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Selenite-gypsum microbialite facies and sedimentary evolution of the Badenian evaporite basin of the northern Carpathian Foredeep

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ABSTRACT

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Facies analysis was applied to the six main facies of the Badenian (Middle Miocene) gypsum deposits exposed along the margin of the Carpathian Foredeep basin, from Moldova to the Czech Republic. These facies, recognised within primary selenite and fine-grained gypsum deposits, are: (i) selenites with vertical crystals; (ii) selenites with horizontal crystals; (iii) selenite debris flow facies; (iv) selenite debris facies; (v) gypsum microbialite facies; and (vi) alabastrine facies. The facies represent various environments (from shallow-brine to subaerial) of a giant salina-type basin without open-water connections with the sea and showing evaporite drawdown. Integration of facies analysis and event stratigraphic studies in the gypsum basin allowed reconstruction of its sedimentary history. The architecture of the gypsum facies suggests that the margin of the basin was occupied by a system of variable perennial saline pans (dominated by selenite deposition) and evaporite shoals (dominated by gypsum microbialite deposition). The basin was infilled with evaporite deposits by aggradation. After initial evaporite drawdown, the northern margin of the basin evolved from a large perennial saline pan (or system of pans) into an evaporite shoal and then back again into a perennial pan, whereas the east area of the basin was a vast evaporite shoal dominated by gypsum microbialites. Separate selenite pans of oligotrophic-type developed both at the periphery and in the interior of this shoal. Later, predominantly clastic gypsum deposition developed throughout the basin margin, presumably due to a drastic change in the chemistry and salinity of the brine. Evaporite deposition was arrested by a flood of marine waters and rapid deepening.

Key words: Facies analysis, Selenites, Gypsum microbialites, Evaporites, Salina basin, Oligotrophic, Eutrophic, Debris flow, Miocene, Carpathian Foredeep.

INTRODUCTION

Facies analysis is a key tool for the reconstruction of the palaeogeography and depositional history of sedimentary basins. However, application of the method to ancient evaporite basins is limited by the common, often complete, diagenetic transformation of the evaporites. This obliterates the primary features required for analysis of the original depositional facies. Primary gypsum deposits are particularly sensitive to dehydration and rehydration processes, which operate both during the deep burial-exhumation cycle and in the original depositional setting. Therefore, the environments of the giant ancient gypsum basins, with no recent equivalents in scale and variability, are still relatively poorly known.

The Badenian (Middle Miocene) basin of the northern Carpathian Foredeep is one of the largest evaporite basins in which the primary gypsum deposits are both

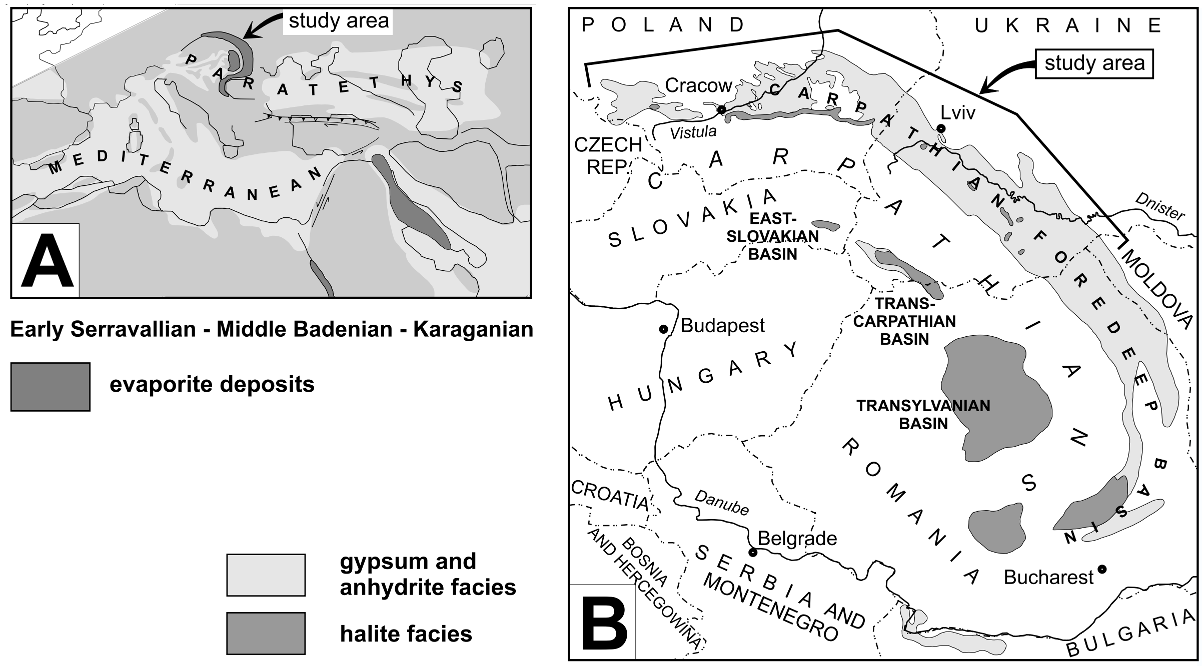

Fig. 1. Palaeogeography and distribution of Badenian evaporite basins. A) Palaeogeography of Paratethys and Mediterranean in the Middle Miocene and location of the Badenian evaporite basin studied (after RÖGL 1999). B) Present distribution of the Badenian evaporites in the Carpathian area (after KHRUSHCHOV & PETRICHENKO 1979, GARLICKI 1979, modified)

very well preserved and exposed (Text-figs 1A-B). The undisturbed gypsum strata extend over vast areas and the numerous outcrops permit detailed recognition of their depositional architecture. These features make the Carpathian Foredeep a basin unique for the analysis of ancient gypsum facies (see KWIATKOWSKI 1972; KUBICA 1992; KASPRZYK 1993, 1999; PERYT 1996, 2001; PETRICHENKO & *al*. 1997; ROSELL & *al*. 1998).

The Badenian gypsum facies of the Carpathian Foredeep were previously studied by the author in a small area exposed in the Nida river valley in Poland (Text-fig. 2A; BĄBEL 1999a, b). The present study is an extension of the former investigations, ranging from Moldova, Ukraine, Poland, to the Czech Republic. The fieldwork was carried out in the period 1992-2002. More than one hundred sections were studied in detail (BĄBEL 2005, On-Line Appendix).

This paper reconstructs the sedimentary history of the Badenian gypsum evaporites in the northern Carpathian Foredeep on the basis of facies analysis and event stratigraphic methodology (Text-figs 3-4, BĄBEL 2005). After presenting the facies analysis, focused on several very important, new, or poorly recognised gypsum facies, the general sedimentary history of the gypsum evaporites is discussed.

The terms: facies, selenite, gypsum microbialite, gypsified microbial mats, monomictic, meromictic, polymictic, epilimnion, hypolimnion, mixolimnion, monimolimnion, pycnocline, a salina basin, a saline pan, evaporite drawdown, brine sheet, majanna, are used in the sense defined or described in BĄBEL (1999a, 2004a, 2004b). Lithosomes are defined as ‘masses of rocks of similar lithology that intertongue and grade into rocks of different lithologies’ (FAILL 2003, p. 410, with references).

GEOLOGY OF THE BADENIAN EVAPORITE BASIN

The Carpathian Foredeep basin is the largest evaporite basin developed during the Badenian salinity crisis in the Central Paratethys area (Text-figs 1-2; RÖGL 1999). In its northern part, the evaporites occur as laterally continuous layers of gypsum, anhydrite, halite and carbonate deposits, intercalated commonly with clay, and usually 10-60 m in thickness. The evaporites are underlain by marine Badenian clastics and carbonates, which cover an eroded, mostly Mesozoic and Palaeozoic, substrate transgressively, and are overlain by marine to brackish Badenian-Sarmatian carbonates and clastics. The gypsum deposits crop out along the northern margin of the basin and pass into anhydrite and halite deposits towards the Carpathian Mountains; sulphate deposits appear again in a few places along the main Carpathian overthrust. In the latter area, the evaporites were dis-

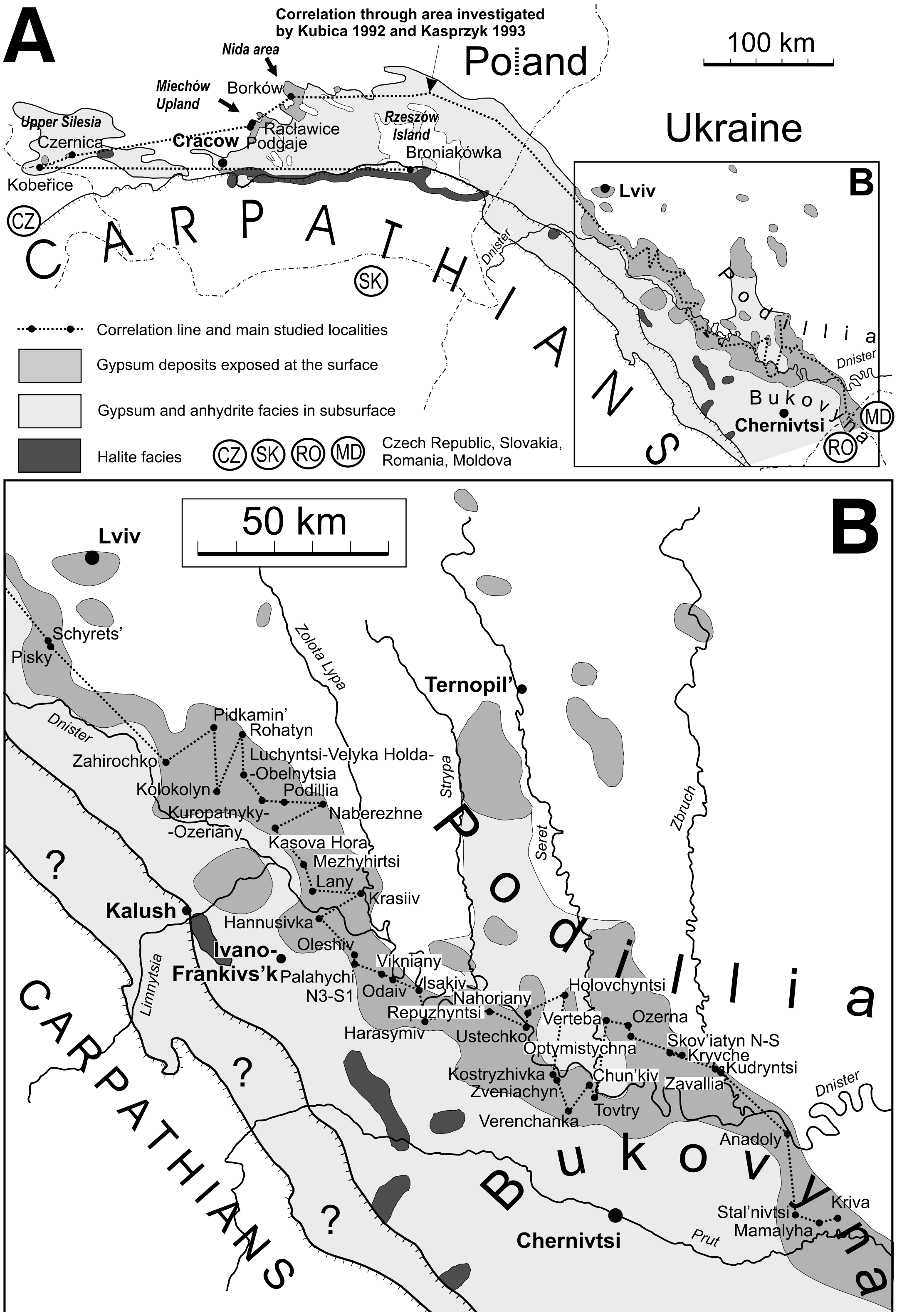

Fig. 2. Distribution of the gypsum sections studied in the Badenian (Middle Miocene) evaporite basin in the northern Carpathian Foredeep in Ukraine, Poland, Czech Republic and Moldova; A-B - Maps of the study area and the correlation line for Text-fig. 3-4; maps after various sources cited in BĄBEL 2004b; 2005, On-Line Appendix

turbed by tectonic movements and are folded in front of the Carpathian nappes, and are not folded when rest on the tectonically displaced nappes. Palinspastic reconstruction indicates up to 50 km tectonic shortening of this area of the saline basin (POŁTOWICZ 1993).

The evaporite basin was subdivided into several subbasins: halite-dominated, containing laminated anhydrites and clay intercalations, in the south; and gypsum-dominated in the north. The gypsum subbasins were very broad and shallow (0 to several metres deep) and they are commonly treated as a single marginal sulphate platform, with slightly undulating relief (KASPRZYK & ORTÍ 1998). Presumed shoals and islands delimit particular subbasins. The largest central area, devoid of evaporite deposits, was interpreted as an island (Rzeszów Island; Text-fig. 2A), although the evaporites could have been eroded subsequently (POŁTOWICZ 1993, OSZCZYPKO 1998). Stratigraphic studies proved that the northern marginal gypsum deposits were isochronous (Text-fig. 4, PERYT 2001, BĄBEL 2005), like the evaporite cyclothems in the halite subbasins in the Polish part of the foredeep (GARLICKI 1968, 1994; GARCÍA VEIGAS & *al*. 1997). The precise stratigraphic relations between the gypsum and halite subbasins remain, however, unclear (see review in ANDREYEVA-GRIGOROVICH & *al*. 2003).

The Badenian gypsum facies in the Carpathian Foredeep display features typical of deposition in a salina-type basin (PERYT 2001, BĄBEL 2004b, CENDÓN & *al*. 2004). At least on its northern margin the basin was a depression with the water level below the sea level. Evaporite drawdown was preceded and followed by normal marine sedimentation. The basin was supplied with marine water, or marine brine, presumably in a similar way to coastal salinas - by seepage or occasional inflows through some morphological barriers. The water-level fluctuations in the gypsum basin apparently did not coincide with the world sea level. The concept of a salina basin (BĄBEL 2005) is crucial for the interpretation of the various gypsum facies, which recorded specific salina environments.

GYPSUM FACIES ANALYSIS

The following facies analysis concerns mainly the selenite and selenite-dominated deposits, which are the most relevant to the general reconstruction of the sedimentary evolution of the evaporite basin. Other important facies like the microcrystalline gypsum, anhydrite and secondary gypsum (after former anhydrite) facies groups, as well as the carbonate facies, were described and analysed earlier (see BĄBEL 1999a, with references; PERYT 1996, 2000, 2001; GĄSIEWICZ 2000, with references; KASPRZYK 2003, 2005).

The primary gypsum facies are grouped into two types: (i) the selenite and the selenite-dominated facies; and (ii) the fine-grained gypsum facies. The selenite facies is composed of four main facies: (1) selenites with vertical crystals; (2) selenites with horizontal crystals; (3) selenite debris flow facies; and (4) selenite debris facies. The fine-grained gypsum facies is subdivided into: (1) gypsum microbialite facies; and (2) alabastrine facies.

SELENITE AND SELENITE-DOMINATED FACIES

Selenites with vertical crystals

Description: This well known facies (e.g. KASPRZYK 1993, PERYT 1999, PETRICHENKO & *al*. 1997, ROSELL & *al*. 1998) is composed of vertically and subvertically elongated, bottom-grown crystals commonly forming rows and thick beds. Volumetrically this is the most important facies. The crystals form both perfect palisade structures and nearly chaotically arranged aggregates, giving many facies varieties which pass gradually one into another. One common variety is a non-bedded or poorly bedded selenite (selenite without macroscopically visible bedding) which usually forms beds several metres thick. This facies grades into a flat bedded selenite, with distinct layering created either by horizontal dissolution surfaces or by thin intercalations of fine-grained gypsum, with some admixture of carbonates or clay. Selenite beds within the latter facies are 0.5-1.5 m, 15-40 cm, several cm-10 cm, and less than 5 cm thick (BĄBEL 2005, On-Line Appendix). The bedded selenite, with beds composed mostly of a single generation of bottom-grown crystals intercalated regularly with fine-grained (microbialite, clastic or pedogenic) gypsum, is referred to as the grass-like facies. When the grass-like selenite components disappear, the facies passes into fine-grained gypsum deposits, mostly into gypsum microbialites or alabastrine facies.

Depending on the morphology and arrangement of the gypsum crystals, two main subordinate facies are distinguished: the giant gypsum intergrowths (Pl. 1, Fig. 1; unit A in Text-figs 3-4) and the sabre gypsum facies. The latter is further represented by two distinct and volumetrically important facies types:

(1) The sabre facies composed of crystals which started to grow vertically and then curved laterally (Pl. 2, Fig. 1). The 100 twins are commonly 'nuclei' of such sabre crystals. A characteristic feature of this facies is concordant orientation of crystal apices traceable over long distances and reflecting the direction of bottom brine currents (BĄBEL & *al*. 1999, BĄBEL 2002). This facies occurs in lithostratigraphic units C-D and F (Text-figs 3-4).

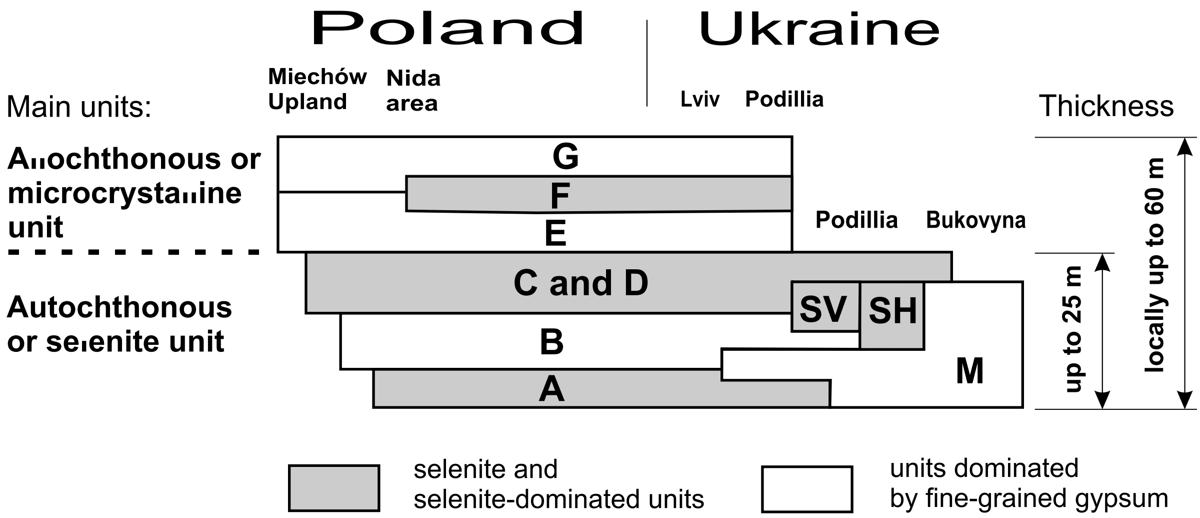

Fig. 3. Lithostratigraphy of the Badenian gypsum evaporites (after KUBICA 1992, supplemented) in the northern Carpathian Foredeep along the correlation line from the Miechów Upland to Bukovyna (see Text-fig. 2)

(2) The sabre facies composed of crystals which started to grow sub-horizontally and then curved upward (Pl. 2, Fig. 2). The sabre crystals commonly developed syntaxially on the small gypsum intergrowths, which are of the same crystallographic nature as the giant intergrowths from unit A. Characteristic giant selenite domes composed of long sabre crystals which are curved upward on the slopes of the domes are common in this facies. This facies occurs in lithostratigraphic unit SV in Ukraine, and in Upper Silesia (Text-figs 2A, 3-4; TREMBECKI 1952).

Interpretation: The selenites with vertically orientated crystals are very common both in ancient and in recent evaporite settings, particularly in solar saltworks and coastal salinas (e.g. SCHREIBER 1988, WARREN 1999). They are typical subaqueous precipitates. These selenites were crystallised in situ in perennial, presumably monomictic to polymictic saline pans (BĄBEL 2004a). The coarsest crystals commonly grew in the hypolimnion zone below an average pycnocline. The thinnest selenite crusts (<5 cm) and intercalated fine-grained gypsum can, alternatively, represent ephemeral saline pans or even evaporite shoals covered by brine sheets oversaturated with calcium sulphate (LOGAN 1987, pp. 23-24). The poorly bedded, coarsest-crystalline selenites, especially those lacking dissolution features, were deposited at a depth not accessible to meteoric water and represent the deepest pans. Well-layered and grass-like selenites intercalated with fine-grained gypsum were deposited at a depth that could be reached by meteoric water and represent shallower brines. The various morphologies of the bottom-grown crystals reflect different compositions and properties of the brine. The giant intergrowth and sabre gypsum facies, characterised by different crystal morphologies and fabric, can represent separate saline pans (BĄBEL 2005).

Selenites with horizontal crystals

Description

This facies, hitherto poorly recognized, is associated spatially with three other facies: the selenites with vertical crystals; the gypsum microbialites; and the microcrystalline gypsum facies. It is characterised by horizontal and subhorizontal orientation of elongated gypsum crystals (Pl. 4, Figs 1-2; Text-fig. 5). The crystals did not grow upward from a single horizontal substrate or depositional surface, but grew from randomly scattered points or a subvertical to vertically orientated substrate, e.g. slopes of some large domal structures. The crystals do not display any abrasion and fragmentation except for compaction breaks, which in some outcrops, particularly in the Nida area and Miechów Upland, are relatively common. The crystals commonly form bundles of split and parallel aggregates. Downward-orientated crystal apices are quite common. In many places, elongated crystals or crystal aggregates show crystal apices orientated in one horizontal direction, but this direction is not constant and varies greatly between adjacent outcrops. As in the facies with vertical crystals, the crystal boundaries show features of competitive growth. Fine-grained gypsum occurs in between crystals but commonly the selenite rock is composed exclusively of tightly intergrown large crystals. Some intergrown selenite crystals appearing within 'non-palisade intergrowths' in the Nida area (BĄBEL 1999a, b) show large empty intercrystalline pores. Fine-grained gypsum commonly covers the upper faces of large crystals and in places shows crenulated lamination typical of the gypsified microbial mats (Pl. 4, Figs 1-2). Sometimes it forms laterally continuous beds intercalating crystal aggregates. The selenite facies with horizontal crystals generally displays very irregular, wavy stratification, and lacks the horizontal dissolution surfaces typical of the facies with vertical crystals. The selenites with horizontal crystals enriched in fine-grained gypsum commonly show soft sediment deformation; load structures beneath large crystals clusters and folds related to sediment creep and slump. Thin intercalations of debris flow deposits containing redeposited gypsum crystals occur rarely.

Based on gypsum crystal morphology, two main subordinate facies are distinguished: giant gypsum intergrowths with horizontally orientated crystals (BĄBEL 1999a); and sabre gypsum with horizontally orientated crystals (Text-fig. 5). In the Nida area, the former facies occurs within the non-palisade giant intergrowth facies and the latter is represented mostly by wavy bedded sabre facies (BĄBEL 1999a, pl. 3, fig. 1; pl. 8, fig. 1). In the entire basin these two facies commonly overlie the selenite facies with vertically elongated crystals.

Near Skov'iatyn and Kryvche (Text-fig. 2B), the unit with sabre facies with horizontal crystals is ca. 20 m thick (unit SH; Text-fig. 4). This unit passes laterally into gypsum microbialites (unit M; Pl. 3, Figs 1-2) and the transitional zone can be observed. In-situ grown clusters of horizontally orientated selenite crystals appears randomly scattered within the gypsum microbialites (Pl. 4, Fig. 1). The microbialite laminae of the fine-grained gypsum are deformed downward below the selenite aggregates, show laterally sharp contacts with them, and coat their upper surfaces in a manner suggestive of stromatolite heads. The gypsum microbialites with selenite clusters pass laterally into tightly intergrown horizontal aggregates of selenite crystals lacking fine-grained gypsum and pores (Pl. 4, Fig. 2), and pass further into selenites with sabre crystals arranged subvertically and radially, forming domes several metres high (Pl. 5). The longest sabre crystals (up to 1 m), commonly split into subparallel aggregates. They are subhorizontal, curved upward, and occur on the slopes of the domes. The giant domes show poor concentric bedding created by intercalations of fine-grained gypsum (Pl. 5). Some domes display peculiar shapes and resemble vertical columns with the sabre crystals arranged radially around a central narrow tube composed of fine-grained gypsum (KLIMCHOUK & *al*. 1995, TURCZYNOW & ANDRIJCZUK 1995). A characteristic feature of the selenites under discussion (unit SH) is the dark honey colour of the gypsum crystals due to the included organic matter, and the lack of macroscopically visible growth zonation.

Interpretation

The selenite facies with horizontal crystals is associated with three different facies (the gypsum microbialite facies; the bedded selenites with vertical crystals; and the microcrystalline facies) and occurs separately, spatially connected with these facies, within different lithostratigraphic units and in various areas (Text-fig. 4). This suggests deposition in three types of saline pans in a salina basin: an oligotrophic pan, an eutrophic pan, and the pan associated with the microcrystalline facies. The first two are described below; the third one is briefly characterised in the section on the selenite debris flow facies. The basic features of saline pans in a salina basin were described previously (BĄBEL 2004a, b).

Oligotrophic selenite pan: The facies associated with the gypsum microbialites and the giant selenite domes (occurring in units SH and M, typically in the eastern part of the basin; Text-figs 2-4) is interpreted as deposits of the oligotrophic pan. It was a low-salinity perennial pan isolated from influxes of land-derived runoff waters, as well as without direct open-water connections with any other saline pans or basins (Text-fig. 5, top). The essential feature of this pan was oligotrophic transparent brine permitting accelerated growth of phototrophic cyanobacterial communities. A high supply of oxygen produced by photosynthetic cyanobacteria limited the bacterial sulphate reduction in the deep (possibly several metres) brines. These brines were thus oxygenated and hence relatively rich in SO_4^{2-}. Gypsum crystals could easily grow in such brines, even at a greater depth, directly on the surface of the microbial mats, within the mats and below them.

The oligotrophic pan was surrounded by vast, flat, seasonally flooded, and permanently wet evaporite shoals (gypsum microbialites; unit M in Text-fig. 4) representing the 'perennial surface brine' biofacies destinguished by GERDES & *al*. (2000). These shoals resembled the wet majanna flats of the MacLeod salina in Australia (LOGAN 1987), the permanently brine-saturated marginal areas of the Solar Lake salina in Sinai, Egypt (GERDES & *al*. 1985, fig. 15.4), and similar flats from the Gavish Sebkha in the same area (EHRLICH & DOR 1985, fig. 15.3; GAVISH & *al*. 1985). Consequently, it may be suggested that the shoals were composed entirely of brine-soaked gypsum-organic deposits (gypsum microbialites) and their surfaces were covered with living cyanobacterial mats. The oligotrophic pan was situated far away from the emerged land area, and separated from it by the shoals. The shoals were wide and flat enough to protect the pan from land water drainage. They also 'sheltered' the pan from the clay-loaded runoff water floods from the land areas, which could possibly have supplied some nutrients washed from soils and contributed to eutrophication of the brine (HORNE & GOLDMAN 1994, JAVOR 2002). It is known that small isolated saline pans with limited water input from runoff are usually poor in nutrients and are oligotrophic (DEL CASTILLO ARIAS & FARFÁN 1997). The Badenian pan was mostly supplied with water from adjacent saline pans or some larger basins, with higher water levels (as in the case of the saline lakes on Christmas Island (Kiritimati), Kiribati Republic, Central Pacific; see TRICHET & *al*. 2001). Like in the MacLeod salina (LOGAN 1987), the water was transported into the pan as brine sheets flowing through the shoals separating the adjacent pans, or as streams in channels cut into the shoals (Text-figs 5-6; Pl. 3, Fig. 2). The rare runoff-water floods could dissolve gypsum substrate on the shoals and carry calcium sulphate-saturated brine to the pan (LOGAN 1987, pp. 25, 77, 80). The brine was also supplied to the pan by seepage and subsurface transport (Text-figs 5-6). The seepage was particularly accelerated during the few decimetre drops of water level in the pan during the driest season of the year, like in recent coastal salinas and lakes (WARREN 1982a, b).

The water or brine flowing into the pan was poor in nutrients, which were largely consumed by microorganisms inhabiting vast shoals. The brine from brine sheets flowing through the shoals seeped into the substrate and could leak out in drainage channels leading to the pan or directly in the pan as underwater seeps or springs (Text-fig. 5). When the brine passed over and seeped through the living mats, benthic microbial communities were able to extract and use the nutrients still available (see ROSEN & *al*. 1996). Therefore the brines flowing into the pan were highly impoverished in nutrients. Such brines were unfavourable for phytoplankton growth (see JAVOR 2002) and showed the great transparency typical of oligotrophic basins.

The great transparency of the brine contributed to the growth of phototrophic cyanobacterial communities throughout the pan. Thick microbial mats most commonly develop in oligotrophic waters and in areas of high insolation (e.g. PAERL & *al*. 1993, TRICHET & *al*. 2001). JAVOR (2002) claimed that a moderate supply of nutrient is optimal for the accelerated growth of microbial mats in shallow solar saltwork pans. When a brine is rich in nutrients, the phytoplankton typical of saline waters (primary producer the green alga *Dunaliella*, haloarcheans or halobacteria) can develop rapidly, leading to a drastic drop in transparency (JAVOR 2002). When phytoplankton blooms are frequent, they shade the bottom and inhibit the growth of phototrophic benthic cyanobacterial communities, thus limiting the deposition of microbialite. Saline waters commonly display a very low transparency (e.g. 0.45-0.5 m in saline heliothermal lakes; SONNENFELD & HUDEC 1980; 0.5-4.0 m in the Dead Sea; NEEV & EMERY 1967) due mainly to the presence of phytoplankton. However, the water transparency can sometimes be very high. For example the Aral Sea showed a standard transparency up to 27 m (DICKEY 1968).

The brine in the oligotrophic pan under discussion was supposedly of a relatively low salinity, enabling benthic cyanobacterial communities to grow rapidly (see BĄBEL 2004a, fig. 4). The salinity presumably fluctuated around that found at the beginning of the gypsum saturation stage, permitting the deposition of a laminated gypsified microbial mat (BĄBEL 1999a, p. 410). This salinity could have been lower than in the eutrophic selenite pans (Text-fig. 5, bottom) connected with the flat-bedded selenite facies. Fluid inclusion analyses from primary selenite crystals suggest that salinity indeed varied greatly throughout the Badenian basin, but the data from particular selenite facies have not been compared; KULCHITSKAYA 1982, fig. 5; PETRICHENKO & *al*. 1997). Due to the relatively low salinity (see FRIEDMAN & *al*. 1985, p. 236; MOUNÉ & *al*. 2003; PAERL & *al*. 2003; and discussion in BĄBEL 2004a, pp. 230-234), oligotrophic conditions and the associated clarity of the brine (HORNE & GOLDMAN 1994), phototrophic benthic cyanobacterial communities could have flourished throughout the pan, even within the zone below the pycnocline (hypolimnion or monimolimnion; Text-fig. 5). Photosynthesis by such abundant cyanobacterial communities was supposedly very intense and sufficient to supersaturate the bottom waters with oxygen, thus preventing the development of anoxia during stratification periods in the same way as in the monomictic Lake Hayward in Australia (BURKE & KNOTT 1997). This saline lake shows a seasonally changing depth from 2 to 3 m and a standard water transparency 1.7-2.6 m.

Because of the poor influx of meteoric or brackish waters, which are important for stabilising a pycnocline, and the relatively low density of the brine, the stratification was unstable and meromixis and associated long-term anoxia could not develop (ROMERO & MELACK 1996). The brine could have been mixed down to the bottom of the pan during longer windy periods. The stratification could have been destroyed by mixing more than once a year, i.e. the pan could have been polymictic. Frequent mixing would have supplied additional oxygen to the deepest zone of the pan. The brine throughout the pan was therefore continuously saturated with oxygen, like in typical oligotrophic lakes (HORNE & GOLDMAN

1994, pp. 465-466; FANG & STEFAN 1997). The brine within organic-rich sediments below the living mats was derived mostly from seepage. It was also relatively well oxygenated and it was more saline than the brine in the pan over the living mats (as observed in some recent coastal salinas and salt lakes; KUSHNIR 1981, KOMOR 1992). The anoxic sulphate reduction zone below the living mats undoubtedly existed, but it could have been very thin (see KOMOR 1992). The brine within the organic-rich sediments below the living mats was presumably more oversaturated with Ca-sulphate than the brine above the mats, as in the case of the Ras Muhammad Pool in Sinai, Egypt (KUSHNIR 1981). Gypsum crystals were therefore also able to grow below the cover of cyanobacterial mats, as documented in the Ras Muhammad Pool as well as in the Solar Lake (KUSHNIR

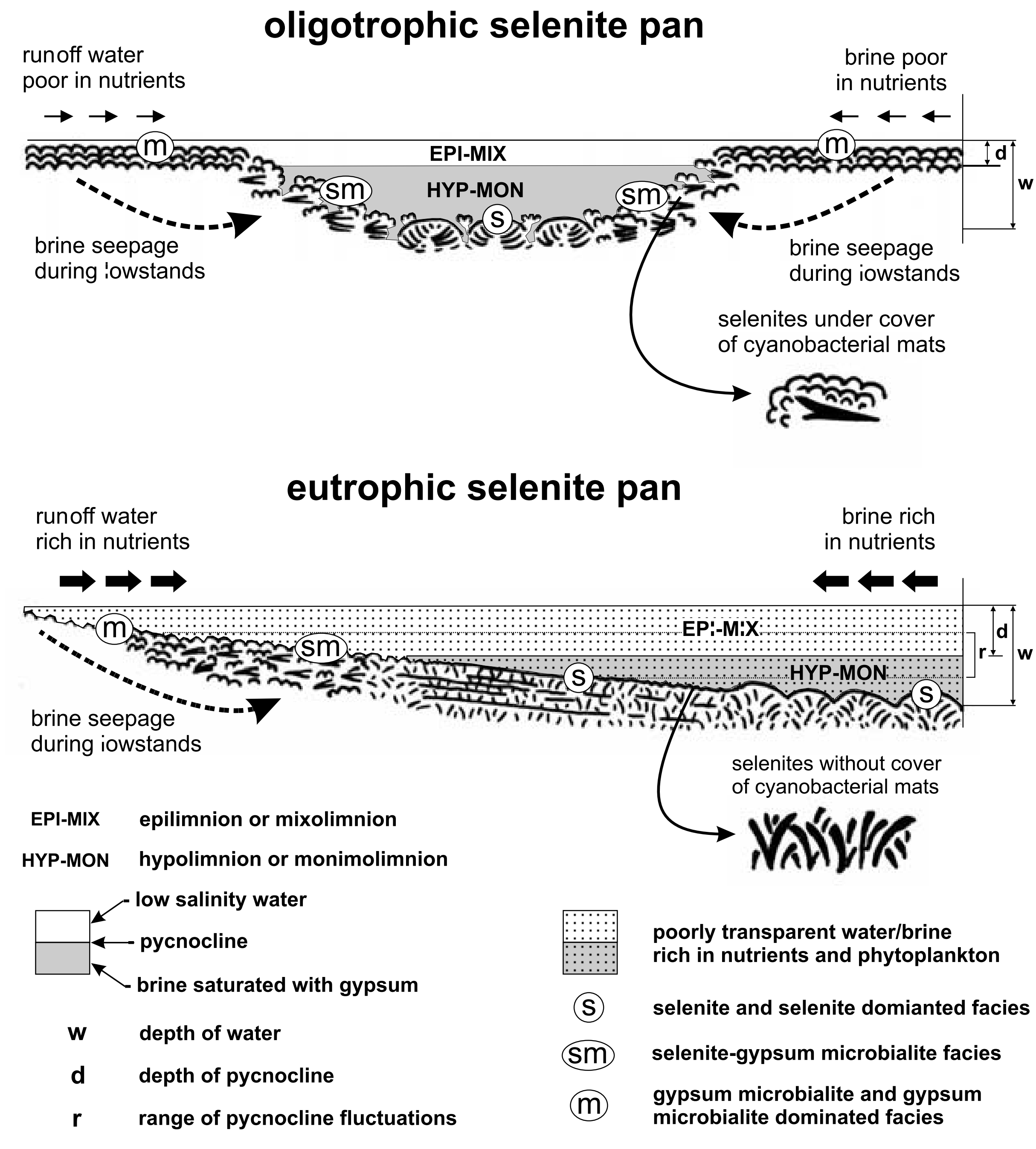

Fig. 5. Models of selenite-microbialite deposition in oligotrophic and eutrophic saline pans (basic model environment is explained in BĄBEL 2004a); size of horizontal arrows indicates volume of water flow

1981, GERDES & *al*. 2000). Large crystals grew displacively (cf. TURCHINOV 1998) within well oxygenated organic sediments – or within cyanobacterial mats – as randomly scattered aggregates. Their growth continued for a longer time than in the Sinai salinas and consequently the Badenian crystals could attain larger (up to a few decimetres) sizes. The crystals developed predominantly horizontal orientation because of the lack of a hard substrate which could stabilize their vertical growth position (cf. VAI & RICCI LUCCHI 1977, p. 226; WARREN 1982b, p. 631). They could grow lying horizontally on the floor of the basin, as noticed in recent evaporite environments (see ORTÍ & *al*. 1984, figs 16.4-16.5; ROUCHY 1982, pl. 17, fig. I; LOGAN 1987). Downward growth of primary crystals, commonly observed herein, is also recorded on steep and 'overhanging' slopes of gypsum and halite domes (see PUEYO & *al*. 2001, fig. 3C; TALBOT & *al*. 1996, figs 5-12, and DE DECKKER 1988, pl. 6, fig. B).

Seasonal lowstands associated with increased evaporation, de-stratification and mixing of brine, were especially favourable for gypsum precipitation throughout the pan, like in the Solar Lake (ECKSTEIN 1970; COHEN & *al*. 1977; KRUMBEIN & COHEN 1977; references in BĄBEL 2004a, tab. 1-2), Ras Muhammad Pool (FRIEDMAN & *al*. 1985), and, in some driest years, in Lake Hayward (ROSEN & *al*. 1996, BURKE & KNOTT 1997). During these periods surface gypsification of cyanobacterial mats could take place. Fine gypsum crystals were precipitated on, within and below the mats, as well as within the mats growing among the large selenite crystal aggregates (Pl. 4, Fig. 1). In situ growth of the selenite clusters and gypsum microbialite deposition was concurrent.

Fine gypsum crystals periodically encrusted the surfaces of the cohesive cyanobacterial mats covering the shoals and margins of the pan, and produced layers of gypsum microbialites with flat and crenulated lamination. In the deeper areas of the pan, below the average seasonal pycnocline, the cohesive laminated cyanobacterial mats developed much less well because of the weaker oxygenation and illumination (as in the Solar Lake; KRUMBEIN & *al*. 1977) and the brine could easily penetrate into the noncohesive loose organic substrate (GERDES & *al*. 2000, p. 204). The brine in these areas was nearly constantly saturated with Ca-sulphate and therefore the gypsum crystals were able to grow continuously in a syntaxial manner and attain larger sizes (see BĄBEL 2004a). They created compact masses of subhorizontally orientated crystals as well as various giant domal structures, some of them resembling vertical columns or tubes (TURCZYNOW & ANDRIJCZUK 1995; Text-fig. 5; Pl. 4, Fig. 2; Pl. 5).

During lowstand, hydrostatic pressure could develop below the cohesive impermeable microbial mats covering the margin and bottom of the pan, like in many coastal salinas (WARREN 1982a, COHEN & *al*. 1977). In some less permeable places, possibly at the lower slope of the pan where the cohesive mats were less developed, the brine from below the mats was able to rise upward as in an artesian system (cf. the Solar Lake; KRUMBEIN & *al*. 1977; Text-fig. 5). Such rising brines could create a network of seeps, vents and salina-bottom springs (present in many saline lakes; LAST & SCHWEYEN 1983, fig. 11; RENAUT & LONG 1989). The brines could mix with the parent brines in the pan, which could lead to a higher oversaturation with calcium sulphate and to increased gypsum crystal growth in the mixing zones. Possibly in such a way the rising brines could facilitate the growth of large vertically-elongated selenite domes (cf. KLIMCHOUK & *al*. 1995).

Brines rising upward from a network of seeps at the bottoms of saline pans are known to control crystallisation of evaporite salts and to create unusual crystalline buildups in the seeping or venting sites (VAKHRAMEEVA 1964, RENAUT & LONG 1989, TALBOT & *al*. 1996). Underwater fissure springs appear to contribute to the creation of the 'gypsum-cyanobacterial mounds' at the bottom of Lake Inneston in Australia (DE DECKKER 1988, pl. 6, fig. B; SCHOLLE in SCHOLLE & JAMES 1996, slide no. 192). The deposits of this 3 m deep lake, which accreted during the last 50 years, are very similar to the Badenian facies discussed herein. Large (2 m high) domes composed of poorly aligned selenite crystals set in a soft microbial (cyanobacterial and diatomic) mush and organic mucilage grow there (WARREN 1982b). The crystals grow loosely on the soft substrate and 'topple into the mush' when they become larger and heavier (WARREN 1982b, p. 631). The water salinity is relatively low, about 150‰ (DE DECKKER 1988). The 'gypsum-cyanobacterial mounds' show fenestral structures and fabrics that are strikingly similar to those of the deposits present in the interiors of some of the selenite domes from unit SH, and also observed in some of the associated layers (compare Pl. 4, Fig. 1; BĄBEL 1999b, pl. 4, fig. 2; pl. 6, fig. 2; with SCHOLLE in SCHOLLE & JAMES 1996, slide nos 193-194).

Sub-fossil subaqueous deposits, similar to the facies studied herein and composed exclusively of randomly orientated gypsum (selenite) crystals, were recorded from many Holocene marine coastal salinas, albeit the crystals were relatively small in those cases (WARREN 1982b, PURSER & *al*. 1987, PERKINS & *al*. 1994, AREF 1998, ORSZAG-SPERBER & *al*. 2001). The best recent analogues of the oligotrophic pan (MacLeod salina, Solar Lake, Ras Muhammad Pool, Lake Hayward, Lake Inneston, Christmas Island lakes), were found among salinas and salt lakes maximally several metres deep. All these basins contain marine or marine-like brines having a relatively low salinity, fluctuating at the beginning of the gypsum saturation stage; many of them are monomictic. In all of them, fine-grained gypsum microbialites or microbialite-like deposits, as well as randomly scattered aggregates of small selenite crystals, can be found. The 5-6 m deep Solar Lake is the best recognised analogue, although it is eutrophic and seasonally develops hypolimnetic anoxia, as well as being devoid of meteoric water influx, attaining a maximum salinity of 199‰ in the hypolimnion (ALI 1999). Cyanobacteria flourish there and form mats which, over a few thousand years, have created the 1.2 m thick cover of organic deposits (KRUMBEIN & *al*. 1977). Gypsum crystals growing displacively within the brine-soaked organic sediments on the margin of the salina may be over 4 cm in size (GAVISH & *al*. 1985, p. 208).

Eutrophic selenite pan: The selenites with horizontal crystals appearing together with the flat-bedded selenites composed of upright crystals (associated with the giant-gypsum intergrowths facies within unit A and with the sabre gypsum facies within unit C-D in the whole western area of the basin; Text-figs 3-4) are interpreted as deposited in the eutrophic pan. They were deposited on a slope of a deep perennial monomictic or occasionally meromictic pan (Text-fig. 5, bottom; BĄBEL 2004a, fig. 6). This particular pan was larger then the oligotrophic pan, and was open to the interior of the evaporite basin. The pan was supplied with meteoric runoff waters, sheet floods and small creeks, carrying considerable amounts of nutrient-rich mud, plant detritus and even tree trunks (BĄBEL 2005, On-Line Appendix, fig. 6A). The zone above the pycnocline (epilimnion or mixolimnion; Text-fig. 5) was thicker than in the oligotrophic pan and its waters were in direct contact with the nutrient-rich soils along the shorelines. These nutrients could have been washed from soils by waves or sheet floods into the pan (HORNE & GOLDMAN 1994, p. 20). It is known that such nutrient-rich saline pans are usually eutrophic and characterised by common phytoplankton blooms (DEL CASTILLO ARIAS & FARFÁN 1997, JAVOR 2002). Such blooms could have shaded the bottom of the pan, limiting the growth of phototrophic benthic cyanobacterial communities, and facilitating syntaxial selenite crust growth in the zone below the pycnocline (see BĄBEL 2004a, pp. 233-234). Syntaxial crystal growth could have been further facilitated by the salinity (in the zone below the pycnocline) which, being possibly higher than in the oligotrophic pan, was unfavourable for the vigorous development of benthic cyanobacterial communities (see BĄBEL 2004a, fig. 4). Cyanobacterial mats could, however, have flourished in the shallow epilimnion or mixolimnion zones covered with less saline or brackish water (Text-fig. 5).

In the deep eutrophic pan, a pycnocline between the epilimnion and hypolimnion (or mixolimnion and monimolimnion) could have been relatively deep, with correspondingly large fluctuations. The range of these fluctuations ('r' in Text-fig. 5) defined a large slope area subjected to drastic temperature and salinity fluctuations. The slope was periodically covered with low salinity or brackish epilimnetic or mixolimnetic waters and, at other times, with hypolimnetic or monimolimnetic high salinity brine. This created a peculiar environment suitable for growth of both cyanobacterial mats and of selenite crystals.

During the larger falls in water level, the slope area could have been supplied with brine by seepage and subsurface transport from the elevated margins of the pan, like in the case of the oligotrophic pan (Text-fig. 5). This could additionally have favoured the growth of selenite crystals below and within cyanobacterial mats.

This environment does not posseses any good recent analogue. A partial equivalent can possibly be found on the upper slopes of the Solar Lake, in the zone between epi- and hypolimnion (KRUMBEIN & *al*. 1977, HIRSCH 1980). It is the zone of particularly abundantly precipitated randomly scattered aggregates of gypsum crystals (together with carbonates) within pinnacle-type cyanobacterial mats (AHARON & *al*. 1977, KRUMBEIN & COHEN 1977, KRUMBEIN & *al*. 1977).

Selenite debris flow facies

Description: This so far poorly recognised and rare Badenian facies (Text-fig. 4; BĄBEL 2005, On-Line Appendix, Figs 12B-C, 13B) consists of broken, abraded or partly dissolved gypsum crystals scattered within a matrix of fine-grained gypsum. The clasts, mostly fragments of elongated sabre-like crystals, show horizontal and subhorizontal orientation (Pl. 1, Fig. 2). The facies appears in layers, up to 1 m thick, within the microcrystalline gypsum facies (sensu BĄBEL 1999a), and locally within the selenite sabre gypsum facies (e.g. in the Nida area in Poland; BĄBEL 1999a; at Ozeriany and Palahychi in Ukraine; BĄBEL 2005, On-line Appendix, Figs 13B, 17B). Layers intercalated within the microcrystalline facies have an uneven base, with features of erosion, and flat top surfaces. Similar facies are particularly common in the Messinian of Cyprus (ROUCHY 1982, ROBERTSON & *al*. 1995).

Interpretation: The fabric of this facies and the occurrence of fine-grained matrix between the crystal clasts suggest a debris flow transport mechanism. The occurrence of the facies within microcrystalline and sabre gypsum facies indicates that it was formed in a subaqueous environment connected with the two latter facies (BĄBEL 1999a, b). This environment was different from that in the oligotrophic and eutrophic pans. The pan was probably meromictic with its brine Ca-depleted (see BĄBEL 1999c), and therefore gypsum precipitation was limited or impossible at the bottom of the anoxic monimolimnion zone. Laminated, largely clastic, thin-grained gypsum accumulated in this zone, forming deposits typical of the microcrystalline facies. Selenite could crystallise only locally on basin slopes or internal shoals as loose aggregates, possibly within microbial mats. These selenites were then redeposited from there into deeper monimolimnion areas as slumps and debris flows. Crystal fragmentation and abrasion took place during redeposition.

A similar environment, with selenites crystallising exclusively on shoals, and a lack of gypsum deposition in the deep monimolimnion, is known from the meromictic Lago Pueblo in Venezuela (SONNENFELD & *al*. 1976, 1977; HUDEC & SONNENFELD 1980).

Selenite debris facies

Description: This facies was formerly referred to as 'gypsum crystal debris' (Text-fig. 4, BĄBEL 1999a). It is an accumulation of broken, abraded and partially dissolved and regenerated gypsum crystals, up to 0.5 m long, lying parallel to the layering and commonly mixed with clay. It passes into compact masses of chaotic selenite aggregates, without matrix between the firmly welded crystals. This facies commonly covers the giant gypsum intergrowths in the Nida area in Poland.

Interpretation: The facies is a product of long-term emersion and destruction of the original palisade selenite crusts by the atmospheric factors and weathering processes acting in the Badenian basin (BĄBEL 1996, 1999a; cf. GARRISON & *al*. 1978). The best analogue of this facies is the weathered selenite regolith covering the coast of Marion Lake in Australia, which is produced by the destruction of the primary bottom-grown selenites exposed during water-level drawdown (SCHREIBER 1978, p. 65; 1988, p. 215; SCHOLLE & JAMES 1996). Another partial analogue is the 'selenite lag' covering the eroded surface of Sebkha el Melah in Tunisia (PERTHUISOT (1975, photos 58-59). The Badenian selenite debris facies represents more complex deposits which recorded not only the destruction but also the in-situ regeneration of crystals. Additionally, in the case of the Badenian regolith, frequent floods of clay-loaded meteoric waters eroded and dissolved the crystals and covered them with clay. Such processes acted mostly in the gently inclined upper slopes of the shrinking saline pans, where typical crystal clasts accumulated. The crystal clasts which accumulated on the lower slopes, closer to the shoreline, could undergo regeneration during occasional inflows of brine from the saline pans. In such more permanently brine-inundated areas, sheltered or distant from clay-loaded meteoric water floods, the common re-growth and regeneration of the crystals obliterated the earlier traces of abrasion and dissolution, and could produce facies similar to the in situ grown (non-redeposited) selenites with horizontal crystals (see ORTÍ & *al*. 1984, figs 16.4-16.6; SCHREIBER & DECIMA 1978, fig. 5, p. 116).

FINE-GRAINED GYPSUM FACIES

The primary features of the fine-grained gypsum facies are commonly obscured by weathering (see BĄBEL & BOGUCKY 2002). Macroscopic field investigation, and limited observation on polished, etched, and stained surfaces, as well as on thin sections, allow the recognition of only two main facies types, with one of them, the alabastrine facies, possibly representing several different environments.

Gypsum microbialite facies

Description: The commonest variety of this facies consists of gypsified microbial mats showing wavy, crenulated laminations described as 'stromatolitic gypsum' by PERYT (1996). These deposits are widespread in Ukraine (lithostratigraphic unit M) but occur also in other areas of the basin, particularly within the grass-like facies of unit B (Text-figs 3-4; Pl. 3, Figs 1-2), and within the selenite facies with horizontal crystals (unit SH). Gypsified microbial mats appear in bed c throughout the basin (Text-fig. 4), and within the 'subfacies with alabaster beds' in the Nida area (BĄBEL (1999a). The other variety of the gypsum microbialite facies contains clay intercalations and small gypsified microbial mounds ('alabaster mounds'; BĄBEL 1996; 1999a, plate 5, fig. 2). This clay-microbialite facies is common in the entire western area of the basin, particularly within unit B. The rarest variety of the microbialite facies contains gypsum 'stromatolitic domes' partially composed of clastic gypsum grains (KWIATKOWSKI 1970, plate 4; 1972, plate 19; BĄBEL 1996, fig. 12; 1999a, plate 7, fig. 2). This facies variety occurs in the Nida area and in a few outcrops in Ukraine (BĄBEL 2005, On-Line Appendix, figs 10A-B).

The gypsified microbial mat deposits of unit M are devoid of clay intercalations, although they occur sporadically in some of the the flat-bottomed shallow channel structures commonly found in this unit. The channels, a few centimetres to several metres wide, are filled with laminated clastic gypsum (PERYT 1996, figs 12-13). The clastic gypsum shows wash-out structures and low-angle cross-lamination. Some narrow (less than 1 m) channels (at Kudryntsi, Ozerna cave, Mamalyha; Pl. 3, Fig. 2; Text-figs 2B, 4) are filled with over 1.5 m thick, continuous sequences of subaqueously deposited, flat, millimetre-laminated gypsum. These channels do not show the sharp erosional surface at the base and banks typical of scouring of the substrate. The channels were very shallow (< 5 cm), and were filled with clastic gypsum laminae concurrently with vertical accretion of gypsum microbialites, mat by mat, on their banks. Some single gypsified microbial mats from that facies are covered with small bottom-grown gypsum crystals (maximum a few mm) indicating a subaqueous depositional environment. Horizontally-elongated, in-situ grown clusters of selenite crystals are common in some places, particularly closer to the selenite facies with horizontal crystals (unit SH; Text-fig. 4). The microbialites from unit M are commonly intercalated with, or replaced with, alabastrine gypsum facies. This latter facies in some palces contains randomly scattered gypsum porphyroblasts.

Interpretation: The depositional environment of the microbialite facies is an evaporite shoal at the margins of ephemeral and shallow perennial saline pans (BĄBEL 1999a, with references; ROUCHY & MONTY 2000; GERDES & *al*. 2000). The ephemeral or perennial pans are recorded by thin grass-like selenite crusts, which intercalate with gypsum microbialite deposits. Gypsum microbialites occurring within selenite facies containing horizontal crystals were deposited in deeper perennial oligotrophic pans (Text-fig. 5). Different microbialite subfacies were deposited on the shoal, depending on the topography of the shoal, the distance from land covered with clay soils and from the nearest permanent pan, as well as on salinity and local climate (BĄBEL 1999a).

Microbialites from unit M are comparable to the 'perennial surface brine' biofacies of GERDES & *al*. (2000). They were deposited on permanently wet majanna-type shoals which could exist between separate saline pans showing slightly different water levels (see Text-fig. 6, LOGAN 1987). Such shoals were regularly flooded with brine oversaturated in calcium sulphate, probably in the form of sluggish brine sheets extending out from the network of drainage channels, or from channels connecting adjacent pans. These channels were very similar to channels associated with permanent brine sheets flowing on the majanna flats in the MacLeod salina in Australia (LOGAN 1987, fig. 53b, p. 64) or to drainage channels cut into the wet surface of the Al-Khiran sabkha in Kuwait (GUNATILAKA 1990). A specific feature of these flat-bottomed shallow channels was that sediment accretion in them was concurrent with the accretion of gypsified microbial mats on the flat surface of the surrounding shoal (Pl. 3, Fig. 2). This can be explained by the fact that microbialite deposition on the shoal was controlled by, and kept pace with, a continuously rising water level in the salina basin. The sedimentary record in unit M indicates that this continuous rise created at least a few metres thick gypsum microbialite beds. Taking into account the typical rapid rates of gypsum deposition and microbial mat accretion in salinas, this rise was also very rapid in a geological sense. Such a rise in water level is difficult to explain by being controlled by the world sea level, but is fully accepted in salina-type basins. Alabastrine and porphyroblastic gypsum intercalating gypsified microbial mat deposits are interpreted as brine sheet or pedogenic deposits formed in the emerged areas of these majanna-type shoals (see below; LOGAN 1987; AIGNER & BACHMANN 1989; BĄBEL 2005, p. 21).

Alabastrine facies

Description: This facies is composed of fine-grained, snow-white, massive, and relatively homogeneous gypsum (PERYT 1996). It typically occurs as intercalations between rows of grass-like selenites in unit B, but also within other fine-grained gypsum units (Text-figs 3-4). Some varieties of this facies contain randomly scattered gypsum porphyroblasts and show micronodular fabric.

Interpretation: The alabastrine facies most probably precipitated from brine sheets (see LOGAN 1987, AIGNER & BACHMANN 1989, PERYT 1996, BĄBEL 1999a). Alternatively, it could also have been a product of subaqueous gypsification of, or gypsum precipitation within, non-laminated microbial 'mats' (KRUMBEIN & COHEN 1977, ORTÍ & *al*. 1984, BĄBEL 1999a). Some parts of this facies are probably a product of pedogenic transformation of gypsum deposits during emersion (cf. MAGEE 1991, KASPRZYK 1993, AREF 2003), or hydration of former anhydrite (see PERYT 1996, KASPRZYK & ORTÍ 1998, TESTA & LUGLI 2000, KASPRZYK 2003).

SEDIMENTARY HISTORY OF THE BADENIAN GYPSUM DEPOSITS

As can be seen from representative sections correlated along the margin of the Carpathian Foredeep basin (Text-fig. 2), the individual selenite facies form several separate lithosomes related to lithostratigraphic units A, C-D, F, SV, SH (Text-figs 3-4). These lithosomes reflect the existence of several different saline pans. The group of fine-grained gypsum facies forms similar lithosomes that roughly coincide with lithostratigraphic units M and B. Microcrystalline facies related to lithosomes or units E and G (BĄBEL 1999a, b) may actually represent different environments, but mostly in saline pans in which selenites were not precipitated.

The lower selenite unit

The gypsum evaporite deposition in the northern- and westernmost Carpathian Foredeep began with selenite crystallisation in deep perennial pans (giant gypsum intergrowths, unit A; Text-figs 3-4). They evolved into a system of evaporite shoals with shallow saline pans (grass-like and microbialite facies, unit B) and then became re-established (sabre-gypsum, unit C-D). This sequence is interpreted as a highstand-lowstand-highstand cycle in a salina subbasin (see BĄBEL 1996, 1999a, 2005; PERYT 1996; KASPRZYK 1999). The first highstand is associated with initial evaporite drawdown in the basin (see DZIADZIO 2000, BĄBEL 2004b). The southern margins of these two saline pan systems (giant intergrowths-unit A, and sabre gypsum-unit C-D) are partly exposed in the Miechów Upland but are hidden in the deep subsurface in the interior of the Foredeep (Text-fig. 2A).

The extensive saline pan systems existing during these two highstands were different, although both were of the eutrophic-type (Text-fig. 5). The pan in which giant intergrowths crystallised was smaller, although presumably deeper than the sabre gypsum setting. The lack of continuity of the gypsum intergrowths layer between Upper Silesia and the Miechów Upland (Text-figs 2A, 3-4) can be attributed to erosion or, more likely, to deposition in separate sub-pans. Similarly, continuity of this layer between Poland and Ukraine, and between particular distant outcrops in Ukraine, could not be proved because of the limited borehole core data, and hence the inference that a single, continuous deep saline pan existed in this area is not fully justified.

The selenite facies with horizontal crystals that commonly overlies the vertically-orientated giant intergrowths (BĄBEL 2005, On-Line Appendix, figs 6A, 8A-E) is interpreted as slope deposits of a deep eutrophic pan, or alternatively as bottom deposits of a slightly shallower oligotrophic selenite pan. This facies is widespread in the northern Nida area (‘non-palisade subfacies'; BĄBEL 1999b, fig. 2). The selenite debris facies covering the giant intergrowths in the southern Nida area (BĄBEL 1999b), and appearing in the Miechów Upland (e.g. at Podgaje, Text-fig. 4, ROMAN 1998), records long-term emersion before the transition of these areas into an evaporite shoal (BĄBEL 1996; 1999a, fig. 6; 1999b, fig. 2; KASPRZYK 1999). KRACH (1947) first noted the selenite debris facies in the Miechów Upland but, because of poor exposures, he attributed this facies to post-Miocene slump processes. A similar sequence of facies and events is recorded in the Czech area of the basin (PERYT & *al.* 1997).

The sabre gypsum (unit C-D) has a wider distribution than that of the giant intergrowths (unit A) and shows an onlapping pattern in Podillia and Bukovyna (PERYT 2001), and on the Miechów Upland (ROMAN 1998). Such onlap (Text-fig. 3-4) is interpreted as the product of aggradational deposition on slopes of the salina basin related to progressive rise of the former drawdown water level in the basin. The rise kept pace with evaporite deposition. Such a water level rise in a salina basin is known as ‘autocyclic transgression' and the resulting deposits as representing the ‘intrabasinal transgressive system tract' (WARREN 1999, p. 95). The sabre gypsum (unit C-D) was deposited in a chain of subbasins or in one giant pan (or a marginal platform with undulating morphology) with open connections to the south to the halite subbasins. This is proved by the conformable record of brine palaeocurrents observed within C-D unit across the whole basin (BĄBEL & *al.* 1999, ROMAN 1999, BĄBEL 2002).

The wavy-bedded sabre subfacies occurring in the southern Nida area is interpreted as slope deposits of this giant eutrophic-type pan (Text-figs 2A, 5). This pan extended to the north, and the flat-bedded subfacies of sabre gypsum occurring in the northern Nida area represents deeper deposits within the same pan (see BĄBEL 1999b, fig. 2). A similar pattern of subfacies and palaeotopography is recorded within the environs of Ozeriany in Ukraine (see Text-figs 2B, 4; BĄBEL 2005, On-Line Appendix, fig. 18B).

The vertical transitions from the flat-bedded to the overlying wavy-bedded sabre facies (i.e. from the facies with vertical selenite crystals to the facies with horizontal crystals with gypsum microbialites) appear in many outcrops, e.g. on the Miechów Upland (ROMAN 1998) or at Broniakówka (BĄBEL 2005, On-Line Appendix, fig. 15A). Such transitions can be interpreted as progradation of the slope facies within the giant eutrophic pan or, alternatively, as environmental change from the eutrophic to the oligotrophic pan related to isolation of a depressed area within the large eutrophic selenite basin. Typical gypsum microbialites and evidences of erosion or redeposition are common at the upper boundary of the sabre gypsum unit C-D across the whole basin, suggesting the shallowing. They also appear at the top surface of the wavy-bedded sabre facies in the southern Nida area.

It is striking that, throughout the basin, the selenites with horizontal crystals appear to form the middle parts of the shallowing-upward sequences represented by units A – B and C-D – E (Text-fig. 3-4; KASPRZYK 1993; BĄBEL 1999b, fig. 2).

Microbialite-selenite units in Podillia and Bukovyna

Unlike in the western area, where gypsum crystallisation was initiated in relatively deep brine, evaporite deposition in Podillia and Bukovyna started mostly with gypsum microbialites representing semi-emerged evaporite shoals (unit M, Text-figs 2B, 3-4; BĄBEL 2005, On-Line Appendix, figs 9, 18A). One such vast area between Mlynki and Kriva (Text-fig. 2B) was interpreted by PERYT (1996, 2001) as the margin of the evaporite basin. The evaporite shoals seem to continue further to the south into northern Moldova and Romania (CEHLAROV & ŢIBULEAC 1996, PERYT & *al*. 2004). Gypsum microbialites are very common in the Badenian evaporites in Bulgaria (Text-fig. 1B, TRASHLIEV 1969). Gypsified microbial mat deposits are less common in the northwestern area of the basin, where they form only thin layers (layer c is the thickest one; Text-fig. 4, BĄBEL 2005). Gypsification of microbial mats perhaps was easier in the southern areas of the Badenian evaporite basins because of the warmer climate and the greater evaporation rate (Text-fig. 1).

It seems that the eastern shoals existed during deposition of the giant intergowths in the west (Text-figs 2-4, PERYT 2001) and then prograded to the west during subsequent lowstand, at the beginning of the deposition of unit B. However during the continuing shallow-water deposition in the west (unit B), separate perennial selenite pans (represented by unit SV and SH) developed in the east. Selenite deposition in these semi-isolated pans was coeval with the microbialite and grass-like gypsum deposition to the west (unit B), and seems to be partly coeval with the sabre gypsum crystallisation (lower part of unit C-D) in the giant perennial pans in these western areas (Text-fig. 2-4). The pan represented by unit SH was of the oligotrophic type (Text-fig. 5).

It is very likely that the gypsum microbialites from unit M were deposited on permanently wet majanna-like shoals similar to those from the MacLeod salina. The shoals were presumably situated between separate perennial pans (like those represented by units SV and SH; Text-figs 3-6) which existed in Podillia, Bukovyna, northern Moldova and Rumania (see CEHLAROV & ŢIBULEAC 1996). The vast shoals were periodically flooded by sluggish brine sheets outflowing from such pans. The brine also flowed through the shoals in channels connecting the pans. The saline pans could have shown different water levels and the shoals could have been gently inclined parallel to the brine tables, like the surface of the majanna flat in the MacLeod salina. Selenite deposition in the saline pans was concurrent with the accretion of microbial mats on these majanna-like shoals. In particular, sediment accumulation on the shoals kept pace with the rising water levels in the nearest pans and the rising brine table levels in the shoals between them. Only rarely was it interrupted by high-energy floods or some longer-term emersions (PERYT 2001, BĄBEL 2005). The depositional system showed generally aggradational geometry, which is typical of sedimentation in a salina basin. It is likely that the gypsum deposition rate was more rapid than in the western areas of the basin.

An event marked by shallowing and dilution related to deposition of marker bed h in the western area (within unit C-D; Text-figs 3-4) has its equivalent in some limestone intercalations, discontinuities and pedogenic horizons in gypsum sections in Podillia, Pokutya and Bukovyna (see PERYT 2001). A limestone bed at Nahoriany occurs at the same 'hypsometric' level in the section as marker bed h to the west (at Isakiv; Text-figs 2B, 4). Even if this limestone is a karst cavity-filling internal deposit related to the 'Ratyn' carbonate deposition, which is highly probable (PERYT 2001), the cavity is presumably in the place formerly occupied by the deposits of the missing marker bed. The limestone bed at Nahoriany separates two different sabre gypsum facies (units SV and C-D; Text-figs 3-4), which presumably represent two different types of saline pans. In Podillia and east Pokutya, unit C-D commonly overlies SV, but the vertical transition between both units is poorly recognised. It seems that this transition can be related to the shallowing and dilution events documented by marker bed h in the west – the presumed inflow of different brines, or to a rapid evolution of the host brines.

The sabre gypsum crystals in unit C-D in Podillia and east Pokutya show a weak development of the horizontal orientation of crystal apices that is present in this unit in the west and interpreted as an indicator of brine palaeocurrents (see BĄBEL & *al*. 1999, fig. 1; ROMAN 1999; BĄBEL 2002). Such a poor orientation of the crystals suggest deposition in relatively calm or weakly flowing brine (BĄBEL 2002), perhaps in some smaller pans separated by shoals. The shoals could have been similar to those represented by the grass-like or microbialite facies which laterally replace the sabre gypsum around the boundary of units B and C-D in the west (Text-figs 3-4) and are marked by the lack or rarity of orientated sabre crystals in the lowermost part of unit C-D (BĄBEL 2002, fig. 3; 2005, On-Line Appendix, fig. 11).

The upper microcrystalline unit

The microcrystalline facies is recorded in the entire western area of the basin, including the Czech Republic, and the tectonically displaced Broniakówka section in Poland (Text-fig. 2A), which originally was on the southern side of the basin, ca. 50 km south of its present position (POŁTOWICZ 1993). Throughout the basin, the transition from sabre (unit C-D) to microcrystalline gypsum (unit E) is abrupt (Text-figs 3-4) and was interpreted as a drastic basinwide change of basin anatomy and/or water chemistry (PERYT 1996, ROSELL & *al*. 1998). The scenario of environmental changes is, however, enigmatic.

The microcrystalline facies represents an environment dominated by allochthonous clastic deposition. Selenites crystallised rarely, and only very locally, not as continuous crusts or beds, as in the previous unit, but rather as crystal clusters scattered within gypsum microbialite deposits, or as agglomerations of horizontal crystals. They were deposited on slopes or isolated shoals rather than in the deepest brine, and redeposited from there as selenite debris flows, such as those recognised in some outcrops in Ukraine (Kolokolyn, Ozeriany; Text-figs 2B, 4). Selenite breccias intercalate microcrystalline facies in the Polish area of the basin (see KUBICA 1992, pl. 7; KASPRZYK 1999) and can be interpreted as debris flow deposits.

Traces of bottom-grown halite crystals are common within the microcrystalline facies in the whole western area of the basin, including Kobeřice and Broniakówka (KWIATKOWSKI 1972; BĄBEL 1991; 2005, On-Line Appendix, fig. 15B; ROMAN 1998), but are rare to the east in Ukraine (they were found only at Kolokolyn and Schyrets'; see Text-fig. 2B; BĄBEL 2005, On-Line Appendix, figs 12A, 13A, 14A). They indicate that the brine was oversaturated with NaCl in these areas. The redeposited halite crystals, preserved as gypsum pseudomorphs, are not rounded by dissolution or abrasion (BĄBEL 1991, pl. 3, fig. 1), and were hence transported in brine saturated with NaCl. On the other hand, the low strontium content of the host gypsum deposits, the clastic nature of these deposits, composed mostly of tiny gypsum grains with abraded and dissolved edges (well seen under the scanning electron microscope), all suggest a low salinity and, consequently, brine dilution by more frequent marine and/or meteoric water inflows (ROSELL & *al*. 1998, p. 75; KASPRZYK 1999).

The flat-laminated gypsum common in this unit was deposited in saline or brackish pans, commonly of the meromictic type. The laminae were deposited by fallout of tiny gypsum grains from suspension clouds rather than from low-density turbidity currents. Each lamina can represent one sheet flood of runoff waters which washed out gypsum detritus from emerged coastal flats (KASPRZYK 1999, p. 459). Runoff waters flowing through the gypsum flats and transporting gypsum grains to the pans readily became saturated with calcium sulphate due to dissolution of the gypsum sediments (LOGAN 1987, CENDÓN & *al*. 2004). Laminated gypsum can also result locally from a subaqueous cumulate of crystals precipitated within the brine column.

In the marginal areas of the basin, the microcrystalline facies (unit E) covers the sabre gypsum (unit C-D), but in the area between the Miechów Upland and Rzeszów, and further to the south-east, to the Polish-Ukrainian border (Text-figs 2-4), it rests directly on the pre-evaporite substrate (OSMÓLSKI 1972, KRYSIAK 1986, KASPRZYK & ORTÍ 1998, PERYT 2000, KASPRZYK 2003). The underlying units A, B, C-D thin from north to south and disappear gradually in the central area of the basin (NIELUBOWICZ 1961, KUBICA 1992), although the detailed pattern of changes is obscured by the dehydration of gypsum. Further south of the Miechów-Rzeszów area, the microcrystalline facies or its anhydrite equivalents (unit E or unit G) passes into the anhydrite deposits of the halite subbasins (GARLICKI 1968, 1979; POŁTOWICZ 1993). In Polillia, east Pokutya and Bukovyna, the microcrystalline facies (unit E) is more areally limited than the underlying sabre gypsum of unit C-D because of subsequent erosion and/or non-deposition (Text-figs 2-4).

The aggradational deposits of unit E follow the basinwide sabre gypsum deposition (Text-figs 3-4). Presumably they covered and 'overstepped' the emerged or semi-emerged area located between Miechów and Rzeszów, the broad Miechów-Rzeszów barrier (Text-fig. 2A). Inundation of this barrier led to the wide opening of the connection between the northern sulphate and the southern halite subbasins. This barrier may continue further south-east into the Ukrainian area, where a narrow belt completely devoid of, or with reduced thicknesses of evaporites, is recognised along the axis of the basin (see CZARNOCKI 1935, pp. 114-115; ANTIPOV *in* LADYZHENSKIY & ANTIPOV 1961, p. 169; ALEKSENKO 1967). However, the existence of this barrier in Ukraine is not proved by sedimentological studies and is questioned by some authors (e.g. POLKUNOV & *al*. 1979).

Unit E contains an abundant and well preserved marine fauna (pteropods and foraminifera), remnants of fishes and plants, and numerous clay intercalations (KUBICA 1992). This suggests large surface inundations of marine water into the salina basin, as well as floods of meteoric runoff waters carrying clays from the adjacent land. Both types of water could have served to refresh the host brine in the study area.

The brines in the halite subbasins were of marine origin, saturated with NaCl, and depleted in Ca^{2+}. This is confirmed by fluid inclusion analyses in the Badenian halites (Ca^{2+} below the detection limit; see GALAMAY 1997; BUKOWSKI & *al*. 2000; GALAMAY & *al*. 2003, 2004). The brines characteristic of microcrystalline gypsum deposition could have been a mixture of waters of various origins, including the Ca^{2+}-depleted brines from the halite subbasins. The mixture of brines could have been relatively impoverished in Ca^{2+} and hence unable to precipitate gypsum (see BĄBEL 1999b, c). Additionally, it seems that the marginal areas of the basin were disconnected from the continuous inflow of calcium sulphate-rich brine which could contribute to the gypsum crystallization and selenite growth. Such an inflow took place during deposition of the lower autochthonous unit.

The upper selenites

Selenite unit F records a short-term return of the basin hydrochemistry to the former selenite pan conditions, with the brine fully saturated with Ca-sulphate (Text-figs 3-4). The return was presumably preceded by a basin-scale emersion. Re-connection of the area with the source of calcium sulphate-enriched brines, together with presumed isolation from the halite subbasins, led again to selenite deposition. The course of this selenite deposition was similar as in the lower autochthonous unit (see BĄBEL 1999b, 2005 for more details).

The selenite pan or pans, represented by unit F, were less extensive than the previous sabre gypsum pan (unit C-D; Text-figs 3-4). The distribution of unit F in Poland suggests a reappearance of the barrier separating the northern sulphate and the southern halite subbasins. Unit F is up to 4 m-thick in the northern part of the basin (KASPRZYK 1989, KUBICA 1992), where it contains unique gypsum oolite deposits (BĄBEL & KASPRZYK 1990); it thins to 1.5 m and finally disappears in the Nida area. Since the unit has never been recorded south of Gacki in the southern Nida region (see OSMÓLSKI 1972, KRYSIAK 1986), it can presumably be inferred that the shoreline of the selenite pan passed through this area (see Text-fig. 1A; BĄBEL 1999b, fig. 3).

Final stages of evaporite deposition

A period of variable microcrystalline facies deposition (unit G) followed the selenite event (unit F) and continued up to the end of evaporite sedimentation (Text-figs 3-4). Evaporite sedimentation in the salina basin was arrested by permanent connection of the basin with the Mediterranean, and consequent flooding with marine water. The rapid deepening, and the appearance of marine deposits overlying the evaporite strata, have long been recognised as the 'transgression on gypsum' (FRIEDBERG 1912, DZIADZIO 2000). In the northern and eastern parts of the sulphate subbasins this flooding event was preceded by emersion, karst development and locally by variable calcareous deposition (see KASPRZYK 1991, fig. 8; 1999; PERYT & PERYT 1994). Records from borehole cores suggest a more complex scenario of final evaporite deposition in the northernmost areas of the basin in Poland, where separate small selenite pans and brackish lakes with carbonate microbialite deposition developed (KASPRZYK 1993, 1999). In the emerged Podillia and Bukovyna areas, deep karst processes operated presumably long before the final marine flooding. Erosion and karst processes removed a significant part of the gypsum deposits in these areas (KOLTUN & *al*. 1972, PERYT 2001). No traces of emersion were found in the southern halite subbasins, where the transition from hypersaline to marine sedimentation was gradual and connected with anoxia (GARLICKI 1968, 1979; GONERA 2001). Some authors believed that subaqueous erosion removed a portion of the evaporites in the central areas of the foredeep just after evaporite sedimentation (POŁTOWICZ 1996, 1997, 1998; cf. PRYSJAZHNJUK 1998). OSZCZYPKO (1999) related this event to isostatic relaxation and substrate uplift promoted or facilitated by removal of 50 m water column load by evaporation.

Tectonics and evaporite sedimentation

According to KUBICA (1992, pp. 31-33), the greatest thickness of gypsum deposits in the northern margin of the basin resulted from the increased rate of subsidence in this area during gypsum accumulation. In general, the individual lithosomes within the lower selenite unit increase in thickness from the south (from the Miechów-Rzeszów barrier) to the north, as well as from the west (from the northern Nida area) to the east (NIELUBOWICZ 1961, KUBICA 1992, KASPRZYK 1999), with the maximum thickness found at Palahychi in Ukraine (Text-figs 2-4). The central area of the basin, the Miechów-Rzeszów barrier, can be considered as having been gradually uplifted or tilted both during and soon after the gypsum deposition (see OSZCZYPKO 1999). Tectonic uplift is the simplest explanation for the lack of sabre gypsum at Podgaje (Text-fig. 2A, 4) and in similar sections from the Miechów Upland, and along the Miechów-Rzeszów barrier. Alternatively, the thickness differences can be explained by variable relief of the salina basin and by deposition in subbasins or saline pans showing different water levels and different sedimentation rates (see discussion in the next chapter). Compaction is another factor which could have changed the original thickness, although the original thickness of the massive selenite units remains unchanged. As the rate of gypsum deposition is extremely rapid in comparison with the average rate of subsidence and uplift (e.g. SCHREIBER & HSÜ 1980) these factors are commonly ignored in the sedimentological analysis of evaporites.

Rapid tectonic events could have influenced the evaporite sedimentation. After an earthquake in 1819 the 80 km long area of the Great Rann of Kutch subsided by 1-5 m and was flooded by tidal waters (WYNNE 1872 in GLENNIE & EVANS 1976; and other similar examples in SONNENFELD 1984). The Badenian gypsum was deposited in a tectonically active area in front of the Carpathian orogen and therefore significant rapid tectonic movements could have taken take place and have influenced the pattern of gypsum deposition (e.g. ALEXANDROWICZ 1964; KWIATKOWSKI 1972, with references; KASPRZYK 1999; PERYT 1996).

Tectonic movements are the best explanation for the great thickness differences observed in the upper allochthonous unit. The thickest sections of the allochthonous gypsum unit seem only to be preserved in grabens (PERYT 2001). Various gypsum breccias are common in the allochthonous unit and were considered to have been produced by earthquakes (PERYT & JASIONOWSKI 1994), although many of them appear to be halite-solution collapse breccias (BĄBEL 1991, 1999b).

Remarks on palaeogeography

This study enabled only a general reconstruction of the palaeogeography, and many palaeogeographic problems remain unresolved. The two most important are discussed below.

The first is the location of the presumed evaporite shoals separating the saline pans and subbasins. Although evaporite shoals, represented by thick gypsum microbialites, are clearly recognisable in Podillia and Bukovyna in Ukraine, such microbialite facies are either missing or are very poorly developed in the Polish and Czech area of the basin (Text-fig. 2A); they are not recognised in the area of the presumed Miechów-Rzeszów barrier. The reason for that may be the lack of gypsification of the microbial mats in this part of the basin. The north-western part of the basin was presumably subjected to slightly wetter and colder climatic conditions, and hence was influenced both by a larger influx of meteoric waters and by slower evaporation (Text-fig. 1), conditions unfavourable for gypsification of the microbial mats. However, the living mats would have been able to flourish there and create considerable organic deposits, like the in case of the modern Solar Lake (KRUMBEIN & *al*. 1977). Such a cover of exclusively organic sediments could be a very effective barrier between saline pans albeit with no chance of preservation in the geological record. Additionally, the cohesive microbial mats would have protected the substrate from erosion. Hence significant clastic deposition, which would suggest existence of subaqueous uplift or emerged land, was excluded.

The second problem to be discussed concerns the water-level relationships between the saline pans or subbasins, which are crucial for a proper reconstruction of the basin palaeogeography. The salina basin model assumes that the water levels in adjacent saline pans could be different. In the case of very broad evaporite shoals separating the saline pans, the water level of the lower pan could even have been topographically below the bottom level of the upper one (Text-fig. 6). With the exception of ideal cases, the evaporite shoals were certainly not horizontal but gently inclined, with their surfaces controlled by inclined water-table levels spread between adjacent saline pans (like the surface of the majanna flats in the MacLeod salina, LOGAN 1987). For example, the giant evaporite shoal which developed in the Badenian basin during deposition of layer c was certainly not horizontal, but was inclined parallel to the local water or brine table levels (Text-fig. 4, BĄBEL 2005).

The majanna flats in the MacLeod basin show gradients ca. 0.02-0.03 m/km (LOGAN 1987, p. 37) and slope to the salina depression, which is 4.3 m b.s.l. Such gradients mean that the 100 km long slope of some ancient majanna flats would show topographic differences of 2-3 m. This value could have been much higher in the case of ancient salina basins, where drawdown to a level of tens or hundreds of metres below the original sea level certainly would have caused the water-table levels to slope more steeply.

The MacLeod basin example indicates that the evaporite deposits that accreted at the lower slope of the inclined majanna-type shoal in the Badenian basin could have been situated topographically lower than the

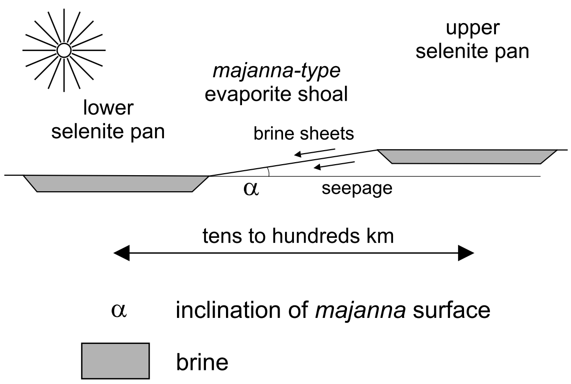

Fig. 6. Scheme showing topography of depositional environments in a salina basin, sizes and angles exaggerated; detailed explanations in the text

isochronous sediments of any saline pan on its upper slope (see Text-fig. 6 and LOGAN 1987, figs 20, 57). Thus, the semi-emerged to subaerial deposits of such a shoal, e.g. gypsum microbialites, could have been topographically lower than the subaqueous deposits of the pan, for example grass-like selenites. This is diametrically opposite to what would be expected with sedimentological models of marine basins, including saline lagoons, which assume that shallow-water facies were deposited topographically higher than the isochronous deep water facies. Therefore, the simple interpretation that all the Badenian gypsum microbialites in the south-east area of the basin, in Podillia and Bukovyna (Text-fig. 2), represent uplifted margins of the western selenite pans, is not necessarily correct. Further studies are required to reconstruct the details of the palaeogeography and geological evolution of these eastern areas.

CONCLUSIONS

1. Facies analysis of the primary Badenian gypsum deposits of the northern Carpathian Foredeep permits the recognition of some poorly known ancient environments, representing mostly various types and zones of saline pans (or subbasins), and semi-emerged shoals between them, in the giant shallow (maximum several metres deep) salina-type basin.

2. The newly recognised subaqueous selenite facies comprise selenites that are composed predominantly of horizontal crystals and are commonly associated with gypsum microbialites. Many mutually interrelated factors (nutrient supply influencing phytoplankton blooms, brine transparency controlling the growth of cyanobacterial mats, depth, pycnocline position) favoured the growth of such selenites in particular types of saline pans or in particular facies zones of larger pans. The selenite crystals largely grew displacively, within and under the cover of the growing microbial mats, at the bottom of small isolated oligotrophic pans or on the slopes of deeper eutrophic pans. Such selenites could also crystallise on the margins of the meromictic pans and could occasionally be redeposited from there as slumps and debris flow deposits into the deeper monimolimnion zones, where deposition of predominantly clastic, laminated gypsum took place.

3. A particular type of semi-emerged shoal surrounding and separating some of the saline pans was recognised. These shoals resembled the permanently wet majanna flats of the modern MacLeod salina in Australia and were dominated by in-situ gypsification of microbial (cyanobacterial) mats. The accretion of gypsum microbialites, attaining up to several metres in thickness, was continuous and uninterrupted. The accretion apparently kept pace with the gradually rising brine or water level which was controlled by the water levels in the nearest pans and in the salina basin in general.

4. The stratigraphic framework (set of marker beds interpreted as isochronous or near- isochronous) superimposed on the facies architecture of the gypsum deposits permitted a general interpretation of the history of sulphate deposition in the Badenian basin on the northern periphery of the Carpathian Foredeep. Various selenite lithosomes, including those composed of vertical and predominantly horizontal crystals, represent different types of perennial pans in the salina basin. The fine-grained- and gypsum microbialite-dominated lithosomes mostly represent evaporite shoals, some of which were of the majanna type.

5. After an initial evaporite drawdown, the northern and western areas of the basin evolved from a large perennial saline pan (or system of pans) into an evaporite shoal and back again into a perennial pan (which is interpreted as highstand-lowstand-highstand cycle in the salina basin), whereas the eastern area of the basin was a vast evaporite shoal dominated by gypsum microbialites. The selenite facies with horizontal crystals is commonly found overlying the selenites with vertical crystals (representing deep eutrophic pans), and is covered with gypsum microbialite facies (representing shoals); i.e. it is the middle part of the shallowing-upward units. The eastern area represents the basin margin, as well as vast majanna-type shoals possibly spreading south into the basin interior. Separate oligotrophic-type selenite pans existed both at the margin and in the interior of this shoal.

6. The gypsum deposits accumulated mainly through aggradation. In some places, successive gypsum lithosomes show onlap onto the basin margin and onto morphological barriers in the basin interior. This onlap is interpreted as autocyclic transgression (WARREN 1999).

7. The geological and sedimentological data suggest that a broad morphological barrier, the Miechów-Rzeszów barrier, separated the northern, gypsum-dominated, subbasins and the southern, halite-dominated, subbasins in the Polish part of the Carpathian Foredeep. The barrier was emerged at the beginning of gypsum deposition, but subsequently inundated and covered with predominantly clastic gypsum deposits that commonly contain traces of dissolved halite. The halite and gypsum subbasins were well connected at that time.

8. Evaporite deposition on the northern margin of the salina basin was arrested by a flood of marine waters and rapid deepening. This event, known as 'transgression on gypsum' was preceded by emersion and erosion, which removed the top parts of some gypsum sections

particularly in the eastern area of the basin. In the southern halite subbasins the transition from hypersaline to marine sedimentation was continuous and connected with anoxia.

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PLATES 1-5

PLATE 1

1 – Giant gypsum intergrowths; Leszcze quarry, Nida area, Poland
2 – Selenite debris flow; Kolokolyn N, Ukraine

1

2

PLATE 2

1 – Sabre gypsum with long crystals curved laterally, typical of units C-D; Ozeriany, Ukraine

2 – Sabre gypsum with long crystals curved upward, typical of unit SV; Holovchyntsi, Ukraine


1


2

PLATE 3

Gypsum microbialite deposits representing gypsified cyanobacterial mats showing crenulated-domal structures (Fig. 1); with laminated clastic gypsum-clay deposits infilling channel structure (Fig. 2); Schyrets', Ukraine, below bed b1 (Fig. 1) and Ozerna cave, Ukraine, Zal Hriazi, below bed c (Fig. 2)

1

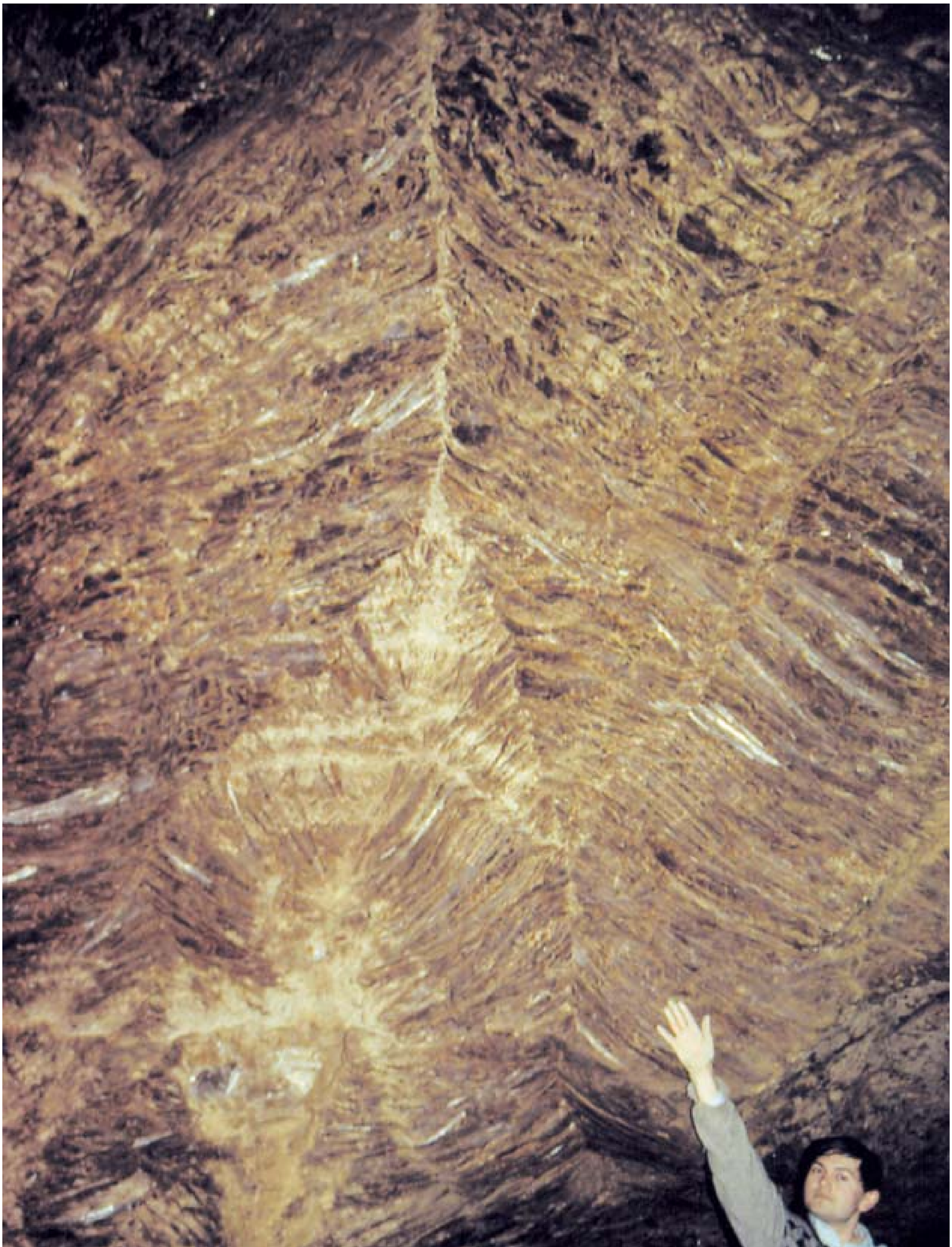
2

PLATE 4

Selenite-gypsum microbialite deposits with sabre crystals orientated horizontally, typical of unit SH; fine-grained gypsum microbialite deposits (white to orange) occur between long selenite crystals (dark and brown); note microbialite domal structure (Fig. 1, left) passing laterally into massive aggregates of crystals; walls of Krystalna cave, Kryvche, Ukraine

PLATE 5

Giant selenite domes with sub-horizontal sabre crystals curved upward on slopes; note vertical boundaries of the domes produced by competitive growth of sabre crystals; unit SH; Krystalna cave, Zal Hlyb, Kryvche, Ukraine



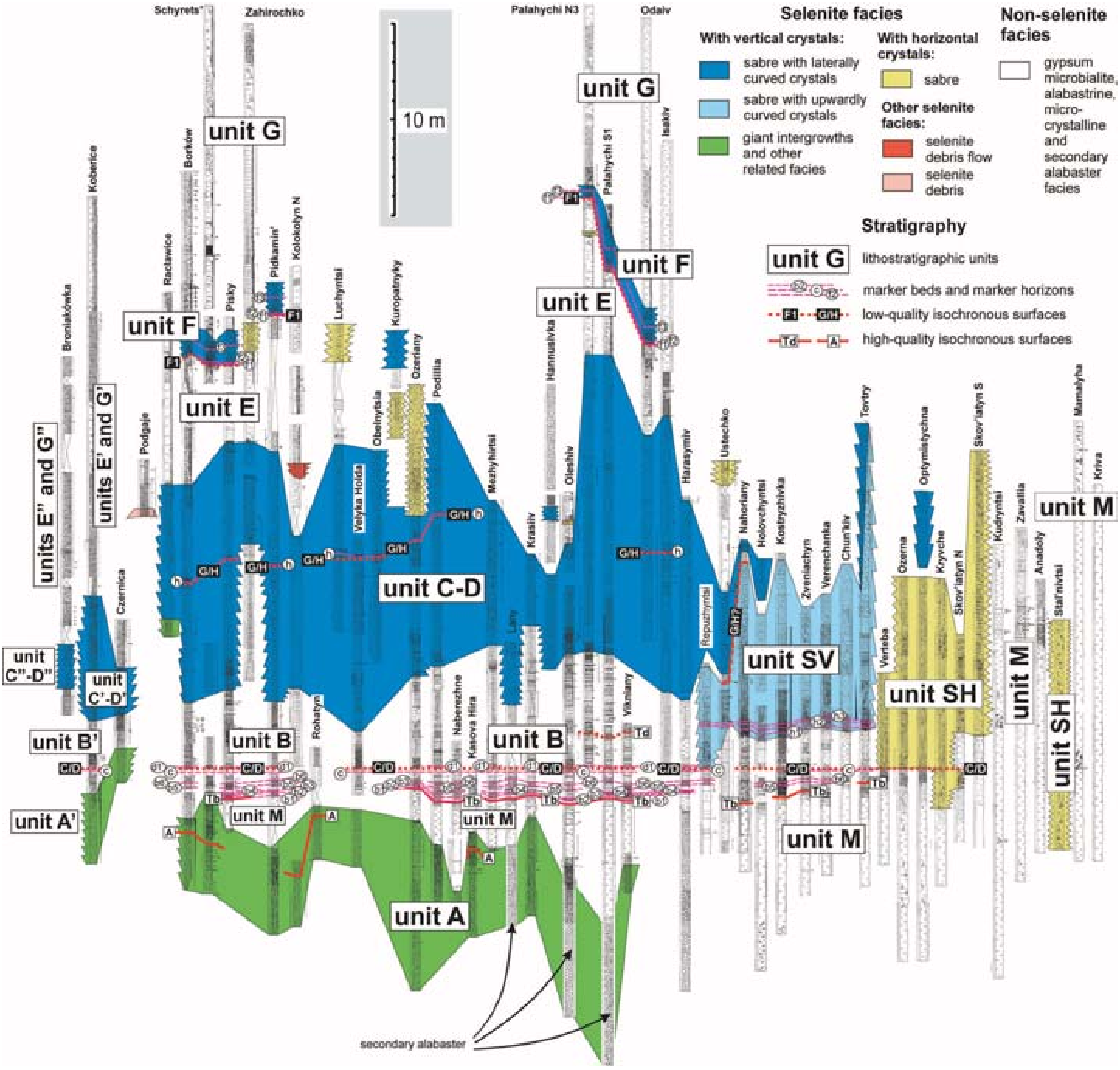


Fig. 4. Summary of facies and stratigraphic relationships in representative sections of the Badenian gypsum deposits in the northern Carpathian Foredeep along the correlation line shown in Text-fig. 2 (complete documentation and details are shown in BĄBEL 2005, On-Line Appendix, World Wide Web Address: http://www.geo.uw.edu.pl/agp/table/appendixes/55-1/)