanna flats are parallel to the inclined brine tables and are permanently wet, when the brine table coincides with, or is close to, the surface, or dry, when the brine table is well below the surface.

Giant flats similar to the Australian majanna were recorded in the area of Kara-Bogaz-Gol, which gradually dried in the early 1980s, when the brine depth fell to 2–5 cm on the surface of a few thousands of square kilometres (Terziev *et al.* 1986). Similar permanently wet but smaller flats surround coastal salinas in the Red Sea coast (Friedman & Krumbein 1985). They are commonly covered with living microbial mats creating specific 'perennial surface brine' biofacies (Gerdes *et al.* 2000).

Many salt flats in the continental playa environment show features resembling the majanna when they are covered with halite crystallizing from seeping or rising capillary brine. Such salt flats occur only in places where the groundwater table coincides with the playa surface, or is at a depth less than the depth of the capillary rise (Ullman 1995; Wood *et al.* 2005). These efflorescent salts accumulate on the surface and are easily dissolved during any inflow of fresh water or even when the humidity is elevated. Unlike in such salt-flats, brine sheets are permanent elements on the majanna flats (Logan 1987). There is a significant difference between the majanna in a salina basin, and the salt flat from continental salt lakes or playa lakes, where the former is commonly flooded by high salinity brine sheets (because the salina basin is supplied with seawater or seawater brine) whereas the latter is flooded mainly by freshwater or brackish water sheet floods (because continental lakes are supplied with meteoric water). Run-off sheet floods also inundate the majannas after rains and the dry majannas are subjected to deflation and pedogenic processes (Fig. 4b). The majanna surface is, however, dominated by *in situ* crystallization of salts from brine sheets, clastic deposition or re-deposition of earlier precipitates by the subsequent brine sheets and freshwater sheet floods, and microbialite deposition controlled by cyanobacterial mats inhabiting submerged and permanently wet areas (Fig. 4b; Logan 1987).

The depositional environment of majanna-type shoals in a model salina basin is peculiar. Astronomical tides are insignificant in the closed basins and such tides can be excluded in a salina basin. The shoals are flooded seasonally, following the annual cycle of water level fluctuations which can be up



to a few decimetres in amplitude (see Fig. 4b; Logan 1987, fig. 52; Babel 2004a, Table 1). Flat shoals forming barriers between saline pans can show specific sedimentation controlled by seepage and brine sheet flow, like on the MacLeod majannas. Adjacent saline pans can always show slight differences in water levels and the shoals between such pans can be gently inclined towards the lower pan. The brine sheets can then flow through such shoals predominantly into the lower pan just as in majanna flats of the MacLeod basin (Fig. 4a).

The majanna-type shoals are similar to some salt flats or inland sabkhas surrounding saline lakes, but differ from typical coastal marine sabkhas, which are flooded only rarely, during extremely high tides by seawater, with the salinity around 35‰. The majanna-type shoals are frequently flooded by brine from local saline pans commonly supplied with brine from interiors of salina basin. This brine can be saturated with respect to gypsum, halite or some other higher salts, and show variable salinity up to the very high values (e.g. c. 300‰ for halite brine). The majanna flat is commonly wet (and some parts of it can be always wet; fig. 4b; Tyler *et al.* 2006), whereas the sabkhas are traditionally considered as dry (Kinsman 1969), with the ground-water table 0.5–1 m below the surface (Wood *et al.* 2005). The majanna flat is dominantly formed by *in situ* precipitation at the surface (commonly on or within the surface of microbial mats) directly from the moving brine sheets, and by clastic evaporite deposition determined by sheet flow. Aragonite, gypsum and halite are known as the direct surface precipitates from such brine sheets (Logan & Brown 1986; Bryant *et al.* 1994). The typical sabkhas are dominated by *in situ* crystallization of evaporite salts from subsurface brines within some host sediments below the surface. The majanna-type shoal can display such features only in its emerged parts. In both environments, majanna and sabkha, the surficial salts can be removed by dissolution caused by intense but infrequent rains (Wood *et al.* 2005), but in majanna this process can be minimized because of the elevated position of the brine table and the presence of a protective, poorly permeable cover of microbial mats.

The majanna-type shoals in a salina basin usually show large accommodation. The majanna deposits can be accreted together with the rapidly rising water or brine level in saline pans (and brine table levels in dry parts of the shoals) without shallowing-upwards features typical of the coastal sabkha cycles. These extremely shallow water deposits can be well preserved in the sedimentary record, and can form thick sequences, in the same manner as in some saline lakes occupying deep depressions. It is clearly documented that such lakes can preserve even pedogenic evaporite deposits including gypsum efflorescent crusts (Smoot & Castens-Seidell 1994; Li *et al.* 1996; Bobst *et al.* 2001, fig. 5). Pedogenic evaporite deposits are probably overlooked facies in many basins (Lowenstein *et al.* 2003). Owing to large accommodation, the majanna-type shoal deposits of the salina-type basins can develop the aggradational architecture whereas the marine sabkha typically develop the progradational architecture (Warren & Kendall 1985; Alsharhan & Kendall 1994).

The Badenian evaporite basin as a salina-type basin

This part of the paper presents an attempt of the application of the concepts for the evaporite and selenite deposition in the giant ‘marine salina’ (Grabau 1920) outlined above, for sedimentological interpretation of the Badenian gypsum deposits in Carpathian Foredeep. Depositional features, facies and their architecture are interpreted from the point of view that the basin was a salina (Peryt 1996, 2001; Cendón *et al.* 2004), and the attention is paid to specific selected features which may be indicative of such a basin type.

Badenian gypsum facies and lithosomes

The Badenian gypsum deposits can be roughly subdivided into two main units: the lower autochthonous unit, dominated by primary selenite and gypsum microbialite deposits, and the upper allochthonous unit, containing mainly clastic

Fig. 7. Distribution of the Badenian (Middle Miocene) evaporites in the northern Carpathian Foredeep (Fig. 2) and correlation line of the gypsum sections studied. (a) General sketch map of the study area; (b) map of the studied area in western Ukraine (localities 2–46) and northern Moldova (locality 1). Maps after Atlas Geologiczny Galicyi (1885–1914), Garlicki (1979), Panov & Plotnikov (1999) and other sources. Numbered localities: 1, Kriva (Moldova); 2, Mamalyha; 3, Stal’nivtsi; 4, Anadoly; 5, Zavallia; 6, Kudryntsi; 7, Skov’iatyn S; 8, Skov’iatyn N; 9, Kryvche, Krystalna cave; 10, Optymistychna cave; 11, Ozerna cave; 12, Verbeba cave; 13, Tovtry; 14, Chun’kiv; 15, Verenchanka; 16, Zveniachyn; 17, Kostryzhivka; 18, Holovchynsi; 19, Nahoriany; 20, Ustechko; 21, Repuzhyntsi; 22, Harasymiv; 23, Isakiv; 24, Odaiv; 25, Vikniansy; 26, Palahychi S; 27, Palahychi N; 28, Oleshiv; 29, Hannusivka; 30, Krasiv; 31, Lany; 32, Mezhyhirs; 33, Kasova Hora; 34, Naberezhne; 35, Podillia; 36, Ozeriany; 37, Kuropatnyky; 38, Obelnytsia; 39, Velyka Holda; 40, Luchyntsi; 41, Rohatyn; 42, Kolokolyn; 43, Pidkamin; 44, Zahirochko; 45, Pisky; 46, Schyrets’.

gypsum (Peryt 1996; Kasprzyk & Orti 1998; Rosell *et al.* 1998). More precisely, the evaporites can be subdivided into several lithosomes or lithostratigraphical units (designated by capital letters: Fig. 8) and the boundary between the autochthonous and allochthonous unit is roughly at the base of the 'clastic' unit E distinguished by Kubica (1992). The selenite deposits occur as laterally extensive lithosomes A, C-D, F, SV and SH; the remaining units are dominated by gypsum microbialites and clastic gypsum (Fig. 8). An event-stratigraphical approach based on well-defined marker beds proved that gypsum deposition across the entire basin margin was coeval (Figs 8 & 9; Peryt 2001, 2006; Babel 2005a). The architecture of these gypsum lithosomes or lithostratigraphical units reflects dominantly aggradational style of deposition typical of the salina type basins. The onlap pattern of successive gypsum units in some areas (Peryt 2001; Babel 2005b) can be a product of 'autocyclic' (Warren 2006, pp. 350–351) or 'autogenetic' transgression (Rouchy & Caruso 2006, p. 47) characteristic of the post-drawdown phase in such basins.

Of particular significance among the Badenian gypsum facies are selenite (coarse-crystalline) and gypsum microbialite (fine-grained) facies. The former facies are considered as deposited in several different types of saline pans, the latter as evaporite shoals and the majanna-type shoals in particular, appearing within a framework of the same salina-type basin (Figs 3, 4 & 9). Microcrystalline and clastic gypsum-dominated facies present in the upper part of the section actually may represent several different environments, but also some saline or brackish pans in which selenites were not able to crystallize.

Selenite facies

Similar to the Messinian selenitic gypsum, two main varieties of the Badenian selenite deposits can be distinguished (excluding some other, more complex varieties of selenites): coarse crystalline selenites forming thicker layers with no or poorly discernible bedding planes, and distinctly thin-bedded, grass-like selenites. Similar to the Messinian, 'as selenite grain-size decreases bedding becomes more distinct' (Hardie & Eugster 1971, p. 191). These two varieties are interpreted as representing two different types of saline pans within a salina basin; namely a deep-brine and a shallow-brine pan (Babel 2004a).

The names 'deep-brine' and 'shallow-brine' are used to designate two specific types of saline pans. The 'deep-brine' pan is characterized by a thick zone of brine below a pycnocline. Its pycnocline

can fluctuate vertically over a relatively wide range of space but never (or only exceptionally) drops down to the bottom of the pan. The 'shallow-brine' pan shows a thinner zone of brine below a pycnocline and the pycnocline commonly drops to the bottom of the pan (i.e. the whole pan is diluted to the bottom). Such drops or lowstands of the pycnocline are thought to control the growth of selenite at the bottom (due to possible dissolution of crystal tops by less saline water occupying the upper zones of the pan) and are one of the reasons for the bottom of the shallow-brine pan is flat. By contrast to this pan type, the deep-brine pan (below the pycnocline) shows undulating or uneven bottom morphology because the selenites in this zone are sheltered from dissolution. Both pans create separate environments, and show characteristic gypsum facies (see Babel 2004a); however they can evolve from one into the other, and this evolution can be linked to the changes in the water depth. The deep-brine pan can be treated as moderately deep and the shallow-brine pan as shallow, however there is no fixed water depth defining these two types of pans (they can show comparable depth) and the shallow-brine pan can be even deeper than the deep-brine pan, depending on local environmental features such as size (fetch), salinity and climate (particularly windiness). Both pans show a depth below the depth limit for selenite deposition and their hydrography is the same as in the earlier described general model of the selenite pan (Fig. 6). Further details and discussion of the both types of the pans are given in Babel (2004a, pp. 239–242).

Coarse-crystalline (thick-bedded) selenites as deposits of deep-brine pans

General features Selenites comprising units A, C-D and SV commonly show well-developed palisade structure and coarse to giant crystal sizes (Figs 8 & 10). They appear in thick sequences without well-developed horizontal bedding planes, or the planes are rare or very poorly visible. The Badenian sequences are relatively thin (rarely over 10 m thick; Fig. 8) in comparison with the Messinian equivalents (up to 30 m thick in Sicily; Hardie & Eugster 1971).

Dissolution surfaces Horizontal bedding is very rare in unit A (giant crystal intergrowths; Figs 8 & 10a) considered as representing a slightly deeper environment than the C-D and SV units (sabra-gypsum facies) where the bedding features are more common and crystal sizes smaller (Figs 8, 10b & c). The sole pronounced bedding planes present in unit A are synsedimentary dissolution surfaces. They appear as horizontal

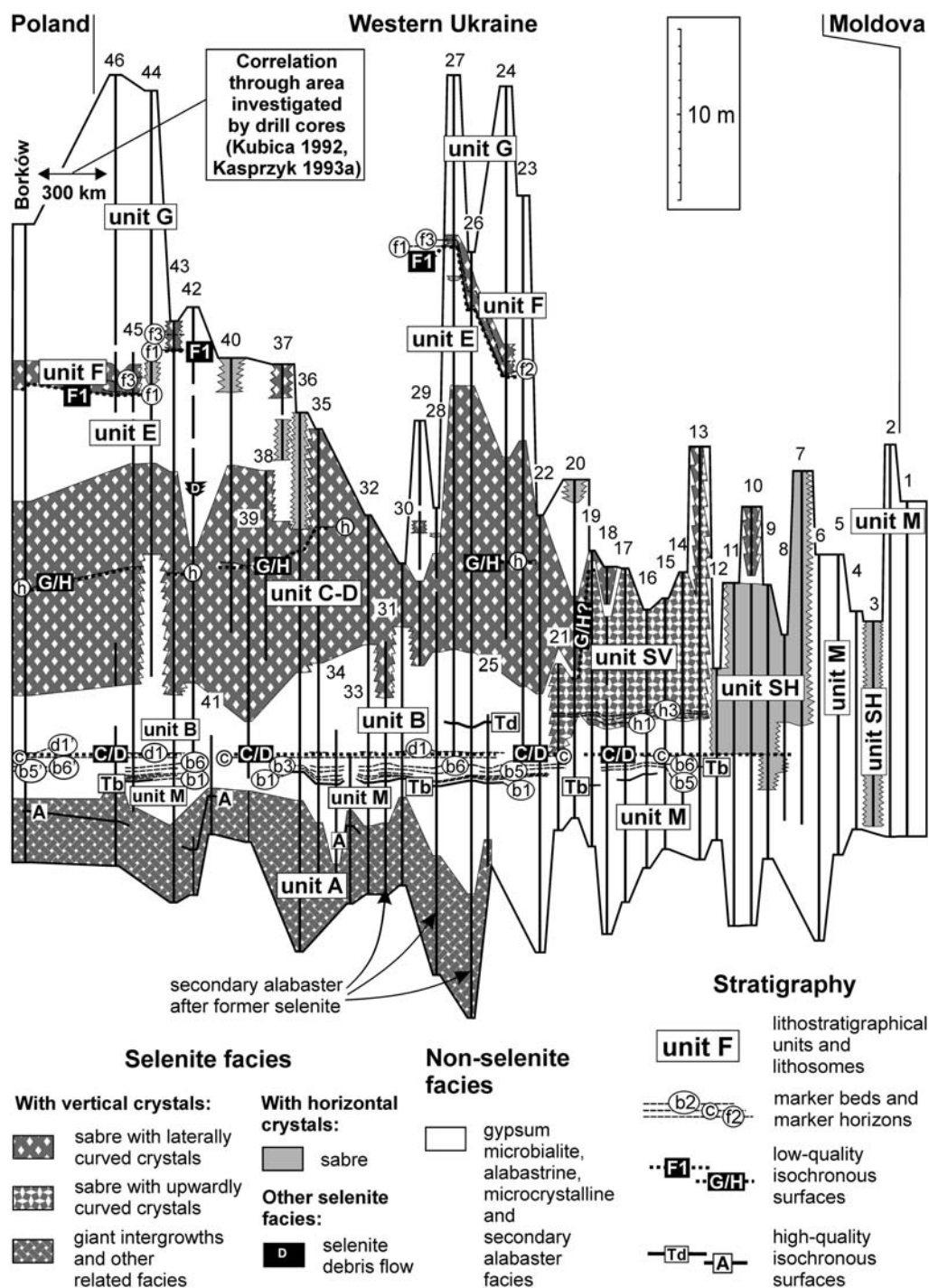


Fig. 8. Scheme showing stratigraphic and facies relations in representative sections of the Badenian gypsum deposits along the correlation line shown in Figure 7. Stratigraphy after Kubica (1992) and Babel (2005a); see also Babel & Bogucki, 2007, figure 4. A list of the numbered sections is given in Figure 7. Complete documentation and details are shown in Babel (2005a), and at www.geo.uw.edu.pl/agp/table/appendixes/55-1/.

discontinuities or fissures cross-cutting the bodies of crystal, (Fig. 10a). Only very rarely are the discontinuities covered with fine-grained gypsum, some clay or carbonates. Even more rarely is the generation of new cycles of grass-like gypsum crystals developed on such surfaces. The dissolution surfaces are flat or slightly irregular, with the shape fitted to the protruding but flattened (truncated) crystal apices. The unusual feature is that such dissolution surfaces, visible as discontinuities or fissures, commonly disappear laterally and are difficult to recognise and correlate even within one quarry (Fig. 10a).

Careful measurement of the sections showed that only the rare and major dissolution surfaces correlate over distances of up to a few kilometres. Correlation over larger distances was not detected in this study although the pronounced long-distance correlation was found within growth zones of the giant crystals showing internal zig-zag shapes characteristic of the crystal apices not truncated by dissolution (Warren 1982*b*; Babel 2005*a*, On-line Appendix, figs 4 & 5). In vertical sections the dissolution surfaces occur more commonly in the lithological transitional zones to the shallow water gypsum deposits represented by units B and M (Figs 8 & 9). Traced laterally the dissolution surfaces appear more commonly in the areas closer to the margin of the basin or on apparent basinal swells, where the thickness of unit A is apparently reduced. In such areas dissolution surfaces are more densely distributed, even over a distance of a few centimetres one from another.

Interpretation of dissolution events in deep-brine pans The dissolution surfaces, described above, differ from their modern analogues observed in selenites from saltwork pans, that are maintained at depths less than 1 m (Ortí *et al.* 1984; Geisler-Cussey 1986, 1997), and from coastal salinas in Australia (Warren 1982*b*). They occur in vertical section as single surfaces that are rarely present within the coarse-crystalline selenite bed present in the modern environments and are not associated with any millimetre-scale horizontal internal lamination within the crystals as recorded in Australia (Warren 1982*b*, figs 9 & 15*b*). This suggests that dissolution events were rarer in the Badenian basin and possibly the accommodation was larger in this basin than in the modern analogues. Substantial accommodation is a feature of salina-type basins.

The selenites are interpreted as deposited in moderately deep, permanent saline pans within a salina-type basin (Figs 3a, 4 & 6) or on the vast platforms within such a basin when it is deep enough to be persistently meromictic (Fig. 3*b*; Babel & Bogucki 2007). The term 'deep-brine' is employed for such moderately deep pans but does not imply

substantial depths (Fig. 11*b*). Large topographical differences of bottom-level and thicker brine layers both below and above the pycnocline are characteristic of the deep-brine pan, which develops when a large volume of brine fills in the differentiated relief (this appears to be particularly common during the initial stages of evaporite deposition; as exemplified by unit A in the Badenian basin; Figs 8 & 9). The pan exists in a salina-type basin and therefore:

- (1) its water level can fluctuate readily, and the amplitude and rate of these fluctuations are high, as in most saline lakes (where the annual water level fluctuations are up to a few tens of centimetres in amplitude, and the mean water level always is rising and falling throughout the ensuing time interval); and
- (2) a stratigraphical record is nearly complete (erosion is minimal or absent because of the high accommodation and the aggradational style of deposition typical of salina basins). The deep-brine selenites do not record small amplitude water and pycnocline level changes (Fig. 11). Deposition of selenite beds is connected with the pycnocline highstands.

In the deep-brine pan the selenites growing in shallower portions are subjected to dissolution by more dilute surficial brines during falls of the average pycnocline level (designated EPI-MIX in Fig. 11). The selenites from below the average pycnocline level grow without interruption (except for some longer meromictic periods), disturbed only by some rare major drops of the pycnocline. These deepest zones are favourable for the deposition of the continuous uninterrupted sequences of coarse-crystalline selenites, which do not display macroscopically visible bedding and are lacking any dissolution features. The bedding planes that are present in coarsely crystalline selenites are commonly marked by dissolution surfaces. It is evident that, because of the uneven basin floor, such bedding planes in the selenites from the deep-brine pans may not show well-developed correlation across the basin (Fig. 11*b*).

Two scenarios, shown in Figure 12, are suggested for the events producing dissolution surfaces in the deep-brine pan in the salina-type basin, both related to common water level fluctuations typical of such a basin (Figs 3 & 11). The growth of coarsely crystalline selenites is assumed to take place in the zone below the average pycnocline in the pan (Figs 6, 11*b* & 12, bottom and top). As in the general model (Figs 5 & 6) the brine column in the pan passes through repeated stratification-mixing cycles, and it is assumed that stratification is

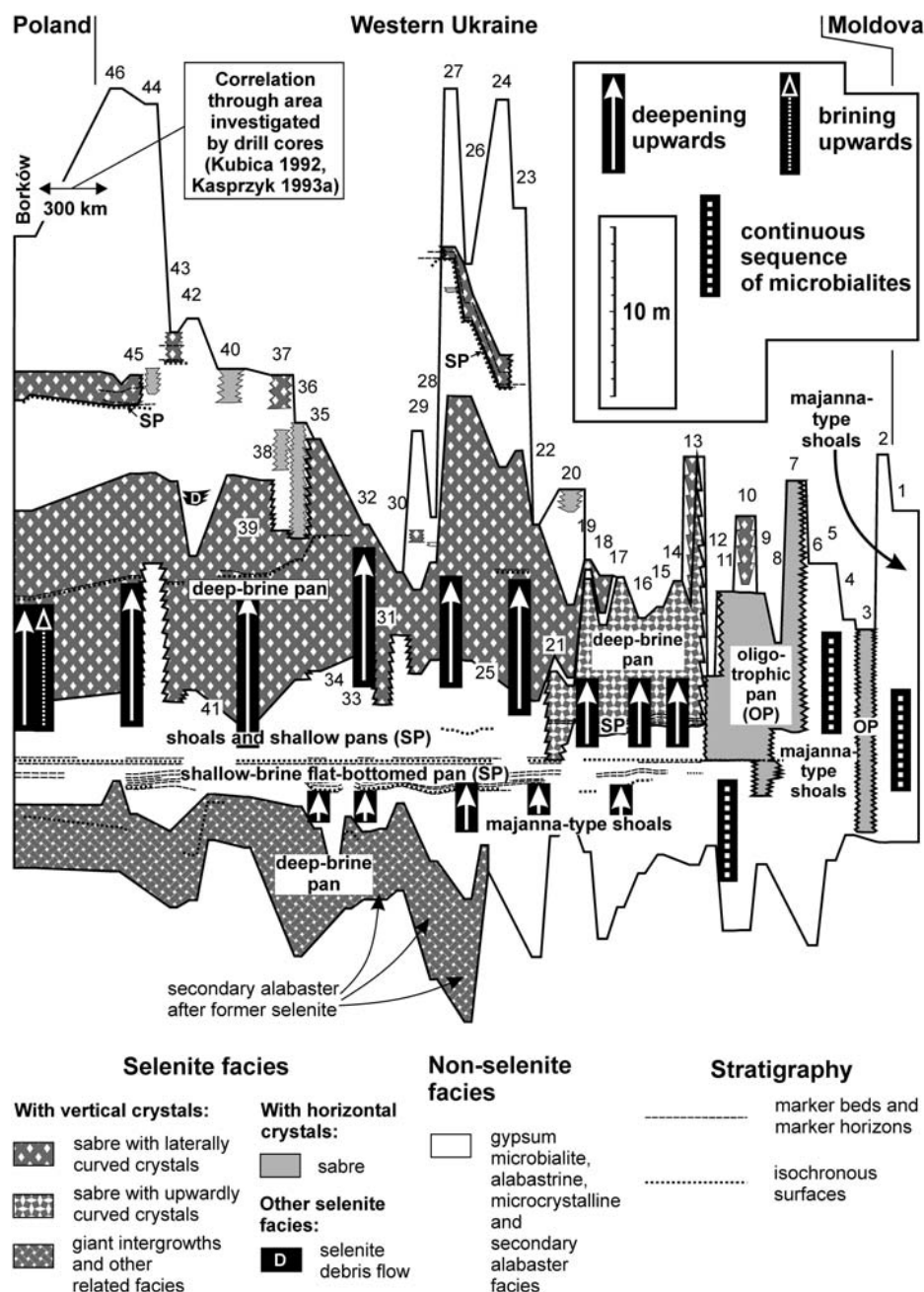


Fig. 9. Environmental interpretation of the selected facies, location of the deepening-upwards and brining-upwards sequences, and continuous microbialite sequences, in the representative sections of the Badenian gypsum deposits along the correlation line shown in Figure 7. Brining-upwards sequence at Borków in Poland (left) was recognized by the rise of Sr content in the selenite crystals from about 600 ppm Sr at the bottom of the sequence, to 1600 ppm Sr at the top (Rosell *et al.* 1998, fig. 9). The same rising trend in Sr content in selenite crystals was documented in this interval of the section in five other sections (from boreholes in the northern margin of the basin in Poland, not shown in Fig. 7, see Rosell *et al.* 1998) and supported by the same trend in Sr content in bulk rock samples in about 20 other sections from this area (Kasprzyk 1989, 1993b, 1994). For more details see Figure 8 and www.geo.uw.edu.pl/agp/table/appendixes/55-1/.

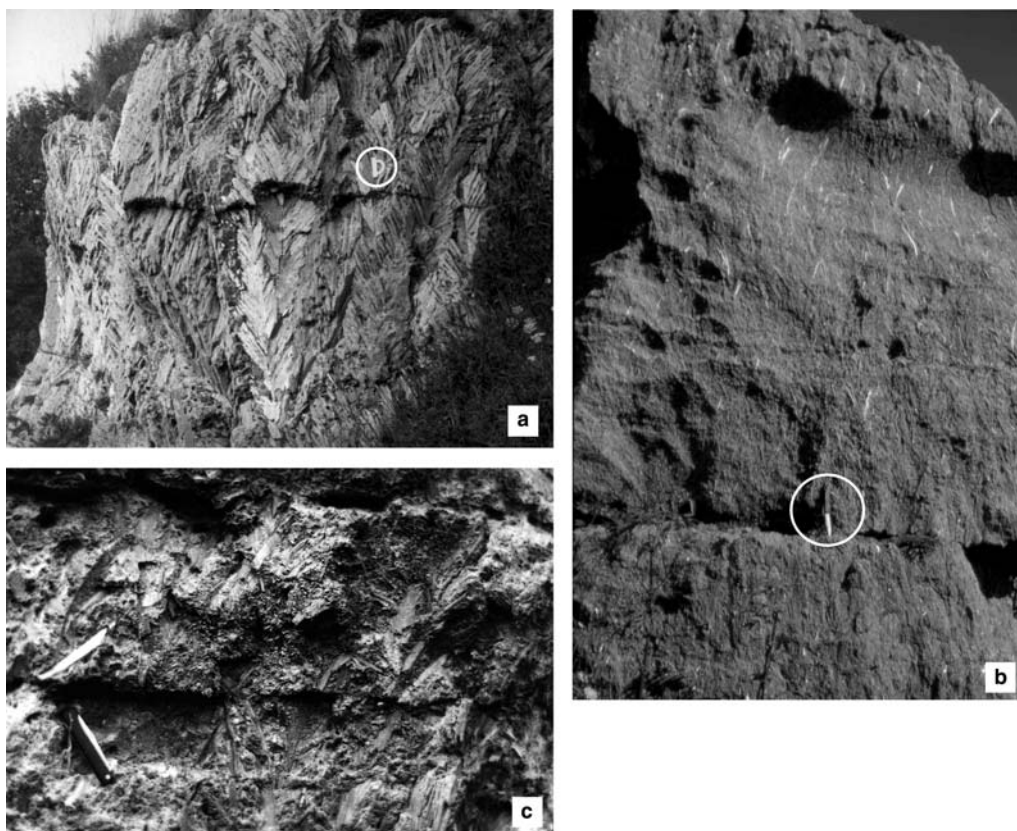


Fig. 10. Syngedimentary dissolution surfaces in coarse-crystalline selenites. (a) The giant gypsum intergrowths, unit A; Marzęcin, Nida river valley, Poland; the protractor (circled) is 10 cm long; (b) the sabre gypsum facies, unit SV, Nahoriany, locality 19 in Figure 17b, Ukraine; the knife (circled) is 25 cm long; (c) the sabre gypsum facies, unit C-D, bed g in local stratigraphy, Skorocice, Nida river valley, Poland; the pocket knife is 14 cm long.

associated with the highstand and the mixing with the lowstand (Figs 12, bottom and top, & 13, top left), as recorded in Red Pond and Green Pond in Arizona, Solar Lake, Lake Hayward and some salinas of the York Peninsula (Cole *et al.* 1967; Eckstein 1970; Cohen *et al.* 1977; Coshell & Rosen 1994; Rosen *et al.* 1996; Warren 2006). The growing crystals develop well-terminated crystal apices during the growth below the lowest pycnocline level in the pan, much like the zig-zag selenites described by Warren (1982b). These apices can be dissolved and truncated by the contact with the EPI-MIX water (or brine) undersaturated with gypsum lying above the pycnocline, which can take place without actual emersion (Figs 6, 11b & 12, centre). This contact is made possible by a lowering of the pycnocline level which can be realized in two possible ways:

- (1) by shallowing of the pan and drop of water level associated with the pycnocline level drop (Fig. 12, centre left); or
- (2) by inflow of the large volume of less saline diluted waters to the pan causing the rise of water level during highstand and associated drop in the pycnocline level (Fig. 12, centre right).

In both cases it is assumed that during stratification periods gypsum dissolution processes take place in the zone above the average pycnocline (zone B in Fig. 6; Fig. 11b), and these processes dominate over the possible gypsum nucleation and growth in this zone during the mixing periods, as predicted by the features of the deep-brine model (Babel 2004a, pp. 227, 240). During the lowering of the pycnocline, the dissolution surfaces can become covered with microbial mats in the shallow water, possibly due to better illumination (Fig. 12, centre left), unlike the the dissolution surfaces produced in the deeper water (Fig. 12, centre right). Thick, cohesive and impermeable microbial mats covering the crystals can also become a

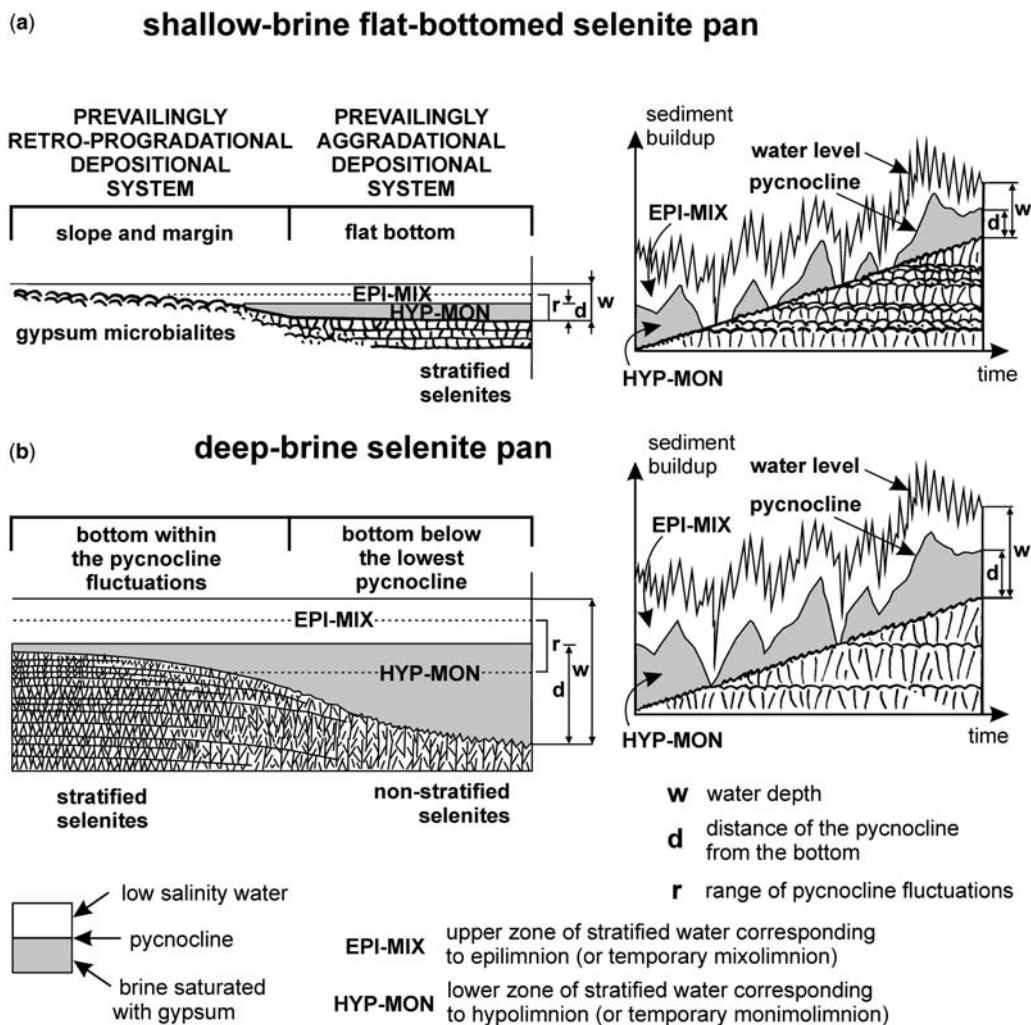


Fig. 11. Depositional models of the shallow-brine flat-bottomed selenite pan (a) and deep-brine pan (b) and their stratigraphical record (after Babel 2004a, modified). The basic concept of the selenite pan is outlined in Figure 6. Detailed explanations in the text.

barrier for the syntaxial growth of these crystals, and, consequently, create a substrate on which a new generation of crystals will grow when conditions for selenite growth return (Figs 6, 11b, 12, top left and centre).

The dissolution events recorded in the deep-brine selenite pans can be longer than one year. In particular, the dissolution events that are related to larger inflows of fresh water to the pan (Fig. 12, centre right) could last longer than one year and could be associated with some short-time meromixis in the pan. It is well known from the observations in the monomictic Dead Sea, Mono Lake and other saline lakes, that large rainstorms have promoted

meromixis that lasted a few years (Romero & Melack 1996; Melack & Jellison 1998; Niemi *et al.* 1997). The inflow floods of run-off water into the Badenian basin is demonstrated by the presence of numerous clay intercalations with floral remains and sedimentary structures suggestive of the sheet flood deposition. Therefore it is highly probable that the Badenian deep-brine pans passed through some short-time meromictic periods promoted by rains or other major influx of less saline water. Some zig-zag growth zones in selenite crystals from unit A were interpreted as recording such meromictic periods promoted by inflow of meteoric waters (Babel 2005a, p. 16); however the correlative

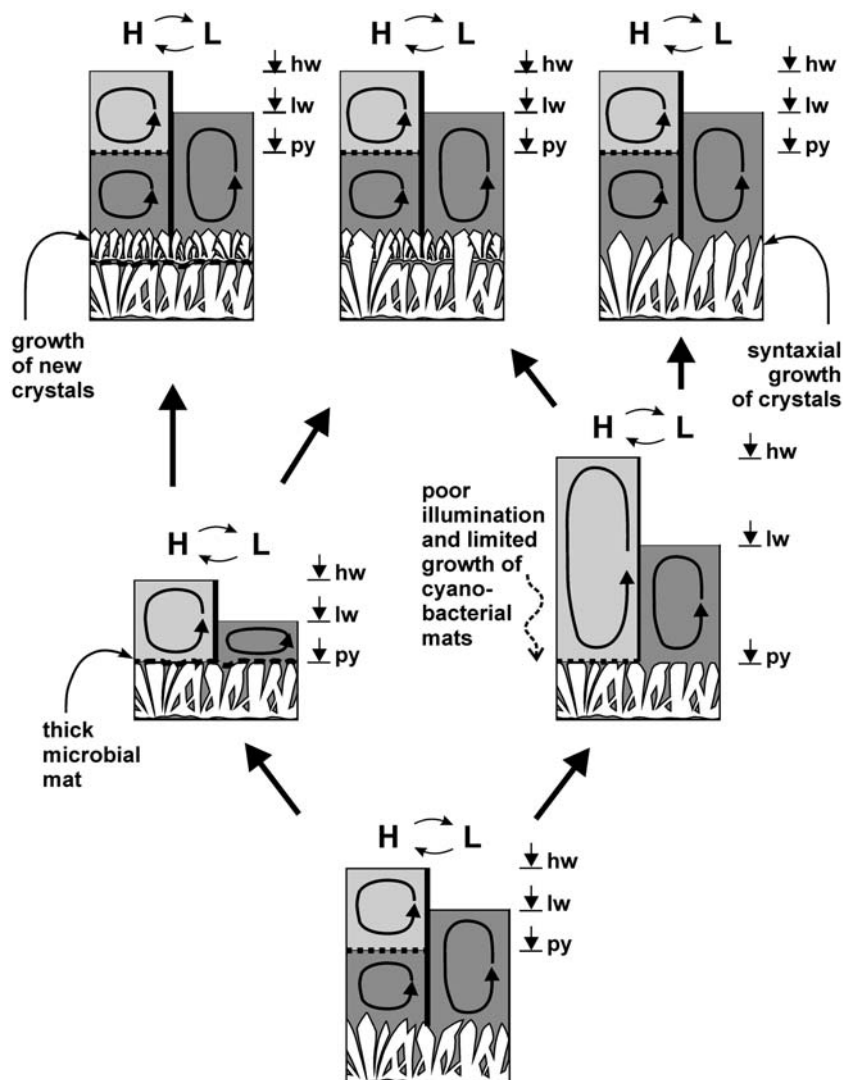


Fig. 12. Scenarios for subaqueous dissolution events in deep-brine selenite pans (general pan models are presented in Figs 6 & 11b) related to pycnocline lowstand associated with moderate shallowing (left), and with relative deepening associated with dilution of the upper brine mass and a pycnocline lowstand (right). Explanations in the text and Figure 13.

dissolution surfaces produced by such waters in the shallower zones are not recognized.

Grass-like (thin-bedded) selenites as deposits of shallow-brine pans

General features Selenite beds in the grass-like facies are laterally continuous and intercalated with fine-grained gypsum. Individual beds of both selenite and fine-grained gypsum are usually less than 20 cm thick (Figs 14 & 15). The fine-grained

gypsum intercalations commonly show crenulated laminations and domal structures, typical of gypsum microbialite or gypsified microbial mat deposits. Fine-grained gypsum is also represented by a more or less homogeneous alabastrine rock variety, in places with scattered larger gypsum crystals and brecciated or nodular structures, which was interpreted as *in situ* crystallization from brine sheets (Peryt 1996) or as pedogenic deposits (Kasprzyk 1993a, pp. 49–51; Bąbel 2005a). Unlaminated clay is intercalated in these deposits.

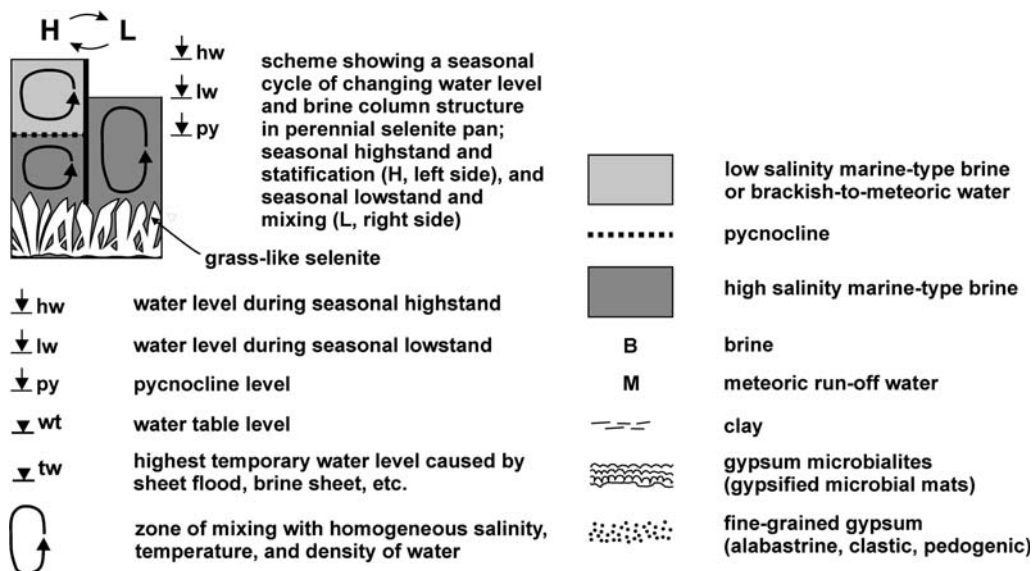


Fig. 13. Key to Figures 12, 18 & 19.

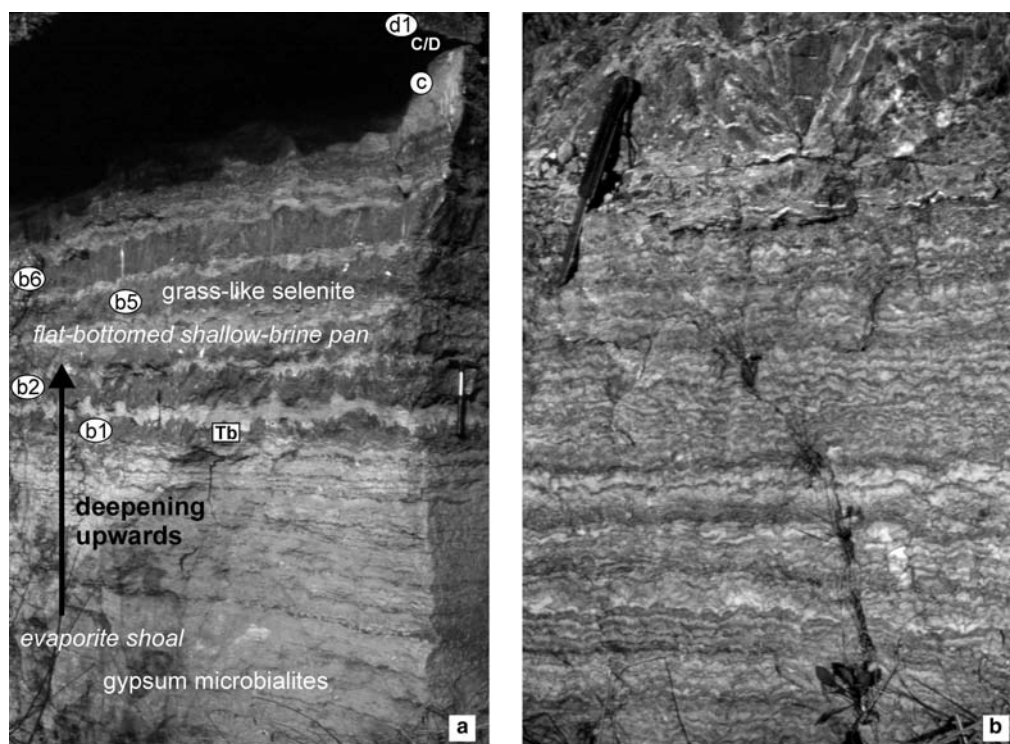
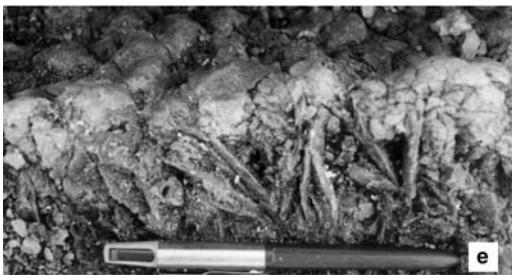
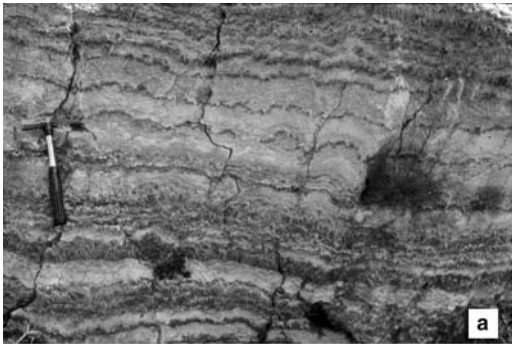


Fig. 14. Deepening upwards transition from gypsum microbialites of unit M (majanna-type shoal facies) to grass-like selenites of unit B (shallow-brine selenite pan facies) (see Fig. 9). (a) Microbialites and sequences of marker beds (described in Figs 8 & 16), Mezhyhirs, Ukraine (locality 32); (b) thick sequence of gypsified microbial mats below the selenite marker bed b1 at Pisky, Ukraine (locality 45); the knife is about 25 cm long.



Shallow-brine pan The grass-like facies is interpreted as deposits of the shallow-brine pan (Babel 2004a). The shallow-brine pan setting seems to have had an extremely flat bottom (with infilled levelling of the bottom irregularities) and much thinner brine zones separated by a pycnocline than the deep-brine pan (Fig. 11a & b). Similarly, as in the deep pan the water level in a shallow pan fluctuates with time (through the years) frequently, with a high amplitude and rate (note that both pans in Fig. 11 show the same rhythm of fluctuations). It is assumed, following some earlier concepts put forward by Lowe *et al.* (1997) and Verschuren (1999), that the pycnocline tends to fluctuate together with the water level fluctuations, although it is generally more stable, because this allows analysis of the stratigraphical record of this selenite facies (Babel 2004a) as in the model presented by Strasser *et al.* (1999) for shallow carbonate platforms.

The shallow-brine selenites record much smaller amplitude changes in both water and pycnocline than the deep-brine pans (Fig. 11a & b). In both pans deposition of selenite beds is connected with the pycnocline highstands. It is evident that, because of the uneven bottom, the bedding planes in the selenites from the deep-brine pans will not develop good correlation across the basin (Fig. 11b). By contrast the selenite beds from the vast flat-bottomed shallow-brine pans are ideal for long-distance correlation (Fig. 11a). The shallow-brine pans develop on the very gentle bottom topography and they appear to be typical of the shallowing events in evaporite basins. These pans may be considered as later stages of the evolution of the deep-brine pans, namely the effect of the sedimentary fill of such pans and associated shallowing (see Figs 8 & 9).

Long-distance correlation Some sequences, made up of several thin selenite beds intercalated with fine-grained gypsum, reveal correlation over distances of tens of kilometres in the Badenian basin. This is similar to some beds present in the Messinian of Sicily (Schreiber *et al.* 1976). The most widespread of these is the sequence of six selenite beds, designated b1–b6, that correlate along

nearly the whole northern margin of the basin (Figs 8, 14, 15c, d, f, 16; Babel 2005a, On-line Appendix, figs 6a and 8). This sequence was interpreted as deposits within an evolving giant shallow-brine pan (Fig. 11a). The other similar sequences show bed-by-bed correlation over smaller distances, evidently due to smaller sizes of the shallow-brine pans.

Isochronous to near-isochronous deposition of selenite beds in the shallow-brine pan

Each selenite bed in the sequence (Fig. 16) originated due to a stable period, under a long-term highstand of a pycnocline in the shallow-brine flat-bottomed pan (Fig. 11a) and can be treated as isochronous or near-isochronous stratigraphical unit (i.e. an event or marker bed; Babel 2005a). The growth of selenite crystals took place below the pycnocline and required a permanent presence of a 'shelter' of calcium sulphate saturated-to-over-saturated brine both during stratification and mixing periods (Figs 5 & 6). The interpretation of associated depositional events taking place in the interval of the section containing the b1–b6 marker beds is shown in Figure 17 and discussed in the next section (see Babel 2005a, for more details).

The growth of selenite crystal tops in shallow-brine pans was controlled by a position of the pycnocline (Figs 11a & 17). The crystals could not grow above the pycnocline level and their tops presumably tended to be limited to the ideal horizontal surface in the same way as upper surfaces of many selenite crystal beds in the recent saltwork pans (Ortí *et al.* 1984; Geisler-Cussey 1986, 1997) and in the Messinian deposits of Sicily (Schreiber *et al.* 1976). The other modern example of such horizontally truncated selenite tops can be found in salinas of York Peninsula, in Australia, in selenite beds from the topmost part of the shallowing-upwards gypsum sequences formed during gradual sediment infilling of pans that originally were several meters deep (see Warren 1982b; Warren & Kendall 1985; and photo by J. K. Warren in fig. 8.22 in Schreiber *et al.* 1986).

Fig. 15. Sedimentary features of the grass-like selenite beds. (a, b) Grass-like selenites intercalated with gypsified microbial mats; note thin selenite layers coating the domal microbialite structures; unit B above marker bed c; Lokutki near Tlumach, S of locality 26, Ukraine (a) and Gacki quarry, Nida river valley, Poland (b). (c–e) Selenite beds with empty fenestral pores between the grass-like crystals, below gypsified microbial mats; (d) details of (c) marker beds b6' and c are shown in (c), bed c represents gypsified microbial mat deposits; unit B, Borków quarry, Nida river valley, Poland; the pocketknife in (c), bottom-left, is 14 cm long. (f) Selenite beds with eroded and corroded top surfaces covered with fine-grained gypsum; unit B, near marker bed b5–b6, Oleshev, locality 28, Ukraine. (g, h) Selenite regolith originated from selenite beds destroyed during emersion; note preserved vertical position of crystals within the selenite debris in (g), the regolith covers the apices of the giant gypsum intergrowths flattened by dissolution; unit A and B, Sielec Rządowy, Nida river valley, Poland; the knife in (f), (g) and (h) is about 25 cm long.

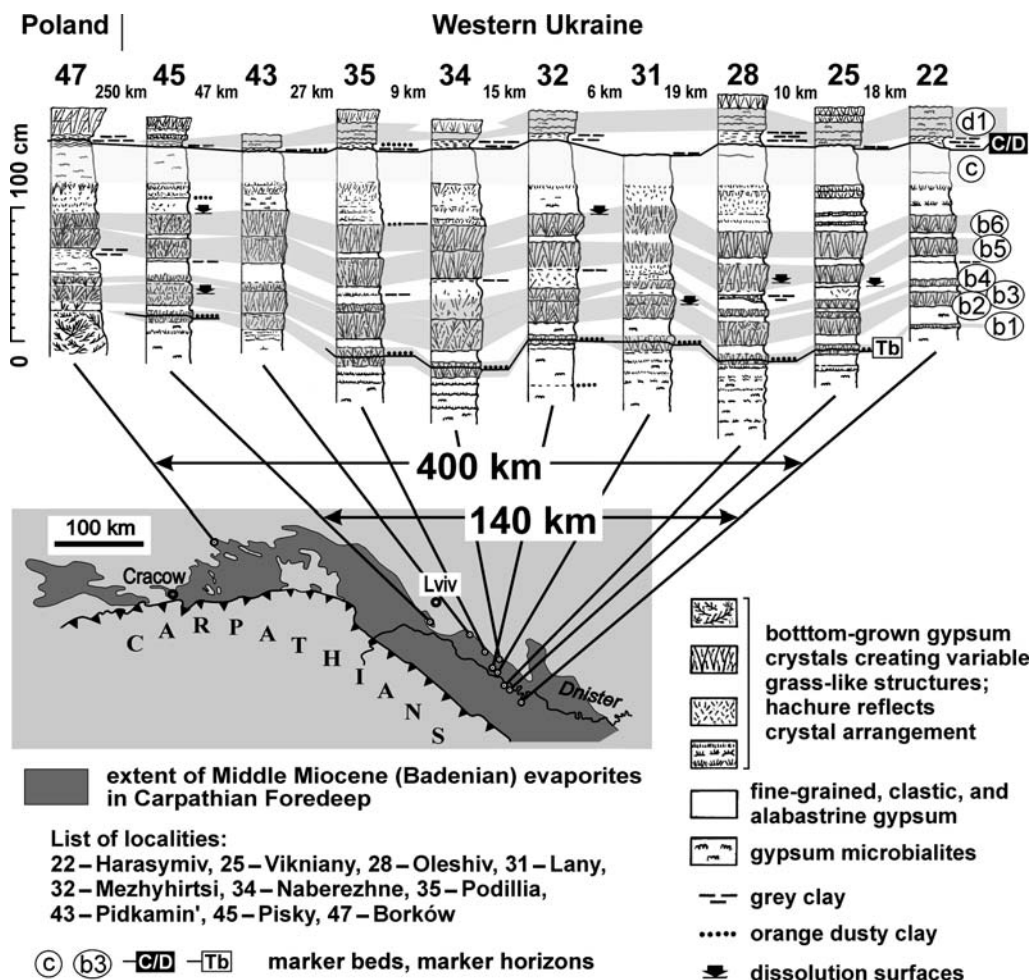


Fig. 16. Long-distance correlation of selenite sequences (marker beds b1–b6, Fig. 8) in the Badenian (Middle Miocene) evaporite basin in the northern Carpathian Foredeep in Ukraine (localities 22–45) and presumed correlation with marker beds b5' and b6' in Poland (locality 47). Complete documentation and details are shown in Bałbel 2005a, and at www.geo.uw.edu.pl/agp/table/appendixes/55-1/.

The other example of similar evaporite growth styles can be observed in trona deposits at the bottom of Lake Magadi in Kenya, where 'the tops of the crystals are roughly at the same elevation throughout the whole lake, which is about 20 km long' (Eugster & Hardie 1978, p. 34). Clear trona crystals from this lake form 2–5 cm thick beds, separated by dark crystals enriched in windblown dust related to seasonal exposure of the bottom of the lake (Eugster 1980). The crystals appear to correlate across the whole lake (see photo by H. P. Eugster in Smoot & Lowenstein 1991, fig. 3.8d). This type of trona deposits was considered by Eugster (1980, p. 215) as product of 'a saline lake at its peak of productivity'. During exceptionally dry seasons the

brine level drops slightly below the surface of these grass-like trona crystals (not more than a few centimetres; Warren 2006, pp. 260, 865) causing the formation of expansion polygons typical of a dry or nearly dry bottom. Similar features suggesting that the brine level dropped below the crystal tops in selenite beds are not noted in the Badenian selenite sequences, presumably because fluctuating water or brine level dropped only sporadically and only just below the sediment surface which was nearly always covered with brine or wet (as discussed in the next section).

Thus the considered selenite beds can be used not only for isochronous correlation, but also as one of the most ideal datum surfaces in ancient

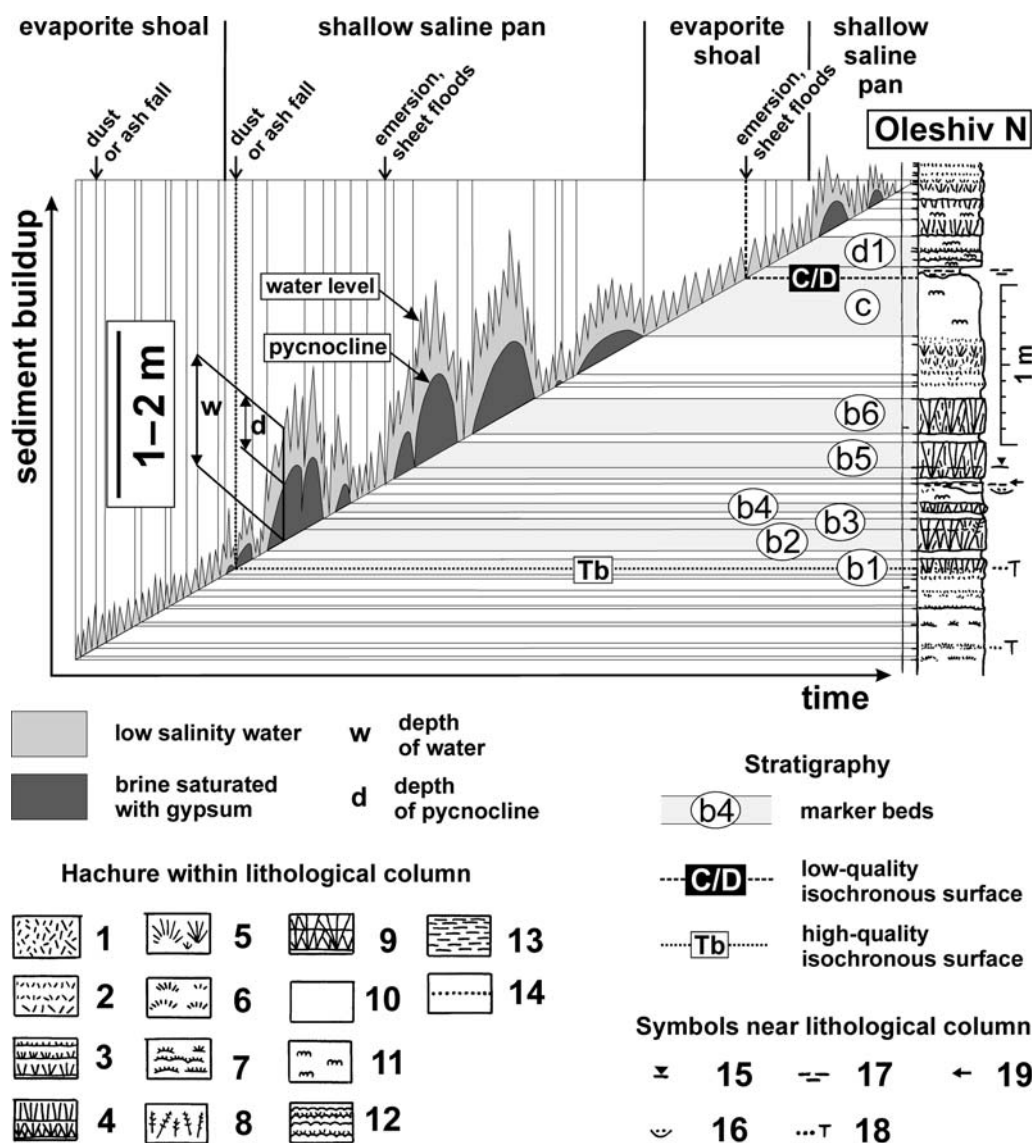


Fig. 17. Scheme showing interpretation of depositional events around marker beds b1–b6, c and d1 in the exemplary gypsum section at Oleshiv, Ukraine (locality 28, Figs 7, 8 & 16). Selenite marker beds are interpreted as response to fluctuations of the average pycnocline level in a shallow flat-bottom saline pan. 1–9, Selenite components (hachure reflects arrangement, sizes, and shapes of crystals): 1, randomly scattered straight rod-like crystals – short (left) and long (right); 2, rows of rod-like crystals creating grass-like structures without sharp common base – short crystals (top), long crystals (bottom); 3, rows of rod-like crystals showing grass-like structures and with flat common base – short crystals (top), long crystals (bottom); 4, straight grass-like crystals showing palisade-parallel (top) and palisade-radial structure (bottom); 5, radial or fan-like aggregates of straight crystals grown from common centres (right) and overgrowing fine-grained gypsum dome (left); 6, rows of small grass-like crystals without common sharp base grown on fine-grained gypsum domes; 7, rows of small grass-like crystals with sharp common base grown on fine-grained gypsum domes; 8, aggregates of crystals resembling palm tree leaves; 9, flat horizontal syndimentary dissolution surface within radial aggregates of the grass-like crystals showing syntaxial growth over this surface; 10, fine-grained homogeneous gypsum (alabaster when massive and white), or other non-differentiated fine-grained or microcrystalline gypsum; 11, fine-grained (alabaster-like) gypsum with traces of gypsified crenulated microbial mats; 12, small grass-like crystals covering surfaces of gypsified crenulated microbial mats and intercalating gypsum microbialite deposits; 13, clay and gypsum-clay deposit; 14, orange dusty clay; 15, syndimentary dissolution surface; 16, small channel-filled with sugar-like clastic gypsum; 17, clay intercalation; 18, orange dusty clay interpreted as aeolian dust or pyroclastic ash deposit; 19, horizontal discontinuity surface significant for correlation.

geological record, traceable over distances of hundreds of kilometres (Figs 8 & 16).

Non-selenite deposition in a shallow-brine pan

The deposits and the structures present between the grass-like selenite beds are critical for the interpretation of the evolving depositional environment of the shallow-brine pans.

The main requirement for non-selenite deposition in such pans is considered the 'exposure' of the bottom of the pan from the shelter of calcium sulphate saturated brine (HYP-MON in Fig. 11); or simply lack of a zone A at the bottom of the pan (Fig. 6). This can be realized in two general ways, by dilution and by shallowing, that in both cases can lead to another type of hydrography without the persistent brine cover at the bottom. Sedimentary features suggest that, in the case of many studied selenite sequences, the shallowing events were responsible for intercalated fine-grained gypsum deposition.

These scenarios assume the significant fluctuations of water and pycnocline level in the saline pan, as expected in any salina-type basin without open water connections with the sea (Fig. 3). The shallowing events begin with the development of the dissolution surface and truncation of crystal apices when they are removed from the shelter of saturated brine to the exposure with the more diluted brines above the pycnocline (as during formation of dissolution surfaces in a deep-brine pan; Fig. 12, centre left). Indeed such truncated crystal tops are very common in the Badenian selenite sequences (e.g. Fig. 15c, d & f). Less frequently, the crystal apices protrude from the top surface of selenite beds (Figs 14a & 15a & b), suggesting that a prolonged dissolution stage was omitted, probably because the pycnocline drop was very rapid (Fig. 18, right). In such cases, concentric coatings of laminated gypsum microbialites drape the protruding crystal apices, indicating that the microbial mats developed directly on the pre-existing well-terminated crystal tops (Figs 14a & 15a & b; see also Hardie & Eugster 1971, fig. 19; Peryt 1996, fig. 11e), as in the scenario in Figure 18, right.

It seems that during the water level fluctuations in the shallow-brine pan the water or brine level did not drop below the sediment surface. This can be demonstrated by a lack of any dissolution features on the sides of long crystal faces creating vertical intracrystalline pores within some grass-like selenite layers (Fig. 15c, d & e). No karst forms, infilling or related internal deposits were found at the bottom of these pores. Some intracrystalline pores show features typical of fenestral structures

and are covered along their upper surfaces by fine-grained gypsum that apparently is a product of *in situ* gypsification of the microbial mat spread across and between truncated selenite apices (Figs 15c, d & e & 18). The presumed existence of such a mat and its gypsification additionally supports the view that the depositional surface created by selenite apices was at least wet. The water level could have dropped to the sediment surface repeatedly during deposition of fine-grained gypsum intercalated with the selenite beds. Such lowering of the water level and associated episodic semi-emersion could be associated with the truncation of the crystal apices (mainly by run-off water sheet floods; Sanz *et al.* 1994), deposition of clastic and pedogenic gypsum as well as deposition of alabastrine gypsum from brine sheets (Logan 1987; Figs 15f & 18 left). Again, these presumed emersion episodes were not associated with significant deep erosion of the grass-like selenite crystals, apparently because the water or brine table level did not drop below the level of selenite apices in the study area. It seems that the water level rose concomitantly with the accretion of gypsum beds in these pans, which occurs in salina-type basins characterized by high accommodation.

Nevertheless, even in a salina basin, the periods of emersion, with depression of water level below the sediment surface, and associated weathering and erosion should be recorded in some way. Indeed, in the southern Nida area and the Miechów Upland in Poland layers of residual selenite debris were recognized. This debris represents the long-term emersion of selenite beds associated with the partial or complete disintegration of exposed gypsum (Fig. 15g & h; Ortí *et al.* 1984, figs 16.4, 16.5 & 16.6). The scenario of events leading to deposition of this selenite lag or regolith (Fig. 19) is nearly the same as suggested for the similar Messinian selenites by Garrison *et al.* (1978, fig. 30) and Schreiber (1978, p. 65), although the Badenian debris contains clay in the matrix between the crystal clasts.

The Badenian selenite debris deposits occur at the same interval of the section as the marker beds b1–b6 originated in the giant shallow-brine pan (Fig. 16). However general facies architecture and sedimentological data suggest that the debris represents reworking not from this shallow-brine pan, but rather some associated flat margin of the deep-brine pan in which the giant gypsum intergrowths were crystallised (unit A; Figs 8 & 9), namely the result of long-term emersion and destruction of marginal selenite beds. This style of reworking is recorded in recently exposed to weathering selenite beds crystallized on the slopes of the Marion Lake in Australia (Schreiber 1978, p. 65; references in Babel 2005b).

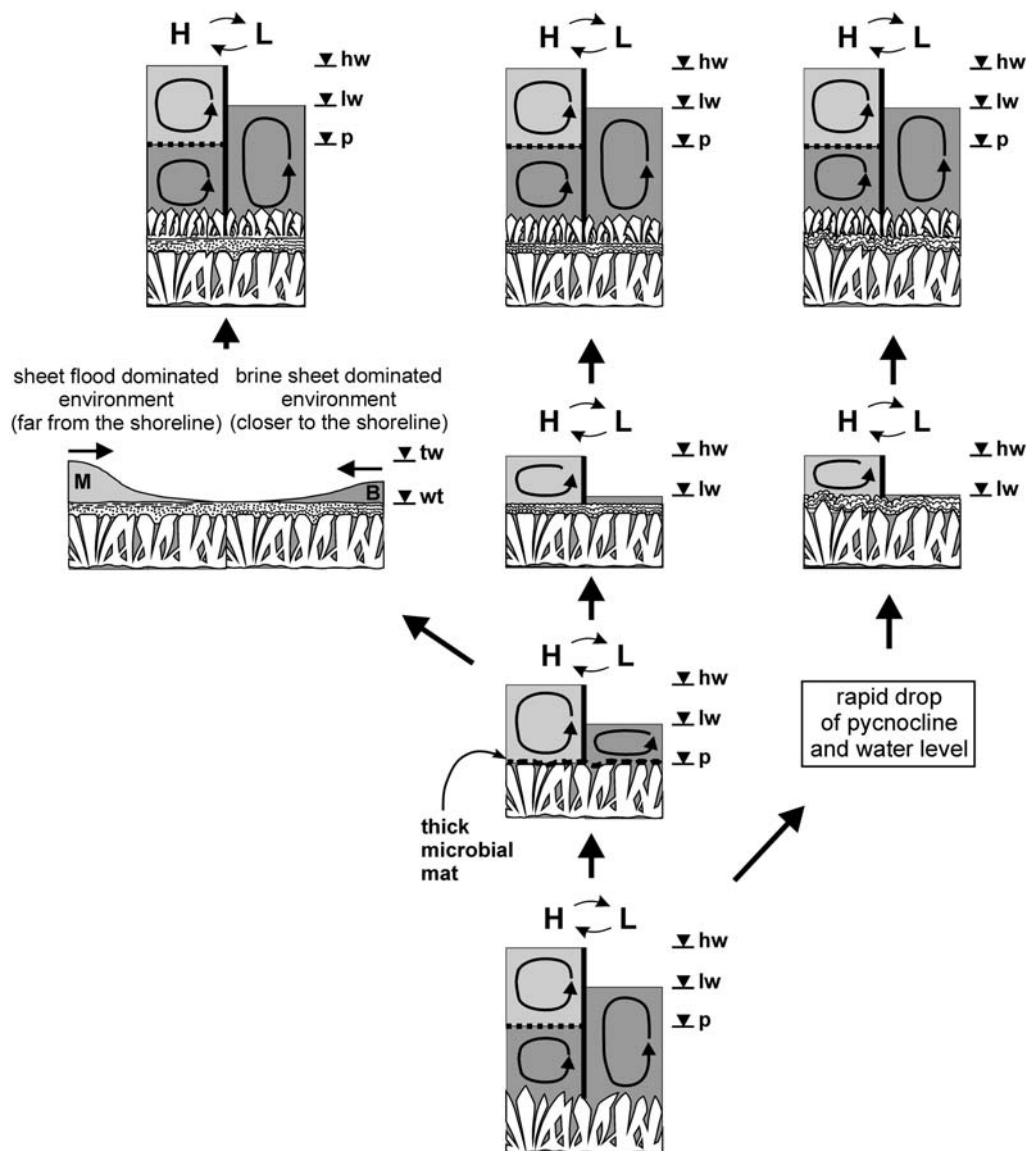


Fig. 18. Scenarios of shallowing events in a selenite pan with transition into majanna-type shoal environment (centre right; see Figs 4, 6 & 11a); further explanations in the text and Figure 13.

Remarks on the concept of a shallow-brine pan and its modern analogs The shallow-brine pan model represents an intermediate form of development between deep perennial saline basin (a deep-brine pan; Fig. 11b) and ephemeral (seasonally drying) lakes. In some aspects the modelled pan is similar to shallow-water selenite salinas, intermittently supplied with seawater, described by Warren (1982b, 2006).

In a manner similar to the shallow-brine pans the ephemeral, seasonally drying saline lakes or

playa lakes and continental salt pans are characterized by a flat bottom. They show a well-developed annual cycle of water level fluctuations and pronounced dry phase (e.g. Arakel 1988). During a dry phase a lake bottom is completely dry and exposed to weathering. A seasonal, more or less significant, lowering of the groundwater or brine table facilitates this weathering. Ephemeral saline lakes are described in many models (Valyashko 1952, 1972; Langbein 1961; Handford 1982; Lowenstein & Hardie 1985; Bryant *et al.* 1994).

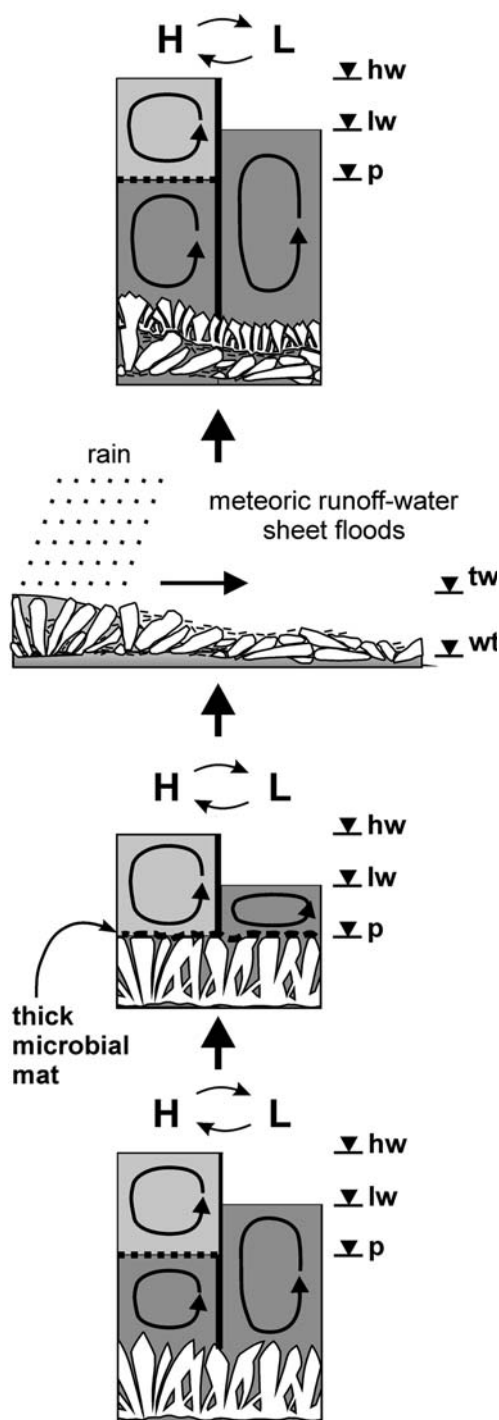


Fig. 19. Scenario of a long-term emersion event with weathering phase and creation of a selenite regolith or lag in a selenite pan (see Figs 6 & 11a); further explanations in the text and Figure 13.

The main difference between the shallow-brine pan and ephemeral lake is that the shallow-brine pan reflects the longer periods of water level fluctuations. Only during the water level lowstand is there a phase of seasonal drying, i.e. temporarily the pan is in an ephemeral lake state, although it is not obligatory for this model. Unlike the typical ephemeral lakes, the shallow-brine pans in the Badenian basin only dried episodically and in such periods the water or brine table level did not fall far below the sediment surface, similar to the brine covering the trona crystals at the bottom of Lake Magadi (Eugster & Hardie 1978; Eugster 1980; Warren 2006). It seems that this Badenian subsurface brine was not able to evaporate during seasonal lowstands.

The shallow-brine pan is particularly similar to saline pan model developed by Bryant *et al.* (1994) on the basis of the Chott el Djerid studies. These authors supplemented the scenario of events in ephemeral saline pan by Lowenstein & Hardie (1985) and distinguished an additional, 'moving' brine pool stage, i.e. brine sheet stage, appearing before the final complete drying of the pan (see Figs 4b & 18 left). Just such a phase of brine sheet deposition is apparently very important in many shallow-brine pans.

The shallow-brine pan shows seasonal water level fluctuations similar to those from ephemeral lakes (indicated by the scenario of Lowenstein & Hardie (1985), and shown by 'hw' and 'lw' in Figs 12, 13, 18 & 19) but these fluctuations are not as important in the depositional record as some prolonged water and pycnocline level fluctuations that are basically responsible for creation of the selenite sequences and their intercalated deposits (from bottom to the top in Figs 12, 18 & 19, and Figs 11a & 17). This basic fluctuation pattern recorded by selenite sequences in the Badenian basin appears to be some intrinsic feature of the salina basin similar to the long-term water level fluctuations observed recently in saline lakes around the world (e.g. Williams 1996; Comín *et al.* 1999).

It is possible that during the non-selenite phase of deposition in the shallow brine-pan its hydrography approaches that of the ephemeral saline pans. Owing to shallow water conditions only the temporary short-term pycnoclines were present in the pan and they were unable to maintain a brine shelter at the bottom (facies zone A; Fig. 6) supporting the continuous growth of selenite crystals (although some thin beds or clusters of grass-like selenites are found within fine-grained gypsum intercalations and can be related to some short-term presence of such a brine shelter).

The extreme seasonal fluctuations in salinity are characteristic for all ephemeral saline lakes. Their

salinity level changes from the entirely freshwater during the run-off of flood water on to the dry floor of the pan, up to halite saturation during the final drying. Such drastic salinity fluctuations are possible because the ephemeral salt lakes are supplied only or mainly with the meteoric water. It was documented by Campbell (1995) that shallow salt lakes continuously supplied with some saline water show more stable salinity characterized by low-amplitude seasonal fluctuations, opposite to those in common ephemeral saline lakes. The modelled pan discussed here is by definition more or less continuously supplied with marine brine produced from seawater flowing down to the bottom of a salina basin (Fig. 3), or some brine flowing in from the intermediate subbasins (Fig. 4).

Selenite-gypsum microbialite deposits of an oligotrophic pan

Unit SH is composed of peculiar gypsum deposits composed of masses of selenite crystals with predominantly horizontal orientation distributed within fine-grained microbialite gypsum, commonly showing the crenulated lamination characteristic of gypsified microbial (cyanobacterial) mats (Figs 8 & 20; Peryt 2001, fig. 16). These selenites create very large domal structures and microbialites are commonly incorporated within these structures. Some domes are entirely comprised of compact masses of selenite crystals and reach several metres in size.

These deposits were interpreted as having accumulated in some smaller saline pans surrounded by vast majanna-type shoals covered with microbial mats (represented by unit M described below; Figs 4, 8 & 9). Because the pan was cut off from terrestrial run-off waters it was poorly supplied with nutrients and was of the oligotrophic-type (Horne & Goldman 1994), which permitted the abundant growth of cyanobacterial mats even in the deep brine. Photosynthetic activity of such benthic cyanobacterial communities contributed to the oxygenation of the deep brine during stratification periods (Cloern *et al.* 1983) in a similar way to Lake Hayward (Burke & Knott 1997). Accretion and gypsification of microbial mats was concurrent with the growth of selenite crystals distributed within the microbial mats (Fig. 20a & b). Partial analogs of this peculiar but quite widespread Badenian facies, can be found in Lake Inneston in Australia (Warren 1982b), the Gotomeer basin in Netherlands Antilles (Kobluk & Crawford 1990) and the Solar Lake (Krumbein & Cohen 1977; Krumbein *et al.* 1977; Friedman & Krumbein 1985) as discussed by Babel (2005b).

Channel structures and gypsum microbialite deposition

Unit M is composed of gypsum microbialites interpreted as deposits of the majanna-type shoals (Figs 4, 8, 9 & 14). The microbialites show flat but crenulated lamination that originated from *in situ* gypsification of thin microbial (cyanobacterial) mats with encrustation by fine gypsum crystals (Fig. 18, centre). The laminae are 1–2 mm thick and some of them are covered with minute grass-like gypsum crystals typical of subaqueous syntaxial growth from supersaturated brine directly at the bottom. The laminated structure is very well preserved (Fig. 14b) which suggests that gypsification was periodic, 'mat by mat', i.e. after gypsification of the mat, suppressed by precipitated gypsum, the next living mat was developed on the gypsum substrate. After some period of growth the new mat was subsequently gypsified. Such deposits probably represented permanently wet, semi-emerged and seasonally flooded parts of majanna-type shoals (see Figs 4b, 14a & 15a, b), similar to wet flats covered with living microbial mats creating 'perennial surface brine' biofacies in the coastal salinas of the Red Sea (Gerdes *et al.* 2000). During seasonal highstand the shoals were flooded by water which was low-to-brackish salinity and permitted the intensive growth of microbial mats (see Logan 1987, fig. 52b & c). Salinity rise during ongoing lowstand, in a dry season, led to gypsification of the mat, in a similar way to the mat observed by Eckstein (1970, fig. 6) on the margin of the Solar Lake, and also similar to the mode of gypsification of microbial mats suggested by Rouchy & Monty (1981, p. 178). The encrustation with gypsum occurring alternately with the microbial mat growth, could also take place during irregular time intervals, dictated by some variable fluctuations of water level and brine sheet flows in the broad boundary zone between the saline pan and the wet majanna-type shoal (Figs 4b & 18, centre). In some instances, in deeper, more saline and permanent brine bodies, minute grass-like crystals (selenite) develop directly on the gypsified mat. Such microbialite gypsum deposits apparently were preserved in sufficiently deep depressions showing much higher accommodation than any known recent coastal salina (e.g. the Solar Lake or MacLeod basin), i.e. when the water and brine levels in the saline pans and majanna-type shoals were rising slowly but permanently.

These microbialites are intercalated and pass laterally into more homogeneous alabastrine facies, sometimes with horizons of scattered larger gypsum crystals. This alabastrine facies was

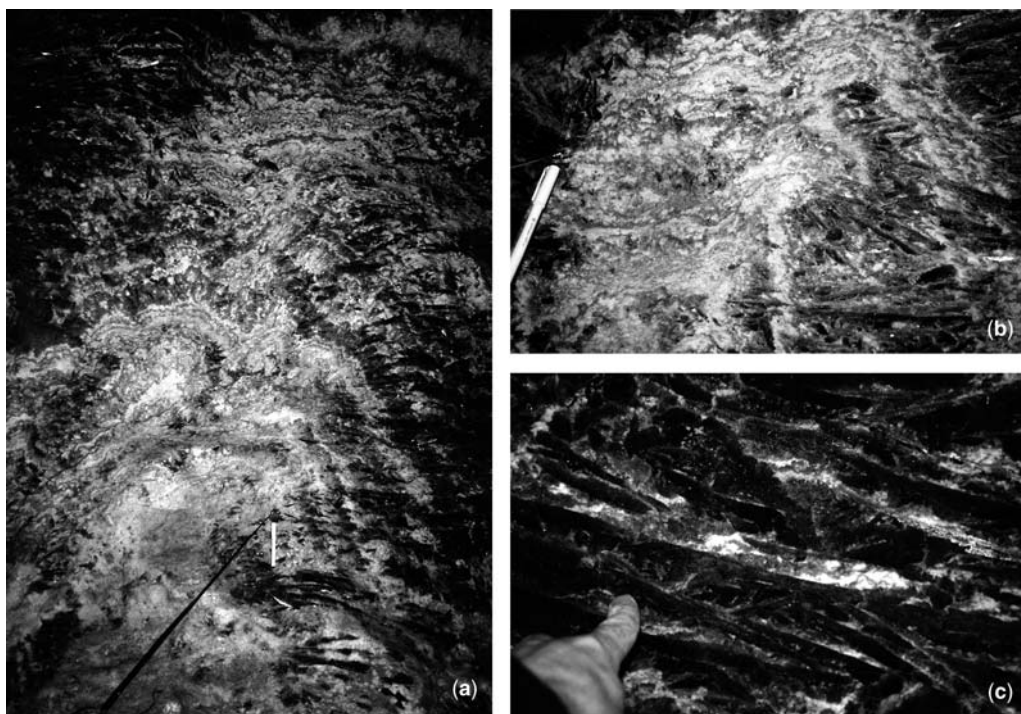


Fig. 20. Selenite–gypsum microbialite deposits representing the oligotrophic-type pan facies, note predominantly horizontal orientation of sabre gypsum crystals; transitional area between units SH and M, walls of Krystalna cave, Ukraine (locality 9, Figs 7–9). (a) Complex gypsum microbialite dome with selenite crystals grown on slopes, pen as a scale; (b) mushroom-shaped gypsum microbialite dome with selenite crystals grown on slopes; (c) horizontally grown selenite crystals typical of unit SH, with fine-grained gypsum showing microbialite laminations in between the crystals.

interpreted as *in situ* precipitates from brine sheets or some pedogenic deposits developed by dissolution and re-precipitation of gypsum on more elevated shoals during phases of temporary emersion (see Figs 4b & 18; Logan 1987; Aigner & Bachmann 1989; Magee 1991; Bryant *et al.* 1994; Peryt 1996; Babel 2005a). However, except for one level within the 20 m thick section, and the top surface of the gypsum section (Peryt 2001, 2006), no other remarkable erosion surface suggesting long-term emersion was recognized and the microbialite sections are conspicuously continuous (Peryt 1996, fig. 11d). The continuous vertical sequences of laminated gypsum microbialite deposits in unit M attain several metres in thickness (Figs 8, 9 & 14).

Specific channel structures are plentiful in such microbialite sequences. They are commonly seen as packages of laminated clastic gypsum forming small vertically elongated bodies (fig. 21; Peryt 1996, fig. 12; Babel 2005b, plate 3, fig. 2). They resemble infillings of karst cavities or neptunian dykes; however the contact with the surrounding microbialite gypsum is not sharp but indicative

of the concurrent deposition (Fig. 21b). Small gypsum microbialite domes are commonly accreted on some clastic laminae within the channels (Peryt 1996, fig. 13).

The laminated gypsum was deposited in shallow (<5 cm deep) flat-bottomed channels present on the majanna-type shoals. The bottoms of the channels do not show scouring features, suggesting the erosion of the substrate. Features produced by lateral migration of channel beds are almost entirely absent (Fig. 21). The channels were evidently infilled by clastic gypsum together with accretion of gypsum microbialites at its banks. Vertically elongated channel infillings suggest long-term existence of the channel beds in one portion of the evaporite shoal. The accretion of the channel structure took place together with the rising water level that presumably coincided with the sediment surface on the shoal (Fig. 22). Such an uninterrupted continuous rise appears to be barely possible in environments directly controlled by seawater level (due to low accommodation); however it is expected and perhaps is indicative of the salina basin where a drawdown of water level

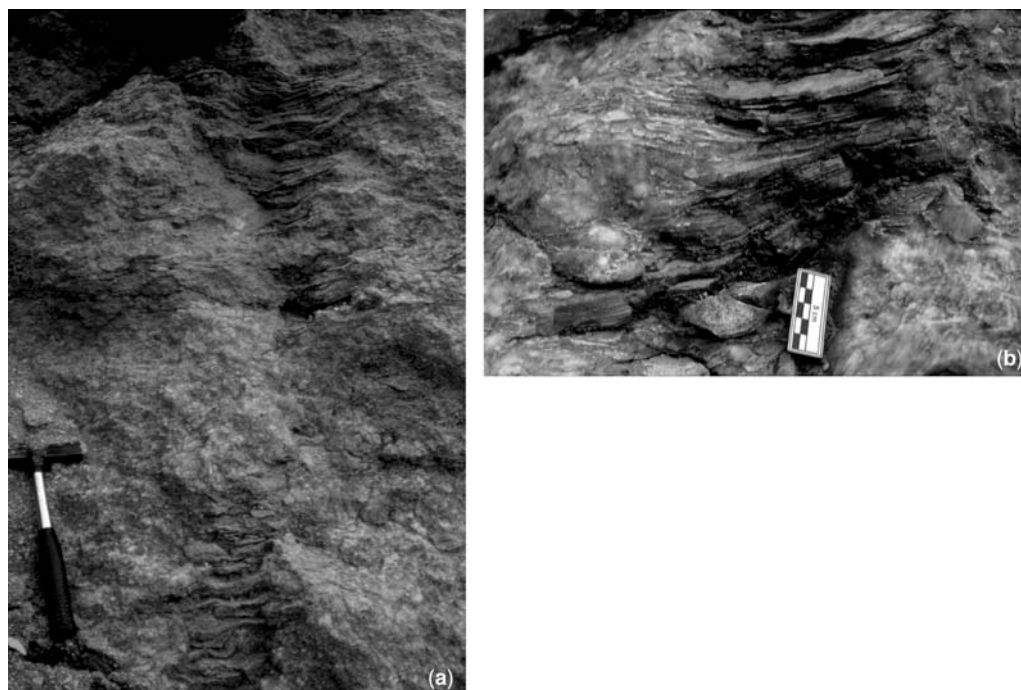


Fig. 21. Laminated gypsum in channels within gypsum microbialite deposits. (a, b) Majanna-type shoal facies, unit M, Ozerna cave, Ukraine (locality 11, Figs 7–9); scale is in centimetres in (b).

is very unstable (Fig. 3). The water or brine levels in the salina basin can easily rise together with the sediment accumulation as in the closed lake basins (Einsele & Hinderer 1997; Lowenstein *et al.* 2003). It is remarkable that one of the thickest continuous sequences of accreted microbial mat deposits (1.25 m thick) was found at the margin of the Solar Lake salina (Krumbein *et al.* 1977), and not on the marine tidal flat.

Similar channels are known from the zone of permanently flowing brine sheets on the majanna flats in the MacLeod basin (Logan 1987, fig. 53b, p. 64) and the drainage zones on the surface of Al-Khiran sabkha in Kuwait (Gunatilaka & Shearman 1988; Gunatilaka 1990). Warren (1982a) described similar forms under the name ‘algal channels’ in the Deep Lake selenite salina in Australia.

Architecture of Badenian selenite and microbialite facies and sequences

The recognition of the deep- and shallow-brine facies in the Badenian gypsum deposits allows analysis of the sedimentary record in terms of shallowing-upwards and deepening-upwards sequences (e.g. Fig. 14a). Both types of sequences are present in

the Badenian evaporites (Kasprzyk 1993a; Bąbel 2004b). In particular deepening-upwards sequences are relatively common and at least one of them apparently also is a brining-upwards one (Figs 8 & 9; Peryt 2001, fig. 10) that can be indicative of the salina basin with a deeply drawn-down water level. Very thick continuous microbialite sequences are also present and they reflect a brine table level rise that kept pace with the gypsum deposition on the majanna-type shoals (Figs 9, 21 & 22), which is also characteristic of such a basin.

It was demonstrated that marker beds b1–b6 and c (Figs 8 & 16) represent isochronous units and datum levels, i.e. they were nearly ideally horizontal at the time of their deposition. A rather complicated pattern of the architecture of gypsum facies arises from this scheme (Fig. 9), although the aggradational style of deposition is clearly visible. The striking features are:

- (1) complete dominance of shallow-water majanna-type shoal facies that occupied the whole thickness of the sections on the eastern end of the basin (near the Ukraine–Moldova border) and testify to a relatively continuous water level rise concordant with gypsum deposition (Fig. 22);

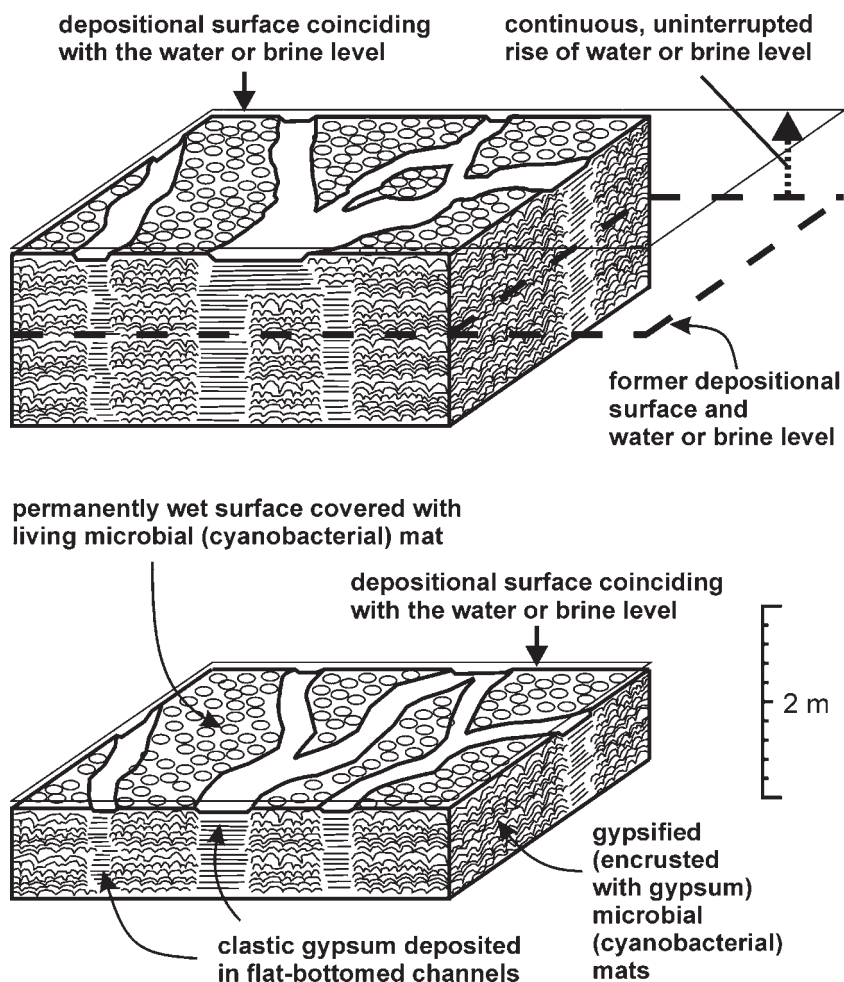


Fig. 22. Scheme showing mode of vertical accretion of gypsum microbialites concurrently with clastic gypsum deposition in shallow channels, controlled by a gradually rising water level on the permanently wet zone of the majanna-type shoal (see Figs 4 & 21).

- (2) the uneven thickness of gypsum sections and particular gypsum lithosomes (especially the selenite lithosomes; Fig. 8, see also Kubica 1992); and
- (3) poor correlation or expression of deepening-upwards and shallowing-upwards sequences present in the western area of the basin (see also Kasprzyk 1993a, b) in the eastern majanna-dominated area.

The most striking feature is that the deep-brine selenites of unit A seem to occur at the same hypsometric level that the microbialite deposits of the majanna-type shoals (unit M) present to the east (Figs 8 & 9; Peryt 2001, fig. 10). This latter feature, if correctly interpreted, appears to be

paradoxical because it means that a deeper water environment, several metres deep, existed at the western side of the basin at the same time when at the same hypsometric level as the basin bottom on the western area a vast semi-emerged shoal, without any significant cover of brine, could exist on the east.

All the listed features are possible in a lagoon-type basin, and can be explained by variable relief in the basin, different rates of sedimentation and subsidence (or uplift) in particular subbasins, differential compaction, as well as some rapid tectonic movements during gypsum deposition (deposition in synsedimentary grabens or half-grabens). However a simpler and more consistent explanation appears when a salina basin concept is applied for

the Badenian gypsum basin. In particular, the latter paradoxical features, different water levels and different bottom levels in particular subbasins, shoals and saline pans, are just possible and expected in a salina basin (Fig. 3). These disparate features can be explained if majanna-type shoals inclined parallel to the brine table levels spread between saline pans occupying different topographic levels and having different water levels. As these areas evolved in time and space they developed these seemingly dissimilar features (Fig. 4; Babel 2005b). Additionally, the peculiarities of depositional architecture can be explained by specific influence of tectonics on the water level and sedimentation in a salina basin.

Tectonic control of water level changes and deposition in a salina basin

When we assume that the Badenian basin was really a salina, we must take into consideration the possible influence of tectonics on the water level fluctuations in this basin and on the depositional architecture. This could be much greater than in the case where it was a lagoon-type basin with one water level always coinciding with the sea-level.

Subsidence, including rapid subsidence of tectonic blocks, can create accommodation both in salina and lagoonal basins; however its possible influence on the water level and the water depth is drastically different in the two basin types. In a lagoonal basin the water will be always supplemented by inflow from the sea, which can lead to deepening, whereas in a salina basin the water body, that always shows the same volume at any given time, will subside together with the basinal bottom and water depth can remain unchanged. Tectonic movements, however, may influence the water level in a salina basin to a greater degree than in a lagoon basin when the basin floor is tilted and one area is uplifted and the adjacent area subsides (Strecker *et al.* 1999; Ilgar & Nemec 2005). In such a case the water can flow from the uplifted to the subsident area and the water levels will be exchange directions in both areas (assuming an absence or limitation of sedimentation). Similar effects will take place when the rate of subsidence is irregularly distributed across a basin floor. The water level can rise in a salina basin due to massive transport of sediments into the basin, for example due to giant slumps which can displace some of the water volume onto the shoals (Ilgar & Nemec 2005). By contrast even very abundant and rapid sediment supply cannot promote any rise in water level in a lagoon basin where the water level coincides with the sea-level and is always controlled by global eustasy.

Tectonic movements, and especially the tilting of the basin floor, is expected in an active foreland basin system, such as the Carpathian Foredeep (DeCelles & Giles 1996; Catuneanu 2004; Oszczytko 2006a, b). Kubica (1992, pp. 31–33) assumed that the increased thickness of gypsum deposits in the northern margin of the basin, in comparison with its central area around the Rzeszów Island, is partly a result of increased rate of subsidence in the north, and many other authors accepted the tectonic activity in the foredeep during gypsum accumulation. If these interpretations are correct, then the possible influence of the tectonic movements on changes in the local water level within a salina basin should be taken into account, as indicted by Kwiatkowski (1972, pp. 69, 92).

Thus a relatively continuous presence of majanna-type shoals on the eastern side of the basin contrasting with occurrence of giant saline pans with fluctuating water levels in the western side (Fig. 9) can be explained in two ways: (1) these two areas were hypsometrically different and showed different water levels in the salina basin (Fig. 4a); and/or (2) vertical tectonic movements were irregularly distributed across the basin floor and were responsible not only for local differences in accommodation but also contributed to different style of water level changes in these adjacent areas.

In sum, analysis of the architecture of the salina-type basins in terms of sequences controlled by water level changes appear to be much more complicated than lagoon basins controlled by one common water level coinciding with sea-level.

Conclusions

Ancient evaporite basins occupying the depressions supplied with seawater through seepage and occasional surface inflows, without open water connections with the sea, show specific features in the depositional record. Such distinctions can help in the recognition of these basins (called here salina or salina-type basins) and they may be discerned from the other basin types, and particularly from the lagoonal evaporite basins permanently connected with the sea. The environments of the salina basin were very similar to those of the modern saline lakes, and based on these lake environments, and of the environments of marine coastal salinas (and the MacLeod basin in Australia in particular), an integrated group of conceptual models was built for facies analysis of such a basin, at the stage of gypsum crystallization. Both permanently subaqueous and semi-emerged environments were modelled, i.e. saline

pans (subbasins) and evaporite shoals in between and around them (they were termed majanna-type sholas by analogy to the specific majanna environment in the MacLeod basin). The models developed here were applied and tested in the Badenian selenite-dominated evaporite basin of the northern Carpathian Foredeep.

Many specific features of these models, i.e. the predicted features of the salina-type basins, were recognized in the depositional record of the Badenian gypsum basin. Some depositional features, including the architecture of gypsum facies, seem more readily explained and understood when it is assumed or accepted that:

- (1) Water level fluctuations in the basin were more frequent, more rapid, and larger in scale than normal sea-level changes (i.e. the basin showed its own pattern of water level fluctuations, more similar to those in modern saline lakes than in the present seas or lagoons).
- (2) The Badenian subaqueous environments (and their depositional record or gypsum facies) can best be described according to the limnological terminology, and characterized by the presence of stratification-mixing cycles typical of monomictic and polymictic lakes and, consequently, by the presence of seasonal to temporary stratification of brine column (i.e. the pycnocline).
- (3) The fluctuations in the level of the pycnocline influenced the course of selenite deposition, which predominately took place below the seasonal (or temporary) pycnocline in saline pans, and mainly during the mixing periods.
- (4) Long-term drops of an average pycnocline level (pycnocline lowstands) were associated with development of dissolution surfaces and deposition of fine-grained gypsum (commonly fine-grained gypsum microbialites). Rises (highstands) of the pycnocline were associated with crystallization of the grass-like selenite beds. Consequently, such selenite beds, when laterally continuous and arranged into depositional bundles showing some constant pattern of thickness, were assumed to record the pycnocline fluctuations in the particular saline pans.
- (5) Some thin and well-recognizable grass-like selenite beds record the pycnocline highstands in the whole gypsum subbasin. These were used as event or marker beds for basin-scale isochronous (or near isochronous) correlation over distances of tens to hundreds of kilometres. Additionally, such beds are treated as ideal datum surfaces, because the growth of gypsum crystal apices was

determined by the horizontal position of the pycnocline.

- (6) Thick continuous sequences of gypsum microbialite deposits (several metres thick), containing specific vertically accreted stationary channel structures, were deposited on semi-emerged permanently-wet majanna-type shoals, periodically flooded by gypsum-saturated brine sheets inflowing from the adjacent saline pans. The long-term continuous accretion of gypsum microbialites on the shoals apparently kept pace with the gradual uninterrupted water level rise in the basin, a case barely possible in environments directly controlled by a sea-level, but characteristic of the salina basin with the high accommodation potential.
- (7) One of the depositional sequences in the gypsum basin is both deepening-upwards and brining-upwards, which is also a case only barely possible in the lagoonal basins but that appears to be indicative of environments not controlled directly by sea-level and showing a high accommodation.
- (8) Poor correlation of shallowing-upwards and deepening-upwards gypsum sequences from different sides of the gypsum basin can be a result of tectonic control of the local water changes in the salina basin (which is specific feature of the lake-type depositional systems), or deposition in two subbasins showing different fluctuations of the water levels.

All these depositional features together consistently suggest that the Badenian gypsum basin (at least during the selenite deposition) was not an evaporite lagoon but a salina basin with a water level drawn down below global sea-level, although salts in the water from which the gypsum crystallized were basically of marine derivation, and could pass through recycling processes within the basin.

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