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CYCLONIC BRINE-FLOW PATTERN RECORDED BY ORIENTED GYPSUM CRYSTALS IN THE BADENIAN EVAPORITE BASIN OF THE NORTHERN CARPATHIAN FOREDEEP

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ABSTRACT: **In the middle Miocene (Badenian), within sulfate evaporites formed in the northern Carpathian Foredeep basin of Poland, Ukraine, and the Czech Republic, the apices of the primary, bottom-grown gypsum crystals (selenites) are similarly aligned over broad areas and have a common azimuth. This crystal orientation is interpreted as the product of a consistent direction of a brine inflow during gypsum crystallization, and such a unique commonality is used as a tool for paleocurrent analysis in order to recognize both the local and the regional brine paleocurrents in the basin. Earlier sedimentologic and stratigraphic studies proved that these beds of oriented selenites were deposited at the same or nearly the same time, in a brine not more than a few meters deep. It is interpreted that the oriented selenites recorded only the mean flow within the basin, mainly from the periods of mixing (in the dry-season lowstands), when the whole brine column down to the bottom was Ca-sulfate oversaturated. The measured paleocurrent vectors showed that the brines flowed along the marginal zone of the Carpathian Foredeep basin predominantly in a counterclockwise direction. This longshore flow is interpreted as a typical cyclonic circulation analogous to those present in recent lakes and semi-closed basins in the northern hemisphere where counterclockwise mean water drift is directly or indirectly forced by Earth rotation (the Coriolis effect). The detected brine flow directions do not reflect downslope gravity flow of dense brines into the central basinal depths or subbasins that were filling with the halite facies.**

INTRODUCTION

Because of the profound effects of diagenetic overprint and the resulting loss of recognizable primary sedimentary features, paleocurrent analysis is rarely applied to ancient evaporite basins. The real brine current patterns in such basins are poorly known, although it has been the subject of many theoretical models and reconstructions (Sonnenfeld 1984; Dronkert 1985). The currents of the recent large saline basins such as the Dead Sea or Kara Bogaz Gol are also inadequately understood (Lepeshkov et al. 1981; Niemi et al. 1997). The rarity of paleocurrent studies in ancient evaporite basins is also the result of the scarcity of the measurable current-related structures, i.e., the structures produced by currents strong enough to transport clastic particles. Such structures are rare in evaporites because these deposits were commonly accreted *in situ*, by crystallization directly on the floor of the basin, under the cover of a relatively calm or even stagnating brine, unable to move and redeposit the growing crystals. Thus the typical structures (ripples, cross-bedding) are present in some clastic evaporites but are commonly obliterated by later diagenetic processes. *In situ* precipitated evaporite deposits formed as crystal beds, generally unable to record any flow directionality. However, there are exceptions. Some deposits contain structures related not to mechanical action of the brine current but to its actual physicochemical influence on the growing crystals.

Unique current-related structures were recognized in some bottom-grown selenite crystals showing conformable upstream orientation of apices in different Miocene evaporite basins in Spain and Italy (Dronkert 1977, 1985; B. Charlotte Schreiber 1982, *in* Folk et al. 1985, p. 352; Stefano Lugli, University of Modena, oral communication). Oriented selenites are particularly widespread in the Badenian of the northern Carpathian Foredeep, and they permit paleocurrent analysis in this area (Bąbel et al. 1999; Roman 1999; Bąbel 2002).

In this paper further arguments are supplied to demonstrate current-related origin of such oriented selenites and to develop some new concepts concerning their depositional environment and the hydrodynamics of brines in an evaporite basin. The method of the paleocurrent analysis is illustrated from oriented selenites in one small area of the Badenian basin which was selected for a detailed case study. The new data are supplemented by the observations from the other areas of the basin and are used for reconstruction and discussion of a general brine-flow pattern in the basin. In particular the discussion considers the "saturation shelf" model of brine transport previously applied to this basin. The second topic is the interpretation of the nature and the origin of the detected brine currents by comparison with the water currents and water circulation in lakes and semi-closed basins following the concepts developed in modern limnology (e.g., Hutchinson 1975; Horne and Goldman 1994).

GEOLOGY AND PALEOGEOGRAHY OF BADENIAN EVAPORITE BASIN

The Carpathian Foredeep basin is the largest of the several evaporite basins which developed during the Badenian salinity crisis in the Paratethys area (Fig. 1A, B; Rögl 1999). It stretches across the northern Carpathian Foredeep, including west Ukraine, Poland, and the Czech Republic (Fig. 2A), and the evaporites are present as laterally continuous

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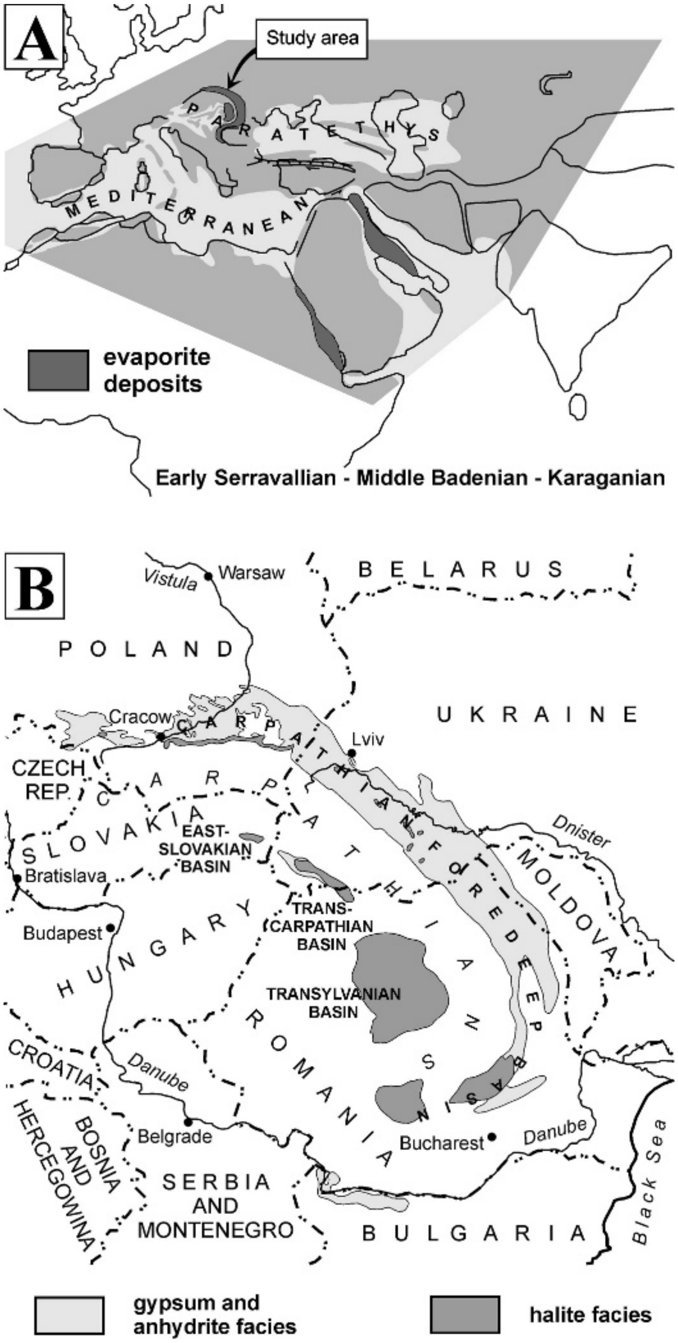


FIG. 1.—Maps illustrating the areas and distribution of Badenian evaporites: **A)** paleogeography of Paratethys and Mediterranean in the middle Miocene and location of the studied Badenian evaporites (after Rögl 1999). **B)** Present distribution of the Paratethyan Badenian evaporites (after Khrushchov and Petrichenko 1979, Garlicki 1979, modified).

layers of gypsum, anhydrite, halite, and carbonate deposits which only locally exceed 60 m in thickness. The evaporites are underlain by marine Badenian clastics and carbonates, up to several tens of meters thick, resting transgressively on an eroded mostly Mesozoic and Paleozoic substrate, and are overlain by marine to brackish Badenian–Sarmatian carbonates and clastics sporadically reaching 3–4 km in thickness. The undisturbed primary gypsum deposits, including layers with the spectacular current-oriented selenites, crop out along the northern margin of the basin, and to the south they pass into deeply buried anhydrite and halite deposits. The southern margin of the basin has been destroyed by subsequent erosion. Along the main Carpathian overthrust the evaporites are folded and tectonically disturbed. They occur both below the flysch nappes and resting on tectonically displaced nappes (Fig. 2A, C). Palinspastic reconstruction suggests ca. 50 km tectonic shortening of the southern margin of the evaporite basin (Połtowicz 1993).

The Badenian evaporite basin of the Carpathian Foredeep, at least in its northern sulfate margin, displays features typical of a marine salina-type basin with a water level drawn down below sea level (Peryt 2001; Bąbel 2004b, 2005a, 2005b; Cendón et al. 2004). It seems that the basin had no permanent open-water connections with the sea and was supplied with marine water by occasional inflows through some morphologic barriers or by seepage (Peryt 2001). The basin comprises several subbasins, halite-dominated and containing laminated anhydrites with clay intercalations in the south, and gypsum-dominated and displaying selenite facies in the north. The gypsum subbasins were very broad and shallow, zero m to several meters deep, and are so similar (both lithologically and stratigraphically) that they can be treated as a single marginal sulfate platform with a somewhat undulating morphology (Kasprzyk and Ortí 1998). Presumed shoals and islands occurred in between the subbasins. The largest central area, devoid of evaporite deposits, is interpreted as an island (Rzeszów Island or Rzeszów Paleoridge; Fig. 2A), although evaporites could have been eroded during or soon after the evaporite deposition (Połtowicz 1993; Oszczypko 1998). The marginal gypsum deposits have some prominent and recognizable emersion surfaces proving that the northern peripheries of the basin were extremely shallow. Similar emersions were not recognized in the halite subbasins, which have been considered to be significantly deeper than the gypsum subbasins (Garlicki 1979; Peryt 2000; Kasprzyk 2003).

The marginal gypsum deposits comprise a dozen or so laterally continuous layers showing similar lithology or facies. The layers were grouped into several lithostratigraphic units (marked by capital letters: from A to G, and M, SV, SH; Fig. 2B). Generally, two main units were distinguished: the lower autochthonous and the upper allochthonous unit (Peryt 1996; Rosell et al. 1998; Kasprzyk 2003). The lower unit, up to ca. 25 m thick, is composed largely of primary coarse-crystalline bottom-grown gypsum crystals and is also called the selenite unit. The upper unit, which locally attains 35 m in thickness, comprises clastic or microcrystalline gypsum but also contains thin, *in situ* selenite layers. The investigated oriented selenites occur in the upper part of the lower unit, within unit C–D, which is up to 15 m thick, and also, but only locally, in the upper part of unit SV (Fig. 2B).

Event stratigraphic studies based on several thin marker beds proved that the marginal gypsum deposits in Poland, Ukraine, and the Czech Republic are coeval (Peryt 2001; Bąbel 2005a). Similarly, the halite-bearing deposits in Poland comprise several cyclothems which are interpreted as deposited in the same time interval (Garlicki 1968; García Veigas et al. 1997). However, precise stratigraphic relations between these gypsum and halite facies, and poorly studied halite facies in Ukraine, remain unclear (Andreyeva-Grigorovich et al. 2003). Based on geochemical data Petrichenko et al. (1997), following some earlier authors (Ladyzhenskii and Antipov 1961, p. 225), suggests that the upper part of the marginal gypsum deposits postdate halite deposition. On the other hand, Kasprzyk and Ortí (1998) believed that the lower autochthonous unit (selenite unit; Fig. 2B) preceded the halite deposition in the southern area of the Polish Carpathian Foredeep. The halite deposition could have been more or less coeval with the allochthonous gypsum unit, which commonly contains traces of dissolved halite (Bąbel 1999a, 1999b, 2005b). Thus it is quite possible that the halite subbasins were not in the active stage of sodium chloride precipitation during sedimentation of the studied oriented selenites in the basin margin.

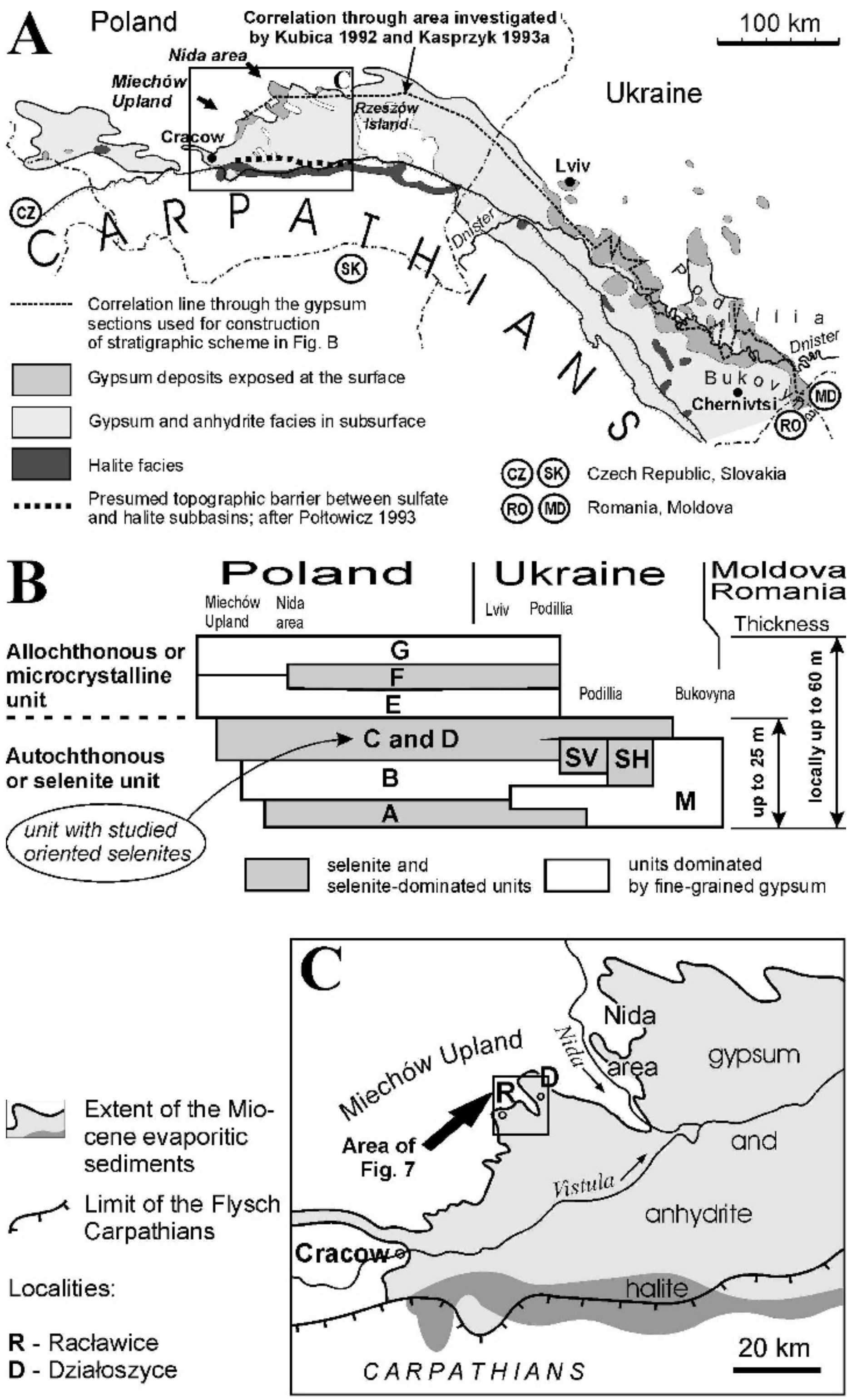


FIG. 2.—Gypsum of the Carpathian Foredeep: **A)** geology of the Badenian evaporites in the northern Carpathian Foredeep (adapted from Garlicki 1979, Panov and Plotnikov 1999, and other sources; see Bąbel 2005a). **B)** Lithostratigraphy of the marginal gypsum evaporites along the correlation line shown in Part A. Lettered units after Kubica (1992) and Bąbel (2005a). **C)** Location of the detail study area in southern Poland.

BRINE FLOW IN THE BADENIAN BASIN

The main source of brine in the Carpathian Foredeep Basin presumably was Mediterranean seawater (Fig. 1A) and to some extent recycling of earlier salts (Cendón et al. 2004). The seawater could enter the northernmost area of the basin (through seepage and occasional surface inflows) from the east (Figs. 1A, B, 2A; Kwiatkowski 1972; Andreyeva-Grigorovich et al. 2003), both from east and west (Garlicki 1979), and, it is not unlikely, also from the south, across the emerging orogenic arc (see Połtowicz 1993, his figs. 2, 5). The real inflow sites have never been documented, and it is very likely that these sites, together with some intermediate subbasins, were completely destroyed by erosion connected with the Carpathian Mountains uplift. Garlicki (1979, p. 33) believed that the brine inflowing into the Polish part of the basin was already saturated with gypsum.

The problem of the brine flow pattern within the Badenian evaporite basin is mentioned in many earlier studies that suggest currents of dense saline brine downflowing from coastal evaporite shoals to the deeper halite subbasins (e.g., Połtowicz 1962, 1977, 1993; Kwiatkowski 1972; Garlicki 1979; Pawlikowski 1982). This view reflects a popular and simplified concept of a nearshore water circulation pattern in evaporite basins that assumes that evaporation led to underflow currents of dense brine and a compensation surface countercurrent of fresher water to the shore (Richter-Bernburg 1955, his fig. 2). Garlicki (1979) and Połtowicz (1993) accepted a model of a "saturation shelf" for the Badenian basin (Richter-Bernburg 1955; Sonnenfeld 1984) and claimed that the water evaporated mainly on the broad and flat areas of the northern sulfate platform, and after Ca-sulfate deposition it flowed down into the deeper halite subbasins (Fig. 2A). Połtowicz (1993) believed that brine flowed through the northern sulfate platform from the east and around the Rzeszów Island, and developed a strong underflow into the southern halite subbasin over the hypothetical longitudinal barrier spreading west of Rzeszów Island and separating the sulfate and halite subbasins along the Rzeszów–Cracow line (Fig. 2A). Brine paleocurrent analysis based on the mentioned oriented selenites in Poland and Ukraine confirmed this view (Bąbel et al. 1999). The brine apparently flowed from the southeast and around Rzeszów Island farther towards the southwest (Fig. 2A). However, there is no evidence that the brine moved directly southwards to deeper areas of halite precipitation either in Poland and Ukraine as assumed by previous authors. This brine flowed more or less alongshore, parallel to the northern margin of the basin. Such a flow orientation is documented in detail in the Nida area in Poland (Bąbel 2002).

The Miechów Upland, between the Nida area and Cracow (Fig. 2A), is crucial in the brine flow reconstruction in the Polish portion of the basin. The Miechów Upland lies along the path of the assumed brine current inflowing from the Nida area and closer to the halite facies. This detailed paleocurrent investigation in the Miechów Upland (Fig. 2C) has been carried out in order to trace the continued pathway of brines and detect the supposed direction of their outflow towards the southern halite facies area as it was predicted by the "saturation shelf" and nearshore brine circulation concepts of Richter-Bernburg (1955) and Sonnenfeld (1984).

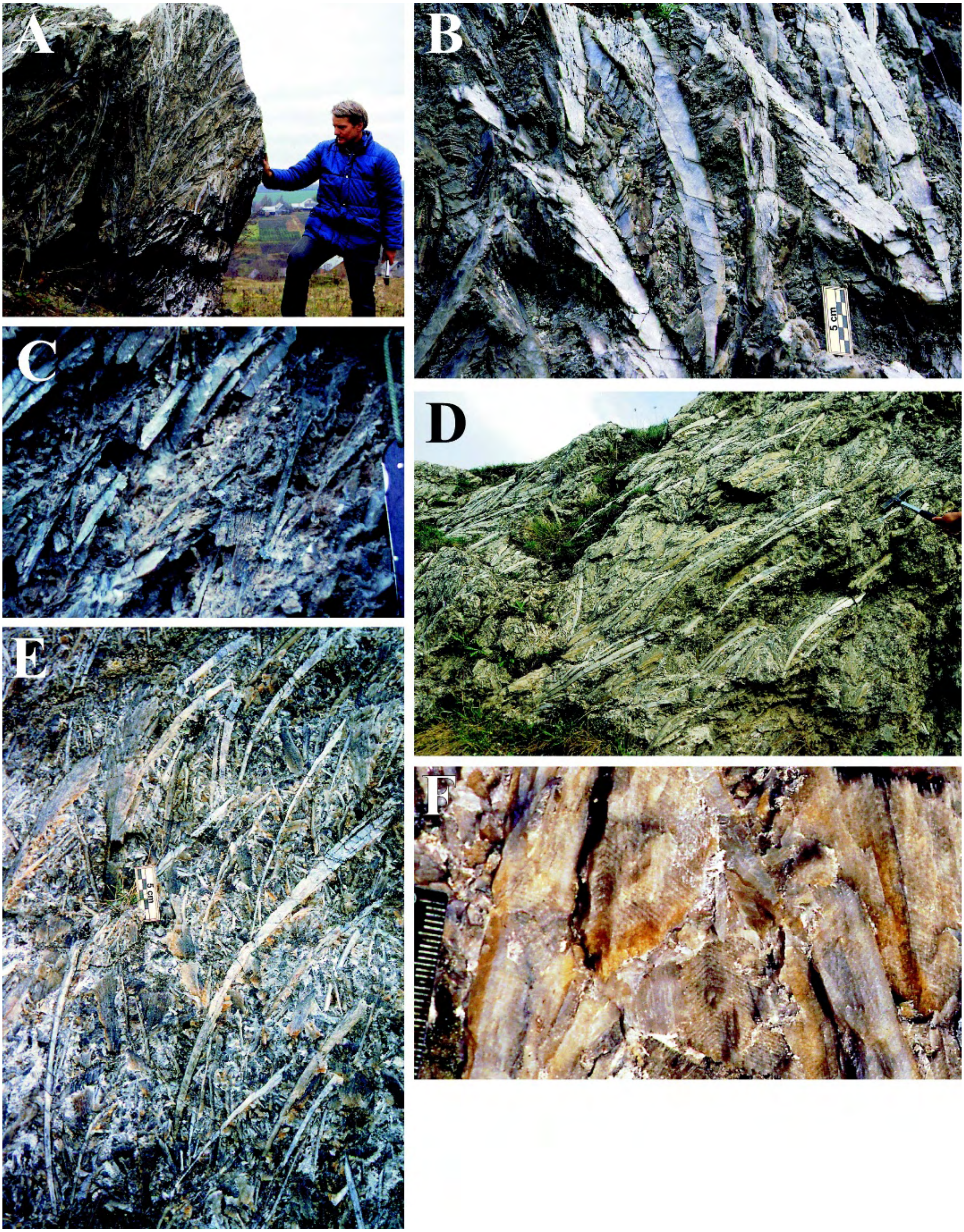
SEDIMENTARY STRUCTURES INDICATING BRINE FLOW

One of the selenite facies in which such systematically oriented crystal structure is recognizable is called "sabre" gypsum (Kasprzyk 1993a, 1993b; Peryt 1996). The name of this facies arises from the presence of large, elongate, curved gypsum crystals resembling sabres (curved swords), (Figs. 3–6). It is further observed that in many outcrops most or even all of the sabre crystals are inclined and curved in the same direction. Such a phenomenon was first recorded in the Messinian gypsum in Spain by Dronkert (1977, 1978, 1985) and then in the studied middle Miocene (Badenian) basin in Poland, Ukraine, and the Czech Republic (Pawlikowski 1982; Bąbel 2002). The sabre crystals are the primary deposit in these areas. They grew directly on the floor of the evaporite basin, which is proved by: (1) primary empty intercrystalline pores or voids indicating lack of any earlier mineral precursors (Fig. 3C), (2) competitive "free-growth" fabric, which suggests an upward growth of gypsum crystals into a free space, i.e., a brine (Figs. 3B, E, 6C; Shearman and Ortí 1978; Bąbel 2002; cf. Dronkert 1985, p. 95), (3) primary millimeter-scale growth zoning traced horizontally in many crystals, indicating their common growth upward (Fig. 3F; Warren 1982; cf. Dronkert 1985, p. 95), (4) compactional breaks of the crystals (Fig. 6A; Dronkert 1978, p. 358), (5) pocket-like hollows between crystal apices filled with clastic deposits (cf. Hardie and Eugster 1971; see Kasprzyk 1993b, her fig. 19), (6) presence of broken and abraded sabre crystals within redeposited gypsum sediments (cf. Hardie and Eugster 1971; Bąbel 2005b, his plate 1, fig. 2), (7) abraded and/or dissolved crystal apices (cf. Schreiber and Kinsman 1975, their fig. 7; Hardie and Eugster 1971, their fig. 21B), (8) horizontal synsedimentary dissolution surfaces crosscutting the crystals (e.g., Peryt 2001, his fig. 11; Bąbel 2002, his fig. 1C), and (9) crystal apices draped by concentric laminations produced by *in situ* gypsified microbial mats (cf. Hardie and Eugster 1971, their fig. 19, p. 212; Peryt 1996, his fig. 11E).

This specific oriented fabric is explained as follows. The common orientation of sabre crystals is a product of competitive growth of crystals on the floor of the basin modified by accelerated growth of selected crystals oriented in one horizontal direction (see Rodriguez-Navarro and García-Ruiz 2000). This acceleration is interpreted as caused by a Ca-sulfate saturated brine current flowing over the crystal apices (Fig. 4; Dronkert 1977, 1978, 1985, p. 205; Pawlikowski 1982, p. 36; Bąbel 2002; cf. Flis 1963, p. 24). It is assumed that the unidirectionally moving brine accelerated growth of the crystal faces on the stoss side. Those crystals which were favorably oriented, with their apices ({120} faces) turned horizontally and faced towards the inflowing brine, grew faster than non-oriented individuals (Figs. 4B, 6C). Long-term competitive growth led to development of entire beds made up of a unique crystal fabric in which many sabre crystals are inclined in the same direction (Figs. 3, 6B). Such crystals can be used as a tool for tracing of brine flow. They are inclined in the direction opposite to the brine inflow direction, i.e., upstream. The reverse azimuth of their orientation indicates paths of brine transport.

The above interpretation is proved by: (1) some experiments on crystal growth in the flowing medium (Newhouse 1941; Armstrong 1943; Mokyevsky 1948; Garrels 1951; Pismenny 1970; Petrovsky 1983; Prieto et al. 1996) documenting an increased growth rate of stoss-side crystal faces (although the laboratory conditions are not really comparable with the considered natural processes); (2) theoretical models of crystal growth in the flowing solution which suggest an increased growth rate of crystals toward the nourishing inflow (Noh et al. 1998; Vartak et al. 2000); (3) coincidence of the studied gypsum crystal orientation with paleocurrent directions indicated by the other structures in the adjacent beds (such as horizontally elongated gypsum microbialite domes; Bąbel 2002, and unpublished data; cf. Hoffman 1967); (4) parallelism and high degree of uniformity of the directions indicated by oriented crystals within the areas, tens of kilometers in size, fitting to the picture of parallel streamlines of the unidirectionally (*en masse*) moving basinal water; (5) horizontal gradual rotation of the directions of crystal orientation towards the same side (up to a few tens of degrees), traced over distances of tens of kilometers, and forming counterclockwise and, rarely, clockwise swirls similar to cyclonic (anticyclonic) water gyres in recent basins (Bąbel et al. 1999, their fig. 1; Bąbel 2002, his fig. 8); and (6) the fact that the pattern of paleocurrents indicated by gypsum crystals fits well to the shape of the basin itself. Deviations from a regular orientation pattern recorded in some areas do not contradict the presented interpretation; they are explained by the presence of shoals and islands disturbing the brine currents.

Although known from experiments and theory, the oriented upstream growth of natural crystals has rarely been noted in recent environments, except for the development of ice crystals (e.g., Streitz and Ettema 2002) and upstream-oriented calcite crystals that are found in some springs (Folk et al. 1985; Jones and Renaut 1998; Jones et al. 2000) and caves (in spray zones of impacting drip water; Gonzalez and Lohmann 1988). More examples of such (supposed) growth are known from various ancient, mainly near-surface and deep subsurface environments. It has commonly been assumed that fluid paths were recorded by elongated carbonate concretions (see Colton 1967; Sperling 1967; Jacob 1973; McBride et al. 1994; Mozley and Goodwin 1995; McBride and Parea 2001; Abdel-Wahab and McBride 2001; and references in Mozley and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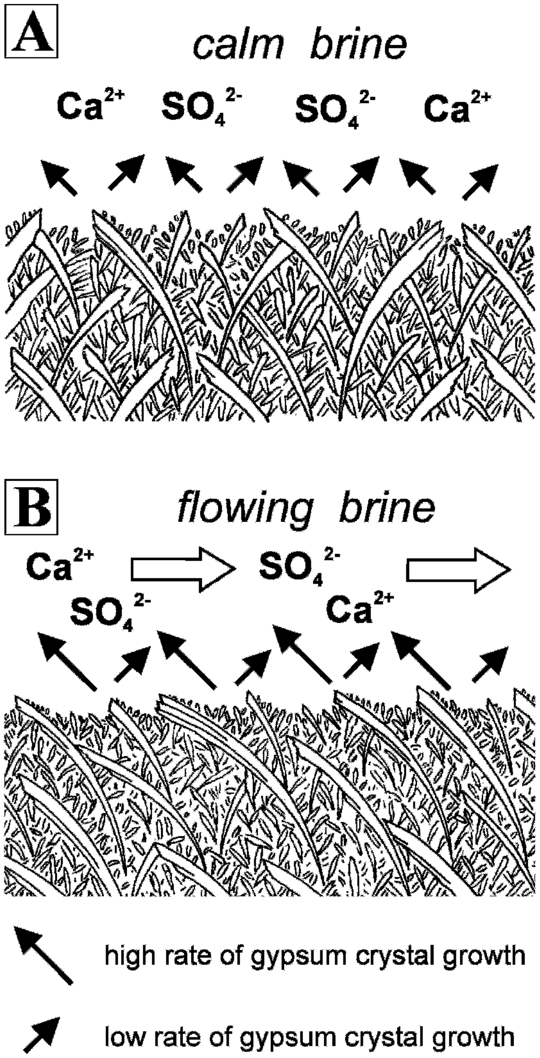

FIG. 4.— Cartoon illustrating the oriented growth of sabre gypsum crystals promoted by bottom current of brine oversaturated with calcium sulfate.

Davis 2005) and asymmetric crystals in mineral veins and druses, particularly by quartz (Newhouse 1941; Grigoryev and Zhabin 1975, with references). Paleoflow analyses from such *in situ* grown mineral crystals (or their aggregates—as in the case of the oriented concretions) have not been made until recently (e.g., Colton 1967; Sperling 1967; Krasnova et al. 1970; Kesler et al. 1972; Jacob 1973; Raiswell and White 1978; McBride et al. 1994; Davies 1999) and the results and the origin of oriented structures have been controversial (see Engel 1948; Grigoryev and Zhabin 1975; Raiswell and White 1978; Punin et al. 1980; and Mozley and Davis 2005). The assumed pore-water or hydrothermal fluid flow is poorly comparable with the free flow of brine in evaporite basins. The mechanisms of selected directional crystallization in the cases cited above were not explained by the competitive growth, as in the studied selenites (see Rodriguez-Navarro and García-Ruiz 2000). The Badenian selenites also differ from the listed examples on a much larger scale of occurrence, the greater distinctness of the current-related crystalline structures, and the greater number of consistent measurements of the crystal orientation over distances of tens of kilometers.

GYPSUM DEPOSITS OF THE MIECHÓW UPLAND

The area selected for a detailed case study is situated near the community of Racławice, on the Miechów Upland, about 40 km northeast of Cracow (Fig. 2C). Gypsum deposits are poorly described because of rarity of large outcrops (Krach 1947, 1962; Łyczewska 1965; Radwański 1968; Kwiatkowski 1972, 1974; Osmólski 1972; Peryt and Kasprzyk 1992). The nearest good and well recognized gypsum exposures exist 20 km northeast of Racławice in the Nida area (Kwiatkowski 1972; Kasprzyk 1993a, 1993b; Bąbel 1999a, 1999b). The maximum thickness of gypsum in the Nida area is greater than 50 m, whereas in the environs of Racławice it is thinner (less than 30 m, Fig. 2C; Osmólski 1972; Kwiatkowski 1974).

In the studied area gypsum deposits overlie the Badenian quartz sands or clay and marls (Heterostegina sands, Baranów beds) or directly lie on the eroded Mesozoic basement. They are overlain by clays and sands of the Badenian and/or Sarmatian age or by Quaternary clastics, especially by loess (Krach 1947; Radwański 1968).

The investigated gypsum sections show generally the same vertical arrangement of facies and lithostratigraphic units as in the whole northern margin of the Carpathian Foredeep, and particularly in the Nida area (Fig. 5; Kubica 1992; Kasprzyk 1993a, 1993b; Peryt 1996, 2001; Rosell et al. 1998; Bąbel 1999a, 1999b, 2005a, 2005b). Six facies are distinguished, from which one, palisade gypsum, is newly recognized, and occurs only on the Miechów Upland:

- giant gypsum intergrowths: composed of vertically arranged large gypsum crystals (up to 3.5 m) commonly joined in pairs resembling twins of the "swallow-tail" type; deposited in a permanent saline pan a few meters deep (Kasprzyk 1993b; Peryt 1996; Bąbel 1999a);
- palisade gypsum: composed of bottom-grown crystals similar to the giant intergrowths, but smaller (up to 1 m) and never twinned or joined in pairs; deposited in a permanent saline pan in shallow brine with common inflows of brackish water (Roman 1998; Becker 2005);
- selenite debris: accumulation of broken, abraded, and partly dissolved gypsum fragments, up to 40 cm long; a product of destruction of the original palisade selenite beds by atmospheric factors and weathering during temporary emersion (Roman 1998; Bąbel 1999a, 2005b);
- grass-like gypsum: bedded selenites with intercalations of alabastrine and stromatolitic gypsum or clay; deposited in very shallow brine (0–2 m), mostly on evaporite shoals and in ephemeral to perennial saline pans (Kasprzyk 1993a; Peryt 1996; Bąbel 1999a, 1999b, 2005b);
- sabre gypsum: built of large bottom-grown curved crystals, with smaller gypsum crystals and microcrystalline matrix; deposited in a permanent saline pan in brines that were at maximum a few meters deep (Kasprzyk 1993a; Peryt 1996; Bąbel 1999a);
- microcrystalline gypsum: very thinly laminated gypsum composed of grains less than 0.05 mm in size with thin intercalations of carbonates and clays; deposited either in shallow and somewhat deeper brine or

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FIG. 3.— Sabre gypsum facies from various parts of the basin: **A)** sabre gypsum with vertically oriented crystals, Holovchyntsi, Ukraine. **B)** Sabre gypsum with relatively thick crystals displaying competitive growth fabric, Ustechko, Ukraine. **C)** Sabre gypsum with primary empty intercrystalline pores; Borków, Poland. **D)** Sabre gypsum with subhorizontally oriented crystals, Ozeriany, Ukraine. **E)** Sabre gypsum with very narrow crystals showing competitive growth fabric, Podillia, Ukraine. **F)** Primary growth zoning of sabre gypsum crystals related to advance of the {120} prism faces, Schyrets', Ukraine. Localities shown are described in detail in Bąbel (2005a, On-Line Appendix).

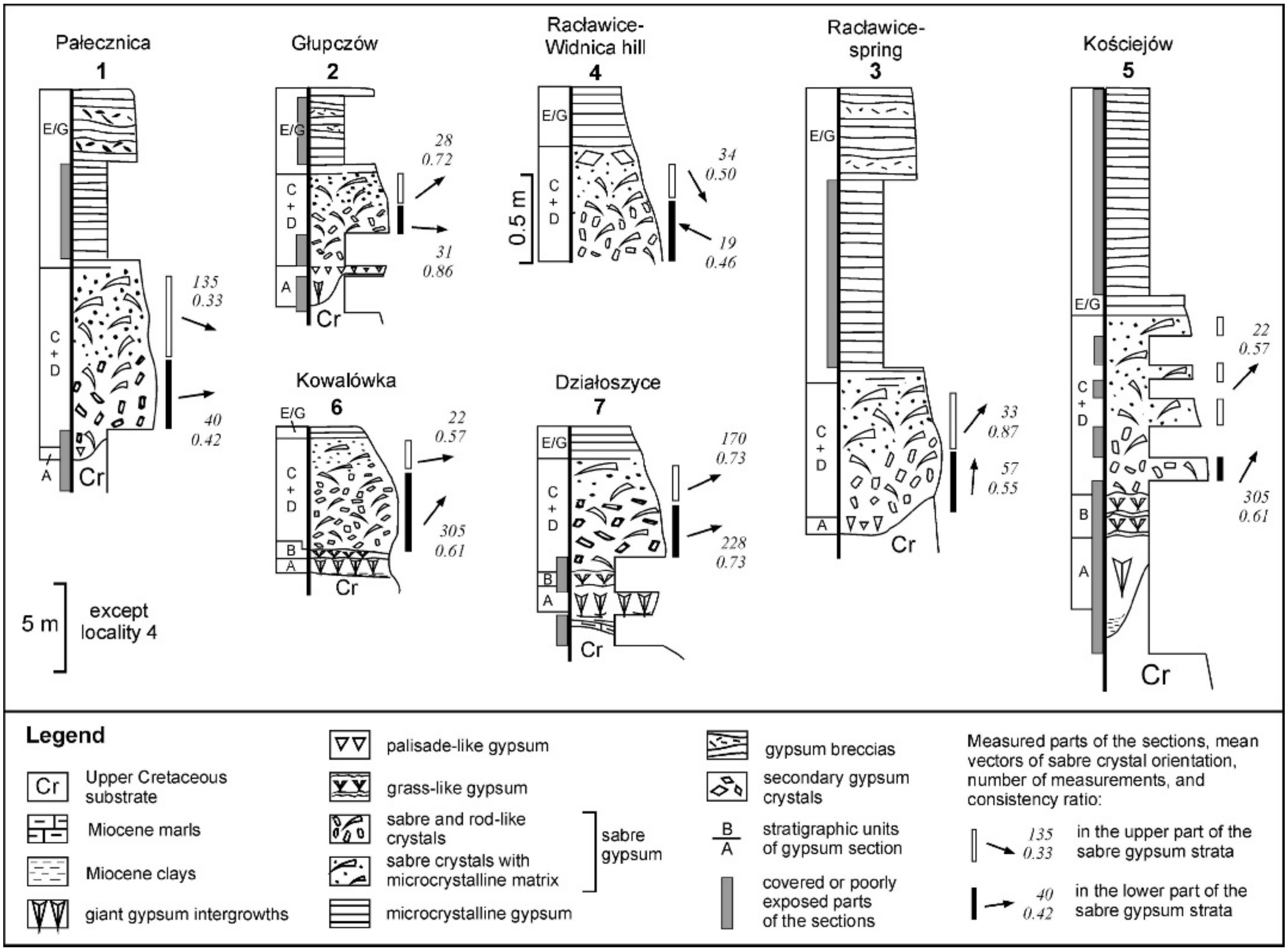

FIG. 5.—Gypsum sections in studied localities 1–7 (see Fig. 7). Covered parts are inferred from surface debris.

water (but no more than 20 m) (Kwiatkowski 1972; Kasprzyk 1993a; Peryt 1996; Bąbel 1999a).

The base of the gypsum section is formed by beds made up of giant crystal intergrowths (unit A; Figs. 2B, 5), which are overlain by grass-like gypsum (unit B). The next layers above the grass-like beds are composed of sabre gypsum (unit C–D). The top of the gypsum stratal succession is composed of microcrystalline gypsum, and the residual collapse breccias formed after the dissolution of halite (unit E and/or G, Fig. 5). In the Racławice area the giant intergrowths and grass-like gypsum strata are greatly reduced in thickness and are commonly represented instead by one thin layer of palisade gypsum (included into unit A, Fig. 5) or by a selenite debris layer which is the product of destruction of the palisade gypsum during emersion. The oriented selenite structures occur in unit C–D, which is present across the whole northern margin of the basin (Fig. 2A, B). A thin layer of clastic clay–gypsum deposits that occurs in the middle part of unit C–D is a marker bed representing isochronous or nearly isochronous deposition (Bąbel 1999b, 2005a; Peryt 2001). This strongly suggests that unit C–D was deposited in the same or nearly the same time across the entire region and the discussed paleocurrent reconstruction is stratigraphically justified. The described marker bed was not found in the Miechów Upland, but it is probably represented by some less obvious dissolution or erosion surface within unit C–D.

In the Miechów Upland unit C–D reaches 10 m in thickness and is present in almost all investigated outcrops (Fig. 5; Roman 1998; Becker 2005). It is composed of sabre gypsum crystals ranging from 0.1 to 1.18 m in length (30 cm on average). Similarly to observations in all of the other areas of the basin, the lower part of the sabre gypsum strata in unit C–D contains smaller, rod-like, chaotically arranged gypsum crystals as well as the large sabre crystals. These smaller crystals correspond to the so-called “skeletal gypsum facies” described by Kasprzyk (1993a) and Peryt (1996). In the upper part of the sabre gypsum strata the intercrystalline spaces are filled with granular gypsum crystals and minor amounts of carbonate and clay, and the lithology is similar to “wavy bedded” sabre facies described from the Nida area (Bąbel 1999a).

METHOD OF MEASUREMENTS AND THEIR STATISTICAL ANALYSIS

The measurements of the orientations of the sabre crystals (azimuths of their apices) were made in seven outcrops (Figs. 5, 7). Measurements were compiled separately for the lower and upper parts of sabre-gypsum strata in each outcrop. Mean vectors of sabre-crystal orientation and consistency ratio were statistically counted for all fourteen groups of measurements (two groups for each outcrop) and for all measurements together. The mean vector is interpreted as parallel to the path of brine flow. The consistency ratio is the measure of differentiation of measured

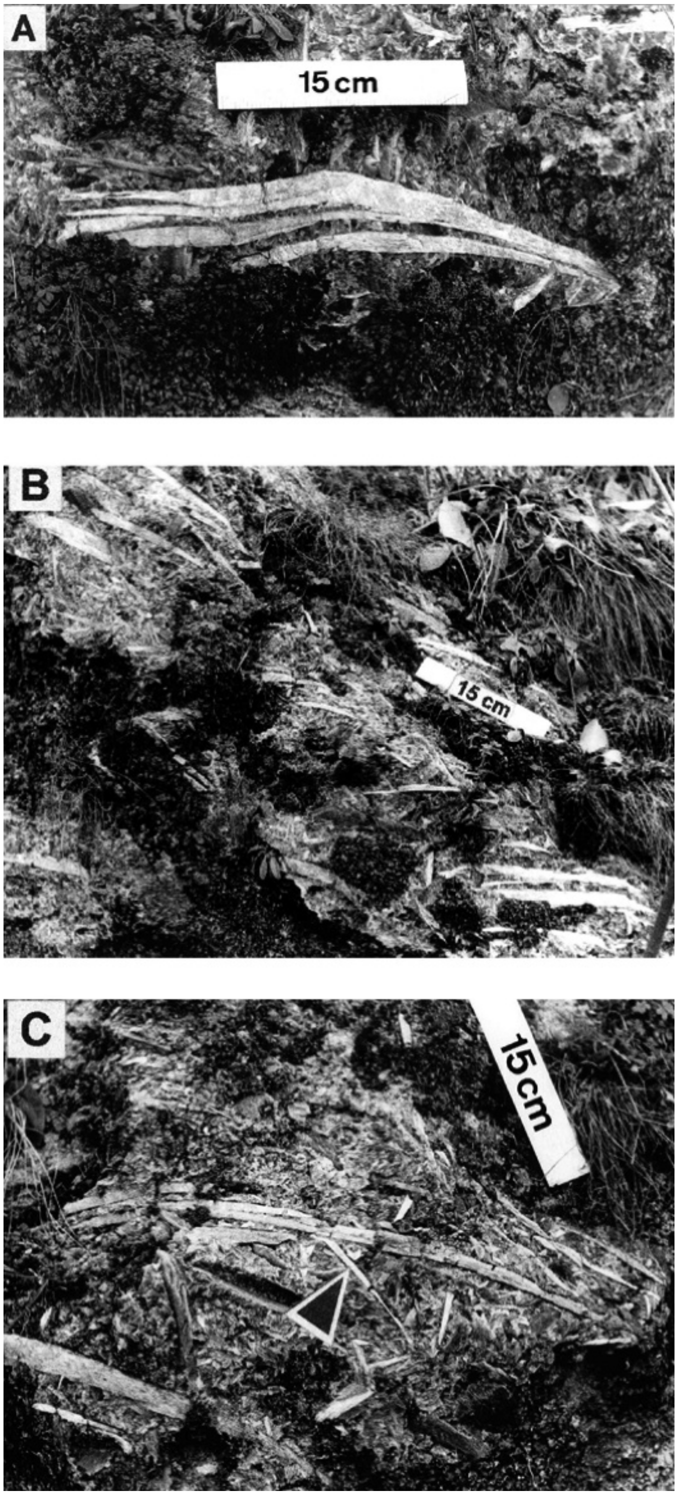

FIG. 6.— Sabre gypsum deposits at Działoszyce (locality 7 in Fig. 7). **A)** Aggregate of sabre crystals deformed by compaction. **B)** Similar orientation of the sabre crystals. **C)** Example of the competitive growth fabric; the growth of small sabre crystal (arrowed) was inhibited by the large crystal because of their competitive growth.

azimuths. Its values range from 0 to 1; the greater the consistency ratio, the narrower the interval containing the measured azimuths.

RESULTS OF MEASUREMENTS

Measurements made on the Miechów Upland confirm regional uniformity of the orientation of the sabre crystals similar to that observed in the Nida area and other parts of the basin margin (Bąbel 2002).

Azimuths of mean vectors from six studied outcrops (excluding locality 4; Figs. 5, 7) range from 4° to 110°. This means that the brine current flowed from the north, northeast, east, and southeast. The azimuth of the mean vector of orientation of all the 1415 measured sabre crystals is 55°, which indicates that the main direction of brine transport was from the northeast toward the southwest.

Azimuths of the crystals are commonly variable and characterized by a low consistency ratio (e.g., localities 1, 4; see Fig. 7). In locality 4 the lowest consistency ratio is 0.21, and this low ratio can be the result of the small number of measurements ($n = 53$). It is also possible that in this outcrop the sabre crystals are oriented in very different directions and that measurements from locality 4 are not of any use for the regional interpretation of the brine flow direction. The results of measurements from locality 1 (the lowest consistency ratio = 0.33) are more useful than those described above, because of the larger number of measurements ($n = 175$). The mean azimuth in this locality indicates westward direction of brine flow, similarly to the results from other outcrops in the studied area (localities 2, 6; Fig. 7). Probably near Pałecznica (locality 1) the brine current did not influence the sabre-gypsum sedimentation for the entire growth period, and it resulted in a high variation of sabre-crystal orientation. High values of consistency ratio and similar mean vector azimuths are characteristic for statistic results from locality 5 and 7, which indicates clearly uniform action of brine current during sabre-gypsum sedimentation.

The crystals from upper part of the sabre-gypsum strata show mean vectors shifted for 20° or so to east and southeast, relative to results (mean vectors) from lower part of the sabre-gypsum strata. This situation is observed in localities 1, 3, 5, and 6 (Fig. 5). This fact is interpreted to be a result of a slight regional change in the direction of the brine flow during gypsum sedimentation. The direction of brine flow apparently shifted to the east or southeast during the period of sabre-gypsum deposition.

BRINE FLOW ON THE MIECHÓW UPLAND

Measurements made on the Miechów Upland indicate that brine paleocurrent inflow moved from the Nida area towards the southwest and west. This suggests that the evaporite basin probably continued farther west, and the present-day limit of the gypsum, especially between Racławice, Działoszyce, and the Nida area, is erosionally constrained (Figs. 2C, 7, 8).

In the Polish portion of the basin there is no evidence of a brine flow to the south, directly towards the halite facies area, as has previously been assumed (i.e., downslope from the shallow to the deeper zones; Połtowicz 1962; Kwiatkowski 1972; Garlicki 1979; Pawlikowski 1982). A simple explanation for such a restricted flow pattern could be the presence of hypothetical shoals or islands, located south and southeast of the study area, that formed an obstacle to the brine outflow toward the south. This is in accordance with the view (Połtowicz 1993; Bąbel 2005b) that there was a topographic barrier that separated the southern halite-dominated subbasin from the northern sulfate-dominated area (Fig. 2A). This barrier could have been broader than suggested by Połtowicz (1993). Indeed, it could include semi-emerged shoals or islands between Rzeszów Island and the Miechów Upland, which extended form the Cracow–

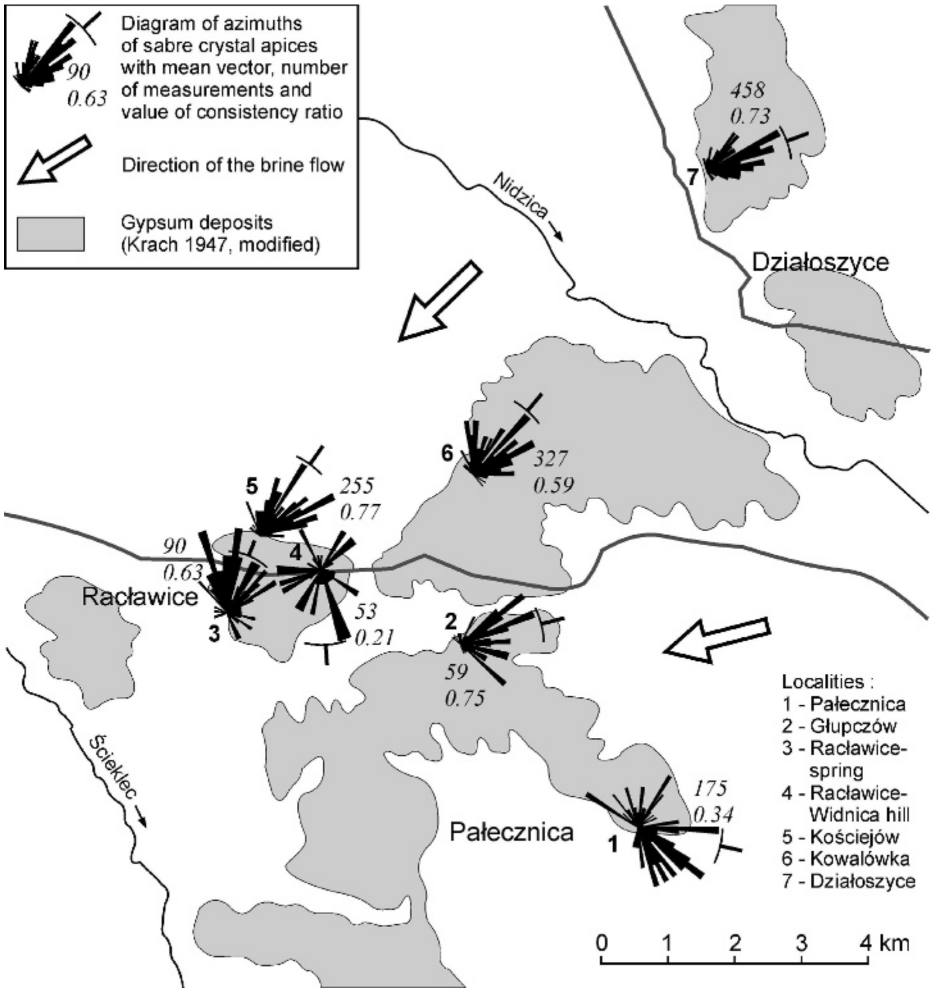

FIG. 7.—Direction of brine flow in the Racławice area interpreted from the orientation of sabre crystals for both parts of the sabre gypsum-strata together (see Fig. 5).

Rzeszów line northward up to the southern Nida area (Fig. 8; Bąbel 2005b). The outflow of brines from the Nida area and the Miechów Upland to the south could have been blocked by this barrier. The brines apparently flowed towards the southwest, towards the Cracow area, and it seems that at some point there they flowed into the halite subbasin. The lack of the sabre-gypsum facies and good exposures in many areas did not permit analysis of the paleocurrents in the vicinity of Cracow. In this area the evaporites are made up mainly of laminated sulfate and clay, presumably deposited in an environment deeper than that of the sabre-gypsum facies (Garlicki 1968; Połtowicz 1993; Kasprzyk and Ortí 1998; Peryt 2000).

The other equally probable explanation of the detected flow pattern in the Miechów Upland, at the time of the sabre-gypsum deposition, is that the suggested barrier did not exist and the slope of the basin was inclined to the south but its inclination was too small to cause downslope density flow of the dense brines. The brine could flow not downslope but instead moved parallel to the isobaths, as is commonly observed in many recent basins.

RECORD OF PALEOCURRENTS IN THE OTHER AREAS OF THE BASIN

Nearly all the paleocurrent vectors obtained for localities scattered along the northern margin of the Carpathian Foredeep basin (in Ukraine, Poland, and the Czech Republic) point to the unidirectional alongshore flow from east to west, although some areas are poorly documented due to lack of exposures (Fig. 8; Bąbel et al. 1999). It appears that the brine flowed from the Ukrainian into the Polish part of the basin, into the Nida area and the Miechów Upland, round the northern shores of Rzeszów Island (Fig. 8).

The pattern of brine flow in the southern part of the basin, in the present Carpathian Mountains area, is poorly documented. The southern coast is represented by only one outcrop at Broniakówka in Poland (locality 19, Fig. 8). The gypsum section at Broniakówka was tectonically displaced from the original position ca. 50 km northward by Carpathian overthrusts (Połtowicz 1993). This section is the only one found with the exposed sabre gypsum from the southern part of the basin and also the only one in the basin where the sabre crystals unequivocally indicate the brine flow exactly from the west to east, unlike as in the whole northern shore (Bąbel et al. 1999, their fig. 1). This apparent direction was supposedly also parallel to the reconstructed shoreline, and its sense suggests that the brine in the southern coast flowed opposite to the direction recorded in the north (Fig. 8).

HYDROLOGICAL MODEL OF THE BASIN

The interpretation of the paleocurrent data needs a brief outline of the hydrology of the basin and the manner of selenite deposition before discussion and interpretation of the nature and pattern of the detected currents. Following the ideas presented in previous investigations, the studied basin was a salina-type basin without an open-water connection with the sea (Peryt 1996; Cendón et al. 2004). As in many coastal salinas the water level fluctuated in this basin and presumably was lower during the dry season (because of increased evaporation) and higher during the

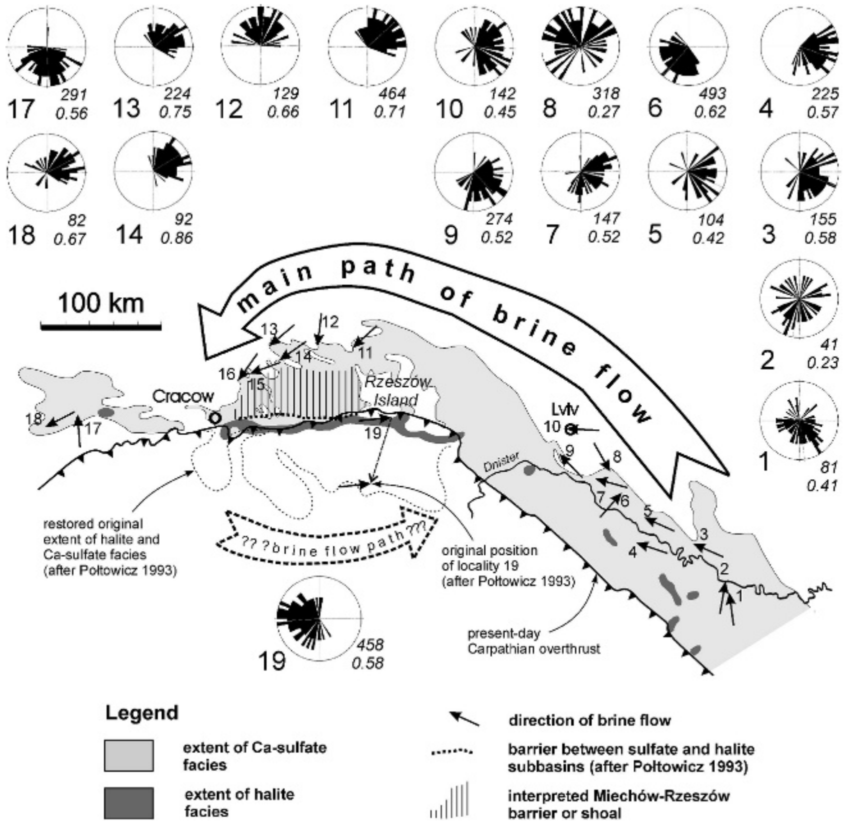

FIG. 8.—Paleocurrents of brine in the middle Miocene (Badenian) evaporite basin of Carpathian Foredeep indicated by orientation of sabre gypsum crystals; arrows reflecting paleocurrents are parallel to the mean vectors of azimuths of crystal apices; numbers of measurements and values of consistency ratio are shown near rose diagrams; local disturbances in flow pattern are omitted (compare Bąbel et al. 1999, their fig. 1). Localities: 1 = Verenchanka, 2 = Kostryzhivka, 3 = Holovchyntsi, 4 = Oleshiv, 5 = Krasiiv, 6 = Podillia, 7 = Zahirochko, 8 = Pidkamin', 9 = Schyrets'-Pisky, 10 = Lviv, 11 = Piaseczno, 12 = Staszów, 13 = Chwałowice, 14 = Siesławice, 15–16 (studied outcrops, see Figs. 5, 7; 15 = Działoszyce, 16 = Kościejów), 17 = Czernica, 18 = Kobeřice, 19 = Broniakówka. Stratigraphic correlation of sabre gypsum strata in sections 1–9, 13, and 17–19 is shown in Bąbel (2005a, On-Line Appendix).

wet season (Fig. 9; Cohen et al. 1977; Warren 1982; Kirkland 2003; Bąbel 2004a). The brine showed density stratification, with the low-salinity water at the surface and the high-salinity brine at the bottom. During such stratification, any driven-by-evaporation precipitation of gypsum at the bottom, i.e., growth of selenite crystals at the bottom, was inhibited or slowed because the bottom brine was entirely isolated from the atmosphere by the upper water mass and could not evaporate (Sloss 1969). Additionally, stratification could lead to anoxia of the bottom brines and consequently to lack, or a very low concentration of, sulfate ions (because of decomposition by sulfate-reducing bacteria) necessary for gypsum precipitation (Fig. 10; Sonnenfeld 1984). Gypsum could precipitate in some stratified and sufficiently oxygenated bottom brines because of temperature changes in the saturated solution (Sloss 1969) and/or the "remnant supersaturation" effect (Stiller et al. 1997, p. 182), but such growth is volumetrically insignificant. Accelerated growth of gypsum crystals could take place only when the entire brine column was fully mixed down to the bottom, well oxygenated and subjected to evaporation, i.e., when the stratification was destabilized (Figs. 9, 10; Warren 1999, p. 14, 44; Kirkland 2003; Torfstein et al. 2005). In such a state the brine showed homogeneous density, salinity, and temperature, and the evaporation could lead to Ca-sulfate oversaturation in the whole brine column, directly promoting the growth of selenites at the basin floor.

It seems that during the sabre-gypsum deposition in the shallow Badenian basin (maximum several meters deep; Kasprzyk 1993a, 1993b; Peryt 1996, 2001; Bąbel 1999a) the stratification and mixing periods occurred repeatedly and seasonally (Fig. 10), as in the 5-m-deep Solar Lake in Sinai (Cohen et al. 1977), and in the shallow coastal salinas and salt lakes in Australia (Warren 1982), and in the 3-m-deep Lake Hayward in particular (Coshell and Rosen 1994, their fig. 3; Rosen et al. 1996). Stratification could appear during seasonal highstand; mixing during lowstand and it could partly be promoted by evaporation of the upper water mass. An obvious bias from that pattern was possible, because of the lag time necessary for setup of the full mixing and homogenization of the brine column as well as for reestablishing the stratification. Such a bias is observed in the Solar Lake (Cohen et al. 1977) and particularly in some deeper lakes like the Dead Sea, Lake Kinneret, or Mono Lake, where the mixing begins at the end of lowstand periods and continues during the highstand even up to its maximum (Serruya 1978, and references in Bąbel 2004a). In the Badenian basin the selenite growth was presumably accelerated during mixing periods and ceased or slowed when the stratification was re-established in the late wet seasons (Fig. 10). The seasonal cycle of growth was presumably similar to the gypsum precipitation pattern recorded in the Solar Lake and Lake Hayward (Cohen et al. 1977; Krumbein and Cohen 1977; Coshell and Rosen 1994; Rosen et al. 1996). Gypsum precipitates in these lakes during mixing seasons, however, are partly or entirely dissolved during subsequent stratification periods. The salinity of these lakes seems to be too low to support the continuous growth of gypsum crystals; this salinity fluctuates at the beginning of the gypsum saturation level.

It seems that the salinity in the Badenian basin was high enough so the bottom brines could be permanently Ca-sulfate saturated (Bąbel 2004a). The mixing periods could be longer and stratification periods shorter than in the Solar Lake and Lake Hayward, and consequently the bottom of the Badenian basin better oxygenated and more favorable for gypsum crystal growth. The Badenian selenites could grow continuously at the bottom in the same manner as the selenites from some Australian salinas investigated by Warren (1982). Warren (1982; 1999, p. 14, 44) interpreted the millimeter-scale growth zoning in the sub-fossil selenite crystals from these salinas just as reflecting the described hydrological seasonal cycle. A very similar, regular mm-scale growth zoning occurred in the Badenian sabre gypsum crystals from the studied unit C–D (Figs. 3F, 11). This zoning was interpreted as a reflection of the annual hydrological cycle (Petrichenko et al. 1997, p. 96; Bąbel 2005a), and it strongly supports the hydrological reconstruction presented here (Figs. 9, 10). Using limnolog-

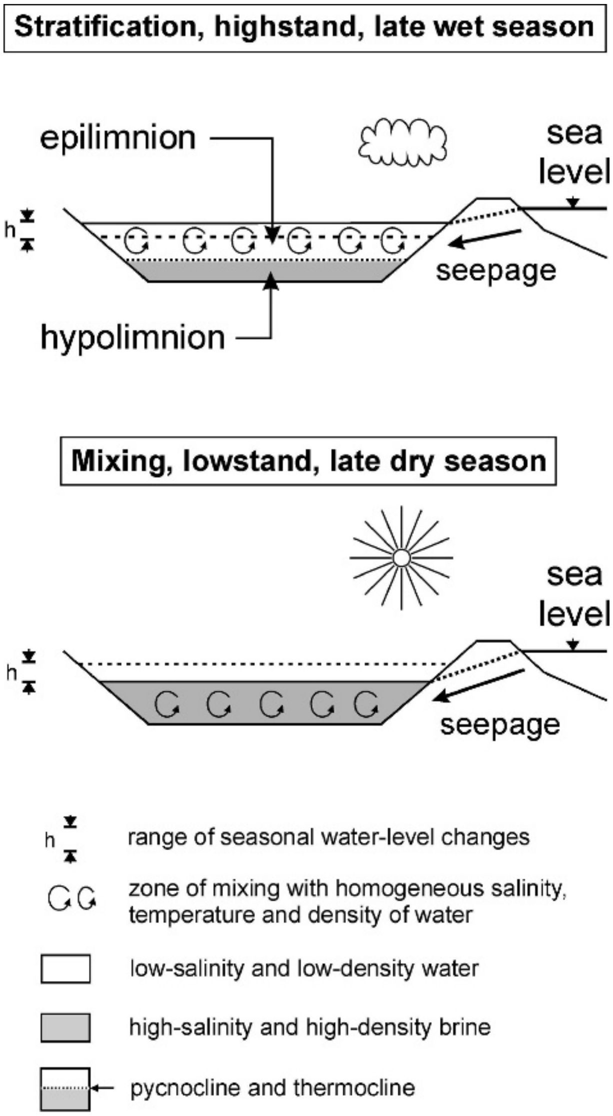

FIG. 9.— Scheme showing interpreted seasonal stratification-mixing cycle in a shallow marine salina-type evaporite basin with the water level drawn down below sea level.

ical terminology the seasonally appearing lower and upper water masses in the basin can be described as the hypolimnion and the epilimnion, respectively, here used in the broadest sense without taking into account the temperature regime of the water masses. The described seasonal hydrologic cycle defines the salina basin as monomictic (Hutchinson 1975; Horne and Goldman 1994).

THE NATURE OF THE RECORDED BRINE CURRENTS

In contrast to typical directional sedimentary structures in the clastic deposits, which commonly are recorded only in some places, the oriented selenites are present in the entire region of the sabre gypsum strata in the basin. They evidently recorded the flow in every part of the bottom. Paleocurrent vectors for the outcrops present at a distance of several tens of meters to several kilometers showed clearly that the brine streamlines were parallel or nearly parallel. This suggests concordant *en masse* flow of brine over the bottom. The sedimentologic analyses (Kasprzyk 1993a, 1993b; Peryt 1996, 2001; Bąbel 1999a, 2005b) have indicated that the brine was no more than several meters deep and the basin had extremely flat bottom topography. The sabre gypsum was deposited strictly by aggradation: by *in situ* accretion of upward-growing crystals without any mechanical redeposition. The oriented selenites form continuous, several-meters-thick sediment columns (except for some dissolution surfaces and/or thin intercalations of fine-grained gypsum). The crystals show the same or a very similar sense of paleocurrent vectors throughout each such column in every particular outcrop, as also described on the Miechów Upland (Fig. 5). Thus the recorded pattern of brine flow persisted in the basin without any significant changes during deposition of sabre gypsum strata up to 15 m thick.

The nature of the detected currents appears to be different from currents recorded by typical directional structures in lagoonal clastic deposits. These structures (e.g., ripples, cross-stratification, channels, etc.) are commonly produced by single rapid events of a short duration (seconds, minutes, hours) which reflect action of the short-term currents of high energy. By contrast, the oriented selenite crystals are the result of long-term processes which continued during the whole time of the particular sabre crystal growth. Assuming that each growth zone (0.3–1.1 mm wide; Petrichenko et al. 1997) represents one year, this time interval could last several tens of years for a typical individual sabre crystal. Thus the oriented selenites reflect some average effect of action of the long-term brine currents flowing for days, months, or years.

The speed of brine currents recorded by the sabre crystals is unknown. Not excluding the possibility that the flow was occasionally rapid, the brine currents were probably relatively slow. In recent environments the selenite crystals are growing mostly in calm or nonmoving brine. Rapid, strong, storm-induced currents certainly were present in the Badenian basin, but they did not necessarily coincide with periods of the selenite crystal growth and Ca-sulfate oversaturation. Even if some storm currents were Ca-sulfate oversaturated, their duration was presumably too short to influence the growth directions of the selenite crystals, because the growth of gypsum crystals is a relatively slow process. It is more realistic to assume that the selenite crystals grew mainly during the much longer normal weather periods associated with increased evaporation and that the crystal-growth directions recorded the uniform brine flow paths typical of such weather—not the episodic flows related to storms.

It is obvious that the paleoflow vectors presented in this paper (Figs. 5, 7, 8) refer only to the periods of Ca-sulfate saturated or oversaturated brine flow. The oriented selenite crystals could not grow during the flow of Ca-sulfate undersaturated brine, fresh water, or brackish water. Accelerated growth of gypsum crystals took place during seasonal mixing, when the brine column became homogeneous, as discussed above (Figs. 9, 10). Thus the pattern of flow recorded by oriented selenites is closely related to seasonal periods of mixing. It is unknown whether the same or different flow patterns existed during wet seasons of the year or periods of refreshment.

Presumably the Badenian basin did not have an open-water connection with the sea, and its hydrology was similar to that of saline lakes (Bąbel 2004a). Therefore the recorded brine paleocurrents can most reasonably be compared with the persistent flow patterns observed in recent lakes and semi-closed basins. The oriented selenites most probably reflect what Emery and Csanady (1973) defined as circulation: "a long-term pattern of motion, or residual motion remaining after the irregular water movements involved in wind drift, seiches, and other short-term phenomena are averaged" (Emery and Csanady 1973, p. 93). The oriented selenites, however, reflect only the Ca-sulfate saturated and oversaturated brine flow pattern from the mixing periods.

CYCLONIC CIRCULATION IN RECENT BASINS

The main driving force for currents in lakes is wind (Simons 1980). The flow regime of the currents depends on the state of weather and

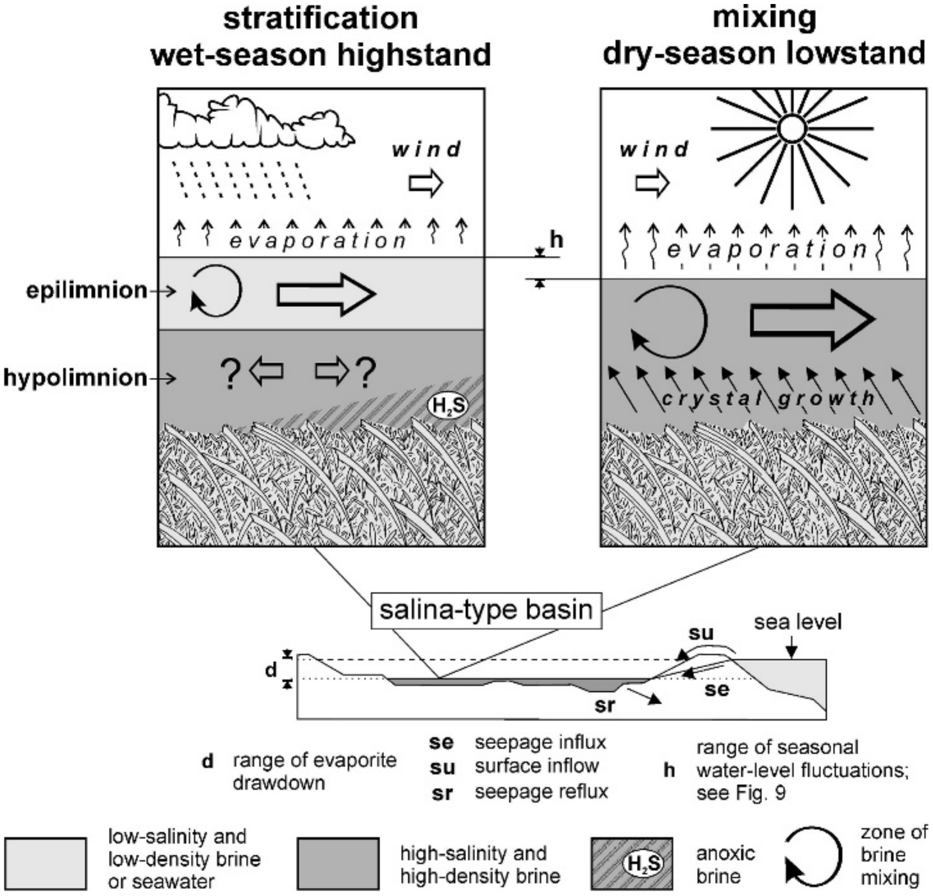

FIG. 10.— Interpreted depositional environment and structure of brine column during the oriented selenite crystal growth. Detailed explanations in the text.

particularly on the direction, duration, and speed of wind, but also on the shape, size (fetch), and topography of the basin. These wind-induced currents change with time. Vigorous currents develop during long-term intense storms, and in simple circular basins they commonly form a double-gyre circulation with two narrow coastal downwind currents and one broad countercurrent in the deeper central part of the lake (Simons 1980; Beletsky 1996). In basins with complicated bathymetry many gyres can appear, rotating in opposite directions. The separate gyres commonly form within particular subbasins. When the wind vanishes these gyre currents gradually slow, and, particularly in the large stratified basins, one gyre flow pattern is established with surface water moving more or less parallel to the shore and slowly encircling the whole basin (Csanady 1978; Beletsky 1996). This flow is the most persistent and constant feature of lakes (and also semi-closed basins) and determines the average or mean surface drift in lakes (circulation *sensu* Emery and Csanady 1973, p. 93; or net circulation, Schwab et al. 1995; mean circulation, Csanady 1977, Beletsky et al. 1999; mean drift, Wunsch 1973). It is a rule that this mean surface drift is cyclonic; it is counterclockwise in the northern hemisphere and clockwise in the southern hemisphere (see Emery and Csanady 1973), although sometimes the typical flow pattern is modified by local factors. For example, the Gulf of California shows alternately cyclonic (counterclockwise) circulation in summer and anticyclonic (clockwise) in winter (Palacios-Hernández et al. 2002).

Several mechanisms are considered to explain what causes such a shift in circulation. Each of them takes into account some direct or indirect influence of the Earth's rotation on the moving air and water masses. The most significant mechanism appears to be the predominant cyclonic vorticity of winds blowing over the water body, exerting cyclonically curled wind stress on the water surface. Such a wind pattern modifies the surface water flows towards a single gyre pattern with a sense of rotation corresponding to the sense of rotation of the wind-stress curl (Lemmin and D'Adamo 1996; Shapiro et al. 2003). Several other complicated mechanisms supplement this factor, and some of them are very important in particular cases (Emery and Csanady 1973; Bennett 1975; Csanady 1977, 1978; Simons 1980; Schwab et al. 1995; Beletsky et al. 1999; Laval et al. 2003; Rueda et al. 2003, 2005; Akimoto et al. 2004). For example, in large stratified lakes the cyclonic net drift can be a result of Lagrangian drift associated with internal Kelvin waves, which are always cyclonic (Wunsch 1973). The cyclonic circulation is less pronounced in shallow poorly stratified polymictic and small lakes, and in reality numerous more complicated flow patterns are observed depending on the season, the shape and size of the lake, and bottom topography. The pattern of flow in deep stratified lakes is even more complex and, for example, includes episodic upwellings and downwellings, which are also influenced by the Coriolis effect (Simons 1980). The lower water mass (the hypolimnion) of stratified lakes is sheltered from the direct influence of wind, and the hypolimnetic bottom currents are controlled mainly by internal waves and the dynamics of the thermocline (Lemmin and Imboden 1987). In such stratified lakes two persistent closed circulation patterns can exist in surface and bottom waters, and the bottom waters can move in a direction opposite to that of the surface waters, although commonly much more slowly than the surface waters (Lemmin and Imboden 1987; Horne and Goldman 1994; Godo et al. 2001). During mixing periods the flow pattern within the shallow and homogeneous water is commonly more uniform and simple.

Dominantly cyclonic circulation was observed in some saline basins such as the Dead Sea (Neev and Emery 1967), the Great Salt Lake

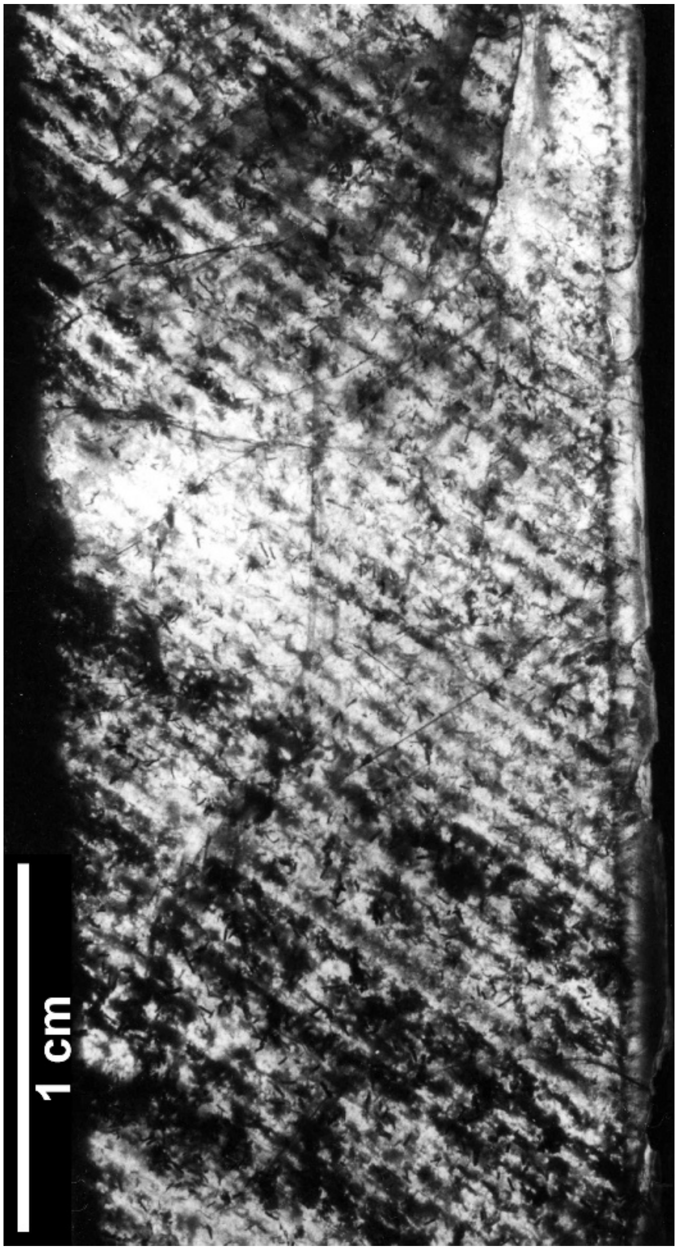

FIG. 11.— Growth zoning related to advance of the apical {120} prism in the sabre gypsum crystal as seen on the {010} cleavage surface (compare Figs. 3F, 4). Growth direction to the top. Siesławice (locality 14, Fig. 8), Poland.

(Cohenour 1968, Butts 1980), the Salton Sea (Cook et al. 2002), and the Kara Bogaz Gol (Dzens-Litovsky 1966; Sonnenfeld 1974, p. 1141), although Lepeshkov et al. (1981) recognized the more complicated pattern of flows in this basin. Cyclonically propagating internal seiches related to Kelvin waves were recognized in the Dead Sea (Weinstein et al. 2000). The Aral Sea, before drying out, was a rare exception, showing a circulation pattern opposite to that predicted by its position in the northern hemisphere and the Coriolis effect (see Emery and Csanady 1973). This discrepancy was explained by a specific pattern of winds (Sirjacobs et al. 2004) and bottom topography (see Blinov 1956). Recently, the more typical cyclonic pattern has been recognized in this drying lake (Zavialov et al. 2003).

INTERPRETATION OF THE BRINE FLOW PATTERN IN THE BADENIAN BASIN

The simplest explanation for the westward *en masse* brine flow or drift along the broad northern shore is that the whole brine mass was pushed by some strong easterly winds. The presumed dry winds coming from the continental interior on the east (Fig. 1A) were able both to mix the shallow brine, down to the bottom, and to intensify the evaporation from the brine surface (Fig. 10). Such dry winds could be the direct driving force for the growth of the oriented gypsum crystals. This simple picture fits to the dominantly easterly pattern of winds in central Europe expected in the Badenian time (see Gebka et al. 1999). Following this interpretation one can expect the same downwind flow of brine along the southern coastal zone and the upwind (from west to east) countercurrent in the deeper central areas of the basin (as predicted by theory and observations of wind-induced currents in modern lakes; e.g. Simons 1980). Consequently, the currents on the shallow southern shore of the basin should flow to the west. The data from the Broniakówka area do not support this view; the currents on the southern shore of the basin flow exactly in the opposite direction, from the west to the east (Fig. 8).

Therefore another interpretation is offered which omits the influence of the hypothetical easterly winds recorded in the selenite structures. The interpretation takes into account all of the paleocurrent data, those from Broniakówka in particular, which together suggest a simple and consistent counterclockwise brine circulation around the whole basin margin (Fig. 8). As proved by limnologic and oceanographic studies discussed above, such counterclockwise (or cyclonic) mean flow is typical of the closed and semi-closed basins in the northern hemisphere. It is commonly a result of a cyclonic wind-stress curl (not dependent on the wind direction) and other effects related to the Earth's rotation. It is reasonable to expect that the typical cyclonic circulation was also present in the Badenian basin. This basin occupied the northernmost area of the Paratethys (Fig. 1A), extending up to nearly 51° north latitude, and the Coriolis effect is not active at the equator but increases with distance from it (e.g., Sonnenfeld 1984; Lewis 1987). Cyclonic (counterclockwise) flow patterns were already suggested for the Badenian evaporite basins in Central Paratethys (Fig. 1B); for the Transylvanian basin as early as by Pauca (1968), and for other basins by Sonnenfeld (1974) and Panov (1983), but until now it was not proved by paleocurrent analysis.

The recorded brine flow pattern obtained from this study of the Miechów Upland does not support the earlier interpretations assuming the direct downslope movement of brine into the deeper halite subbasins. The pattern of brine currents is evidently not centripetal, directed to the halite facies, as predicted by the "saturation shelf" and nearshore brine circulation concepts (Figs. 7, 8). This can be explained by the fact that the broad northern margin of the basin showed slightly undulating morphology with variably directed inclination of the bottom. Moreover, the slope inclination around halite subbasins could be very low and hence did not facilitate easy downslope flow of dense brines. The other reason, however, was possibly more important. The gravity outflows of dense brines to the deepest subbasins were apparently only rare and very short events in the basin and were too short to be recorded by the oriented selenites, which reflected only the average or mean long-term cyclonic flow around the basin shores.

CONCLUSIONS

1. Permanent, nearly unidirectional flow of Ca-sulfate oversaturated brine over the crystallizing gypsum can influence the growing crystals accelerating the growth of stoss-side faces and producing selenite deposits with upstream-oriented crystal apices. These oriented apices can be used for paleocurrent analysis in evaporite basins that have not undergone major burial diagenesis.

2. The oriented primary selenites present in the marginal zone of the Badenian evaporite basin in the northern Carpathian Foredeep were deposited in brine only a few meters deep which showed seasonally (annually) alternating phases of stratification and then homogenization by complete mixing. The oriented crystals grew mainly during the mixing periods associated with dry-season lowstands and increased evaporation when the whole brine column was homogeneous and Ca-sulfate oversaturated down to the bottom. During stratification and/or refreshment periods the bottom brines were not saturated or only poorly saturated with Ca sulfate, and hence the flowing brine could not influence the growth directions of the selenite crystals.
3. The measurements of azimuths of crystal apices and calculated paleocurrent vectors indicated that during crystallization of the oriented selenite crystal beds the brine flowed generally parallel to the basin margin and in a counterclockwise sense, possibly circling the whole basin. This pattern of flow is interpreted as the mean cyclonic circulation typical of lakes and semi-closed basins in the northern hemisphere. Such a circulation is mainly a product of the cyclonic curl of wind stress exerted on the water surface and also the other effects related to the direct and indirect influence of the Earth's rotation on the movements of air and water masses (the Coriolis effect).

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