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Sedimentary evolution of Badenian (Middle Miocene) gypsum deposits in the northern Carpathian Foredeep

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In the northern peripheral part of the Carpathian Foredeep, the Middle Miocene (Badenian) gypsum deposits comprise two major, laterally extensive members: the lower is mostly autochthonous, of selenitic facies and the upper is allochthonous, of clastic facies and cumulate deposits. Towards the south, gypsum is replaced in the subsurface by anhydrite which displays relict textures of the primary gypsum. The facies variation and succession throughout the gypsum section, as well as geochemical indicators, reflect varied sedimentary conditions on the basin margin. Deposition took place on the periphery of a platform made up of a system of widespread shallow-water lagoons (sub-basins) separated by fault-controlled, NW–SE elongated islands or shoals. In these physiographically differentiated palaeoenvironments, facies relationships were largely diachronous. The water depth varied from a few metres to some tens of metres, and subaerial exposure episodically affected the gypsum deposition, as suggested from the sedimentary record and comparison of the facies with modern evaporitic environments. Variations in brine depth, salinity and water dynamics are expressed in the cyclic succession of the progressively changing facies associations. Sedimentary conditions changed drastically at the boundary of the lower (selenitic) and upper (clastic) members, and at the end of sulphate deposition, following major sea-level changes.

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Key words: Carpathian Foredeep, Badenian, gypsum, facies, sedimentology, geochemistry.

INTRODUCTION

The facies variation and lateral relationships of the Badenian (Middle Miocene) evaporites of southern Poland (Fig. 1) express distinct depositional environments, including a sulphate platform and adjacent salt basin. On the platform, shallow-water sulphate deposits display a great variety of lithofacies and sedimentary structures (S. Kwiatkowski, 1972; A. Kasprzyk, 1991; B. Kubica, 1992; M. Bąbel, 1996), whilst in the basin centre more monotonous deposition of laminated sulphates and halite took place (A. Garlicki, 1979).

In this paper, the facies and sedimentary patterns as well as the geochemistry of the platform sulphates and associated siliciclastic-carbonate deposits are discussed and used to reconstruct the gypsum palaeoenvironments. Field and subsurface data and modern analogues provide an opportunity to develop a model of gypsum deposition in the peripheral part of the Badenian basin. This work summarizes and complements previous authors' studies on the lithofacies, sedimentology and geochemistry of the gypsum deposits in the northern part of the Carpathian Foredeep (e.g. A. Kasprzyk, 1989, 1991, 1993*a–d*, 1995, 1997; A. Kasprzyk, F. Ortí, 1998; T. M. Peryt, A. Kasprzyk, 1992*a, b*; O. I. Petryczenko *et al.*, 1995; L. Rosell *et al.*, 1998).

GEOLOGICAL SETTING

The Badenian sediments in the Carpathian Foredeep of southern Poland originated in a foreland basin — the northernmost part of the Central Paratethys (Fig. 1A). It was bounded by the active Carpathian arc in the south, and by the Palaeozoic-Mesozoic folded belts and a platform (the Małopolska Land and Roztocze — Lublin Upland) in the north. A Badenian salinity crisis anticipated the Mediterranean Messinian event by some 9 My, as a result of geodynamic restriction

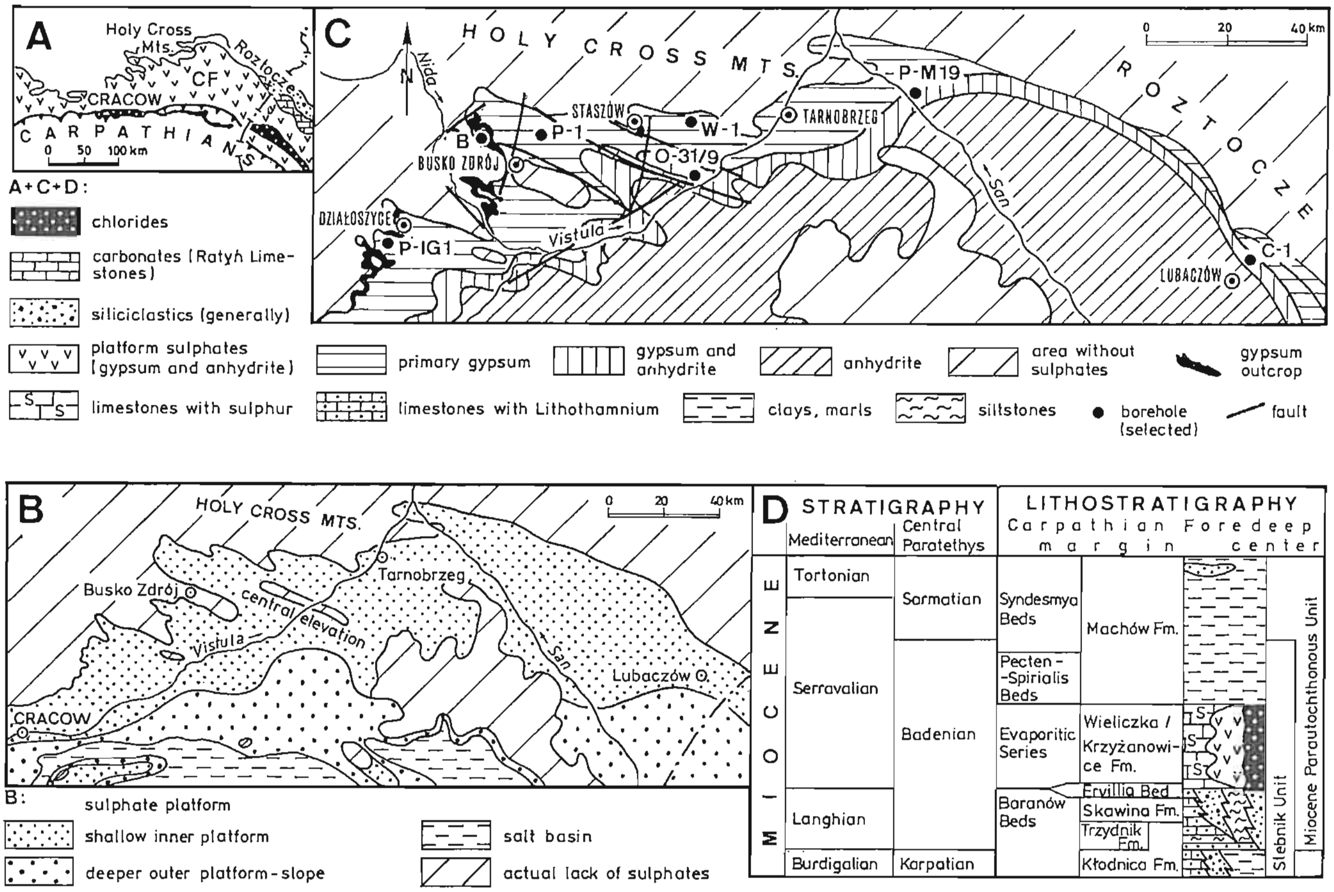

Fig. 1. The study area: **A** — extent of Badenian evaporites and associated deposits in the Carpathian Foredeep (CF) of southern Poland, **B** — palaeogeography during evaporite deposition (after S. Połtowicz, 1993, supplemented), **C** — distribution of sulphate facies (after B. Kubica, 1994*b*), **D** — stratigraphy of the Miocene deposits (after G. Czapowski, A. Gąsiewicz, 1994, simplified)

of the Central Paratethys (F. Rögl, F. F. Steininger, 1983). Basin evolution was controlled mainly by orogenic activity in the Carpathians, which determined the depositional style and the extent of evaporitic facies from Moravia (Czechia) in the west to Moldavia in the east. The Badenian evaporitic basin of southern Poland covered an area of about 27 000 km^2 (A. Garlicki, 1979), and the sedimentation of sulphates occupied about 17 500 km^2 of that basin (S. Kwiatkowski, 1972) (Fig. 1B).

In the northern periphery of the basin (Fig. 1C), the Badenian sequence begins with brackish coaly facies followed by a variety of open marine, siliciclastic and Lithothamnium-limestone facies (Baranów Beds and Skawina Formation) (Fig. 1D). At their top, a thin sandy or marly layer (*Ervillia* Bed) with a monospecific fauna occurs over a large area. The origin of this layer is attributed to the restricted water circulation and density stratification following a regional regression and an increase in salinity (E. Łuczkowska, 1967; M. Pawlikowski, 1982). Succeeding sulphate deposits are widespread and up to 60 m thick, though sulphate-free areas occur (Fig. 1C); they comprise gypsum and anhydrite lithofacies (B. Kubica, 1992; A. Kasprzyk, 1993*a*, 1995; M. Bąbel, 1996). The present limit of gypsum deposits is erosional along much of the northern margin of the Carpathian Foredeep. Sulphates are overlain by deep-water clays and marls of the Upper Badenian and Sarmatian (Machów Formation; Fig. 1D), which in the north are intercalated with and/or overlain by cross-bedded bioclastic deposits (Chmielnik Formation) and serpulid-microbialite limestones, formed in coastal barrier and crestal zones (G. Czapowski, 1984; M. Jasionowski, 1996). These bioclastic and biogenic deposits reflect the late Middle Miocene restriction of the basin, followed by a global sea-level fall (N. Oszczypko, 1996).

The study area is located at the northern margin of the Badenian basin between Cracow in the west and Lubaczów in the east, along the northern periphery of the Carpathian Foredeep (Fig. 1). It comprises a system of depressions (troughs or sub-basins), filled during the Miocene, and local shoals situated along the southern slopes of the Holy Cross Mountains and the Roztocze Upland. Since the early studies of G. G. Pusch (1833–1836) and L. Zejszner (1861), this area has attracted the attention of geologists because of many surface exposures of gypsum and of native sulphur concentrations in limestones genetically related with sulphate strata

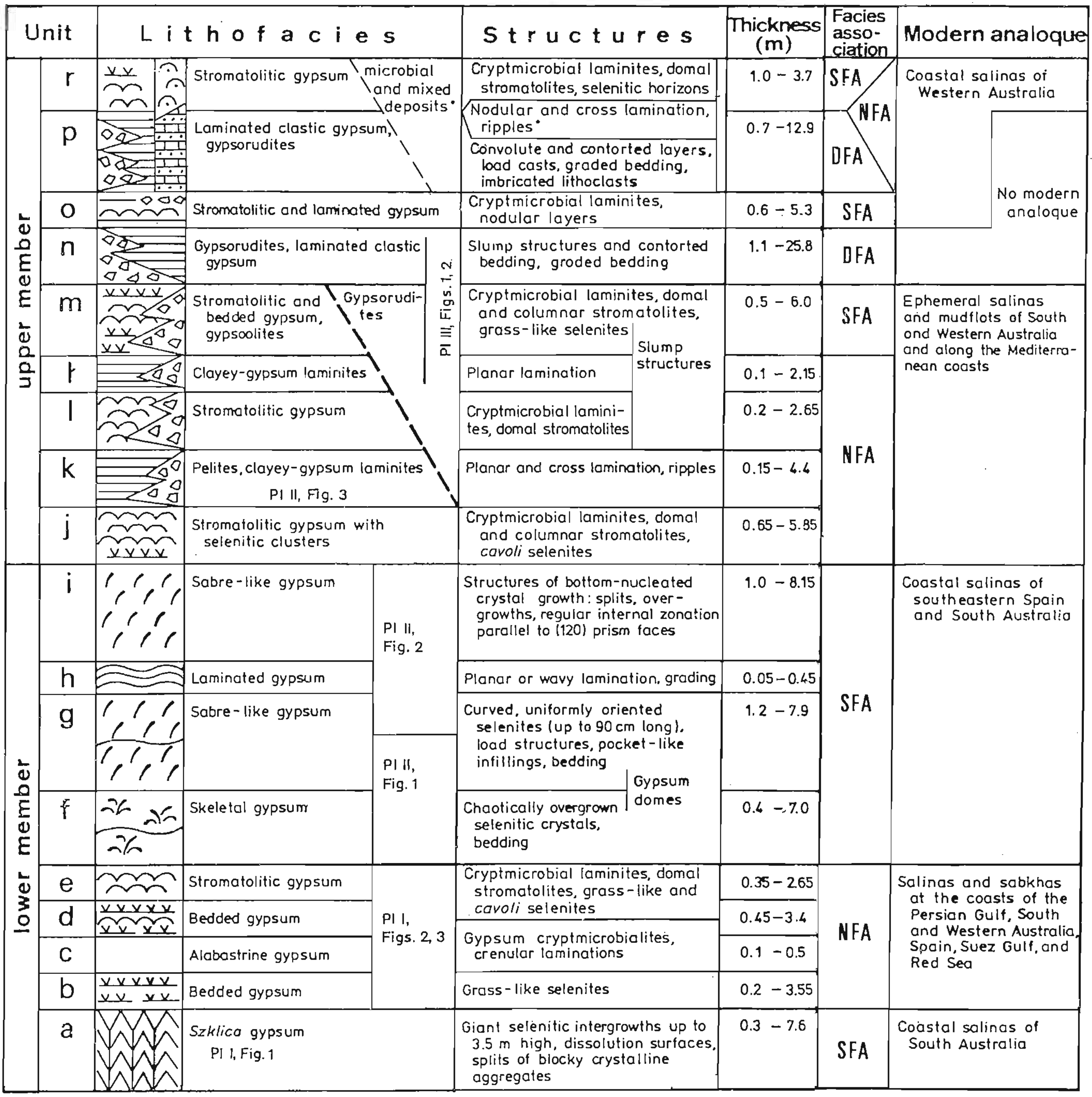

Fig. 2. Generalized lithostratigraphy and lithofacies of gypsum deposits

Facies associations: NFA — nearshore facies association, SFA — shallow-water facies association, DFA — deeper-water facies association

(see reviews by S. Kwiatkowski, 1972; S. Pawłowski *et al.*, 1985; B. Kubica, 1992). The tectonic framework of the study area is characterized by dominant NW–SE faults, most of which have been related to older fault systems rejuvenated during the Miocene, linked to the late Alpian diastrophism in the northern Carpathian Foredeep.

FACIES DISTRIBUTION

Vertical and lateral facies relationships within the Badenian gypsum were studied in many exposures and in subsurface sections in the northern Carpathian Foredeep; the

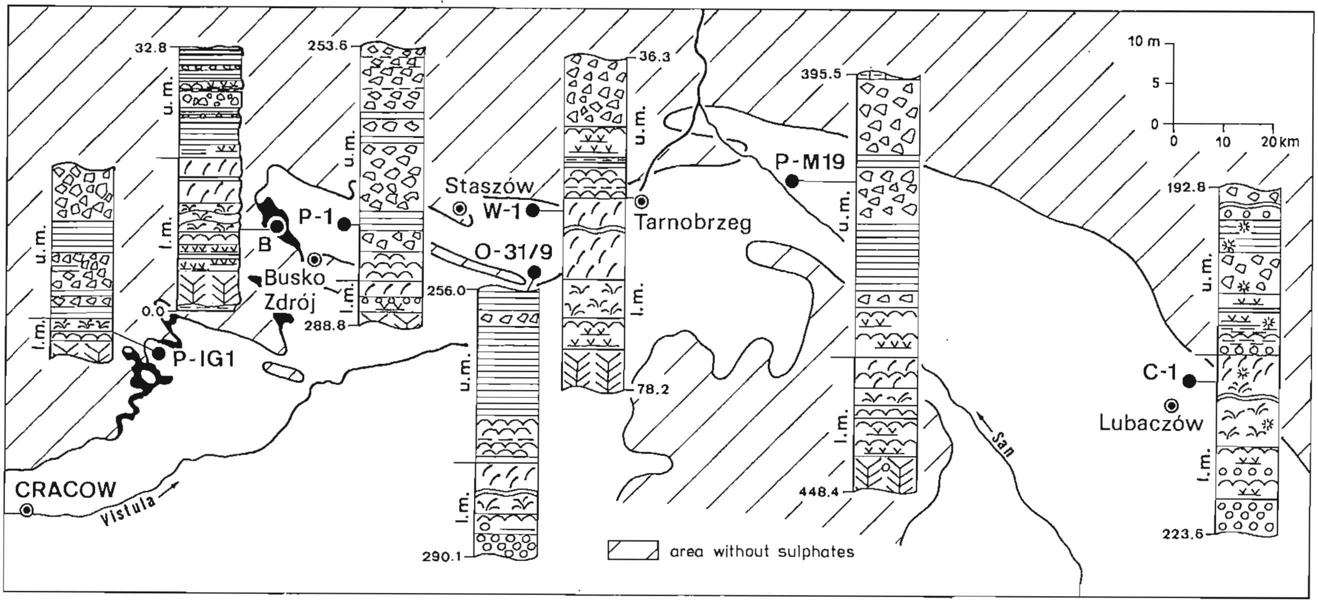

Fig. 3. Selected sections of gypsum deposits

l.m. — lower member, u.m. — upper member; explanations of lithology as in Fig. 4

location of the most representative among them is shown in Figure 1C. Gypsum deposits form a laterally extensive succession of different lithofacies composing two major gypsum members: a lower member (mostly autochthonous, of selenitic facies) and an upper member (mainly allochthonous, of clastic facies and fine-grained cumulate deposits) (Fig. 2). Selenitic facies consist of macrocrystalline, upright bottom-grown gypsum (selenite), while that precipitated and settled through the brine column forms cumulate deposits. Using a local lithostratigraphic division of gypsum deposits in the Nida region (A. Wala, 1980) as a basis, eighteen units (from *a* to *i* after A. Wala, 1979 and from *j* to *r* redefined by A. Kasprzyk, 1989, 1991) have been distinguished in the complete gypsum section in the east-central part of the study area. There is a slight difference in the succession and a more distinct one in the thickness and component lithofacies of these gypsum units in the W–E oriented cross-section through the sulphate platform peripheries, along the southern slopes of the Holy Cross Mts. and the Roztocze Upland (Figs. 3 and 4).

The gypsum succession (Fig. 2) begins with giant gypsum intergrowths called *szklica* (unit *a*), which in the north and west of the study area (from Działoszyce to Tarnobrzeg) are locally underlain by a thin layer (< 0.5 m) of black, bituminous clays with lenticular gypsum aggregates and laminae (Fig. 4). Giant gypsum intergrowths are unique forms composed of blocky crystalline aggregates up to 3.5 m high (Pl. I, Fig. 1), very similar to the Messinian palmate gypsum in the Mediterranean (e.g. J. M. Rouchy, 1982) (Fig. 5). Generally, in the entire study area this lithofacies shows the typical appearance described by M. Bąbel (1996 and references therein), although in the west it abounds in dolomicrite and clay and exhibits common dissolution surfaces and splits of blocky crystalline aggregates, indicating different sedimentary conditions (A. Kasprzyk, 1991). Giant gypsum intergrowths are correlatable over most of the study area and thin and/or pinch out towards the south and west (their westernmost surface exposure was found at Nasiechowice), but they continue farther into West Ukraine and Czechia.

The overlying bedded gypsum (units *b* and *d*) contains grass-like selenites and intercalations of alabastrine and stromatolitic gypsum ("gypsified stromatolites" and "cryptalgal laminites" of J. M. Rouchy, C. L. V. Monty, 1981) (Fig. 2; Pl. I, Fig. 2). Very similar facies without any cyanobacterial ghosts preserved have been interpreted as formed by recent gypsification of microbial mats in the coastal salinas of SE Spain and Western Australia (F. Ortí Cabo *et al.*, 1984; A. V. Arakel, 1980; B. W. Logan, 1987). The middle unit *c* is a layer < 0.5 m thick, distinctive in the gypsum section by a white colour and alabastrine fabric. Its irregular, domal top surface is overlain by clayey-gypsum laminites with deformed and broken gypsum laminae, desiccation cracks, erosional channels and crinkled cryptmicrobial lamination. This layer *c* is an important correlative horizon in the peripheral part of the Carpathian Foredeep and is traceable over a large distance (*ca.* 700 km) from Czechia to West Ukraine. Stromatolitic gypsum facies compose unit *e* (Pl. I, Figs. 2 and 3). Gypsum domal stromatolites are common in the north of the area and pass southward into cryptmicrobial laminites (terms "stromatolites" and "cryptmicrobial laminites" are used here in a descriptive sense after R.V. Demicco, L. A. Hardie, 1994). In the west, bedded selenites locally disappear and their facies equivalents are stromatolitic and nodular gypsum (Fig. 4). This facies association overlying giant gypsum intergrowths is traced over West Ukraine, but selenitic gypsum grades into stromatolitic facies toward the south-east (T. M. Peryt, 1996).

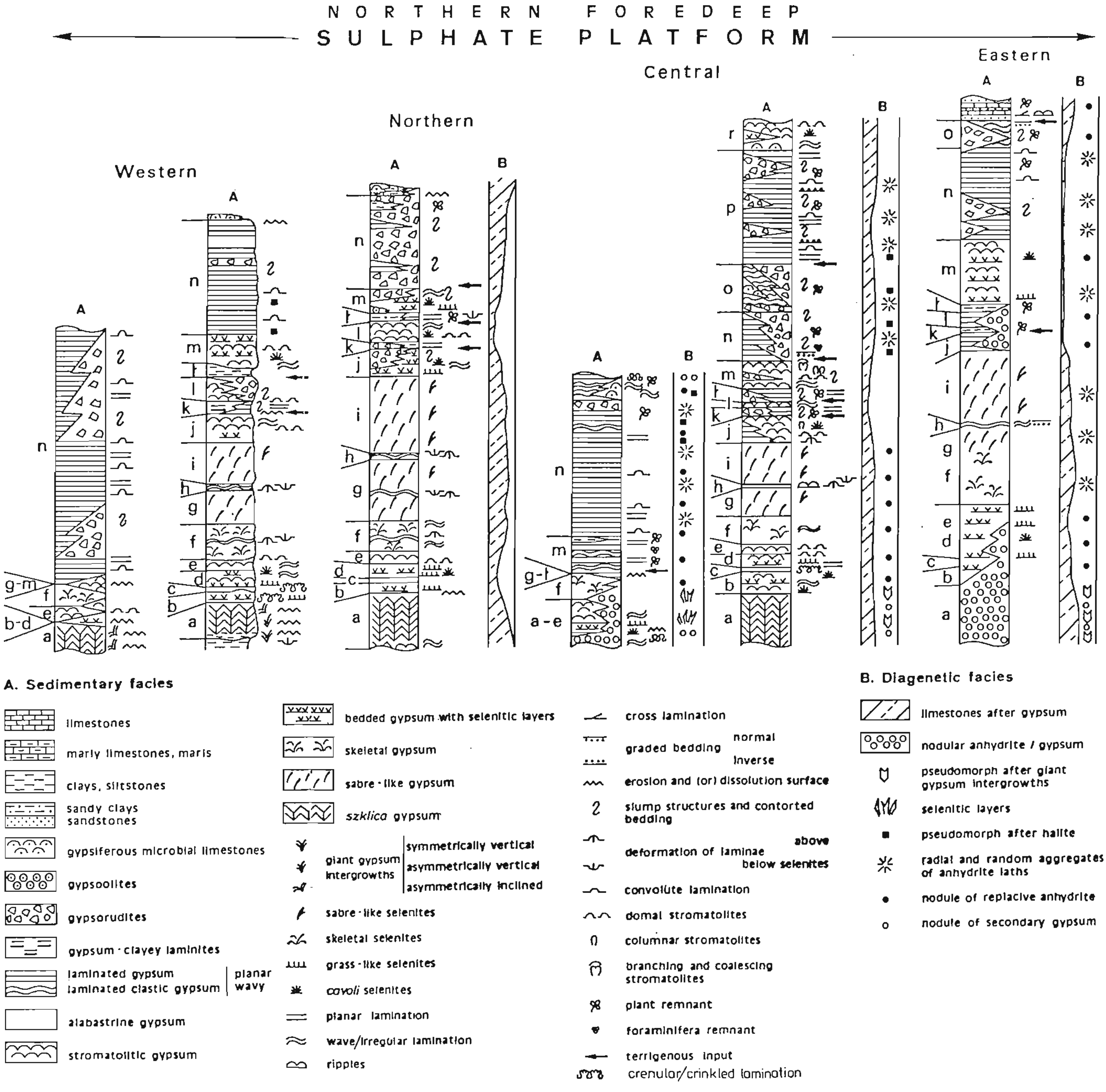

Fig. 4. Lithofacies and successions of units *a–r* from different parts of the study area in the W –E oriented cross-section through the sulphate platform

The increase in the number of selenitic components upwards in the section expresses a gradual transition into skeletal gypsum (unit *f*) (Pl. I, Fig. 2). This is composed of upright prismatic crystals, up to 15 cm long, randomly overgrown within a marly-gypsum matrix (Pl. II, Fig. 1). Intercalations of fine-grained, laminated and stromatolitic gypsum, several centimetres thick, are common. Towards the west of the area, skeletal gypsum grades into bedded selenite and/or stromatolitic facies (Fig. 4). Overlying sabre-like gypsum (units *g* and *i*) exceeds 15 m in thickness in the north (Staszów area). It thins rapidly to the south and locally pinches out in the west (e.g. borehole P-IG1) (Fig. 3), but it continues farther toward the west into Czechia. This variety is characterized by elongated (up to 90 cm), curved crystals showing characteristic structures of bottom-grown selenitic components, such as: splits, bending and breakage, regular growth zones of (120) prism faces, crystal overgrowths, load structures, detrital infills (Pl. II, Figs. 1 and 2). Sabre crystals are oriented randomly or uniformly, and locally they compose large domal megastructures with a radial arrangement of component crystals. Bedding is expressed by intercalations of laminated gypsum, one of which composes unit *h* (Pl. II, Fig. 2). This lithofacies shows common sedimentary structures: lamination (parallel planar or wavy, irregular, flaser), cross lamination, ripple marks, graded bedding, gypsum cryptmicrobial laminites and fine domal stromatolites. Irregular layers and patches of gypsiferous microbial-peloidal limestone similar to that described by T. M. Peryt and A. Kasprzyk (1992*b*) are common within the sabre-like gypsum in the east and north. Atop unit *i*, sabre crystals in reversed position within the clastic gypsum matrix, with an increased content of terrigenous material, precede a distinct change of the facies association composing the upper gypsum member. In the general facies pattern across the platform, selenitic gypsum of the lower member (units *a–i*) thins to the south and west, where laminated and clastic gypsum facies are more common (Figs. 3 and 4) (S. Kwiatkowski, 1972; A. Kasprzyk, 1991; B. Kubica, 1992).

In the central study area (the central elevation of A. Kasprzyk, 1991) (Fig. 1B), the lower gypsum member locally shows a different facies variation and succession. The main lithofacies that compose this member are stromatolitic gypsum and nodular gypsum and anhydrite (A. Kasprzyk, 1993*a*), while selenitic components are minor (Fig. 4). Most features of this facies association apparently resemble those of recent sabkha-evaporite coastal salina evaporites (A. C. Kendall, G. M. Harwood, 1996). Preservation of original crystalline fabrics of the former gypsum (now as pseudomorphs) within the basal nodular layer indicates that this is a structural equivalent of the giant crystalline intergrowths and bedded selenite in other sulphate sections. Throughout the lower member many units are lacking when compared with the complete gypsum section in the east-central area (Fig. 4).

The upper gypsum member (units *j–r*) is composed mostly of clastic gypsum facies over the entire study area (Fig. 2; Pl. II, Fig. 3; Pl. III, Figs. 1 and 2). In the lower part, however, laminated and/or stromatolitic gypsum with minor selenitic components (units *j, l, m*) and siliciclastic-rich layers (units *k and t*) locally occur (Fig. 4). The siliciclastic content increases to the north (landward in a general palaeogeographic sense). Representative of this facies association are gypsum cryptmicrobial laminites and stromatolites (domal and columnar) with selenitic cones, clayey-gypsum laminites, clays, sandy mudstones and marls (Fig. 4). Clayey-gypsum laminites are in places broken and grade into intraclast breccias (Pl. II, Fig. 3; Pl. III, Fig. 1B). All these lithofacies pass laterally into gypsorudites and laminated gypsarenites to the south and west (T. M. Peryt, A. Kasprzyk, 1992*a*), while selenites are more common in the north (Fig. 4). A layer of gypsoolites, 32 cm thick, was locally found within the selenites in the Staszów area (Figs. 1C and 4) (M. Bąbel, A. Kasprzyk, 1990). The succeeding deposits (units *n–r*) comprise mainly gypsorudites, laminated gypsarenites and fine-grained massive gypsum (Pl. III, Fig. 1A). In the north and east (from Staszów to Lubaczów) gypsorudites are composed of selenitic clasts, clay chips and carbonate fragments. Towards the south and west, selenitic components disappear and interbeds of slumped laminated gypsarenites occur within gypsorudites (Pl. III, Fig. 2); these facies are locally transitional to more regularly laminated gypsum deposits showing graded bedding and pseudomorphs after halite (A. Kasprzyk, 1993*a*) (Figs. 3 and 4). The clastic gypsum facies distinctly thicken to the southeast where they are overlain by stromatolitic and nodular gypsum with common intraclast breccias and gypsiferous microbial-peloidal limestones. The laminated gypsum deposits are laterally extensive and correlate over all the area from Czechia to West Ukraine. The top surface of the gypsum deposits is erosional along its present limits in the northern Carpathian Foredeep.

In the east (Lubaczów area), the gypsum succession is topped by gypsiferous, microbial-peloidal sandy limestones and marly sandstones showing irregular and cross lamination, ripples and brecciated layers, referred to as the Ratyń Limestone of southeastern Poland and West Ukraine (T. M. Peryt, A. Kasprzyk, 1992*b*; T. M. Peryt, D. Peryt, 1994) (Fig. 4). These facies grade upward into marly claystones and marls with gypsum impregnation and laminae of lenticular gypsum crystals. Overlying clayey-marly deposits rich in fauna and floral debris belong to the Upper Badenian (*Pecten-Spirialis* Beds; Fig. 1D).

Towards the south and east of the study area, gypsum is partly or completely replaced in the deeper subsurface (> 250 m) by anhydrite and associated secondary gypsum (after former anhydrite) (Fig. 1C). Common features of initial anhydritization of the gypsum are nodules and random aggregates of decussate anhydrite laths throughout the gypsum section (Fig. 4). Locally, vertically aligned pseudomorphs after giant selenites (termed "gypsum ghosts" by J. K. Warren and C. G. St. C. Kendall, 1985) have been observed in the lower part of the section (A. Kasprzyk, 1995). Farther towards the south, a general vertical succession of anhydrite lithofacies may be distinguished in the subsurface as equivalent to the gypsum sequence (B. Kubica, 1992; A. Kasprzyk, 1995) (Fig. 3). This anhydrite succession comprises nodular facies in the lower part, followed by massive anhydrites with common pseudomorphs after selenite; these two lithofacies correlate with the lower (selenitic gypsum) member, and are overlain by laminated anhydrites and breccias displaying redeposition features and therefore roughly correlated with the upper (clastic gypsum) member (A. Kasprzyk, F. Ortí, 1998). In distal areas of the platform, these clastic anhydrites are transitional to central sulphate laminites and halite deposits, considered to be a basinal facies (A. Garlicki, 1979).

Gypsum and anhydrite are locally replaced by secondary (epigenetic) limestones with concentrations of native sulphur (S. Pawłowski *et al.*, 1985; B. Kubica, 1992) (Fig. 4). These diagenetic limestones occur as irregular stratiform bodies of various sizes, from several centimetres to kilometres in length, irregularly developed throughout the sulphate section, but in some areas it is assumed that they completely replace the sulphates (B. Kubica, 1994*a*; A. Gąsiewicz, 1994*a, b*).

INTERPRETATION

FACIES ASSOCIATIONS AND DEPOSITIONAL ENVIRONMENTS

Sulphate deposits show differentiated thickness and lithofacies across the platform periphery, dependent on a palaeogeographic setting (Fig. 6). Genetically related lithofacies

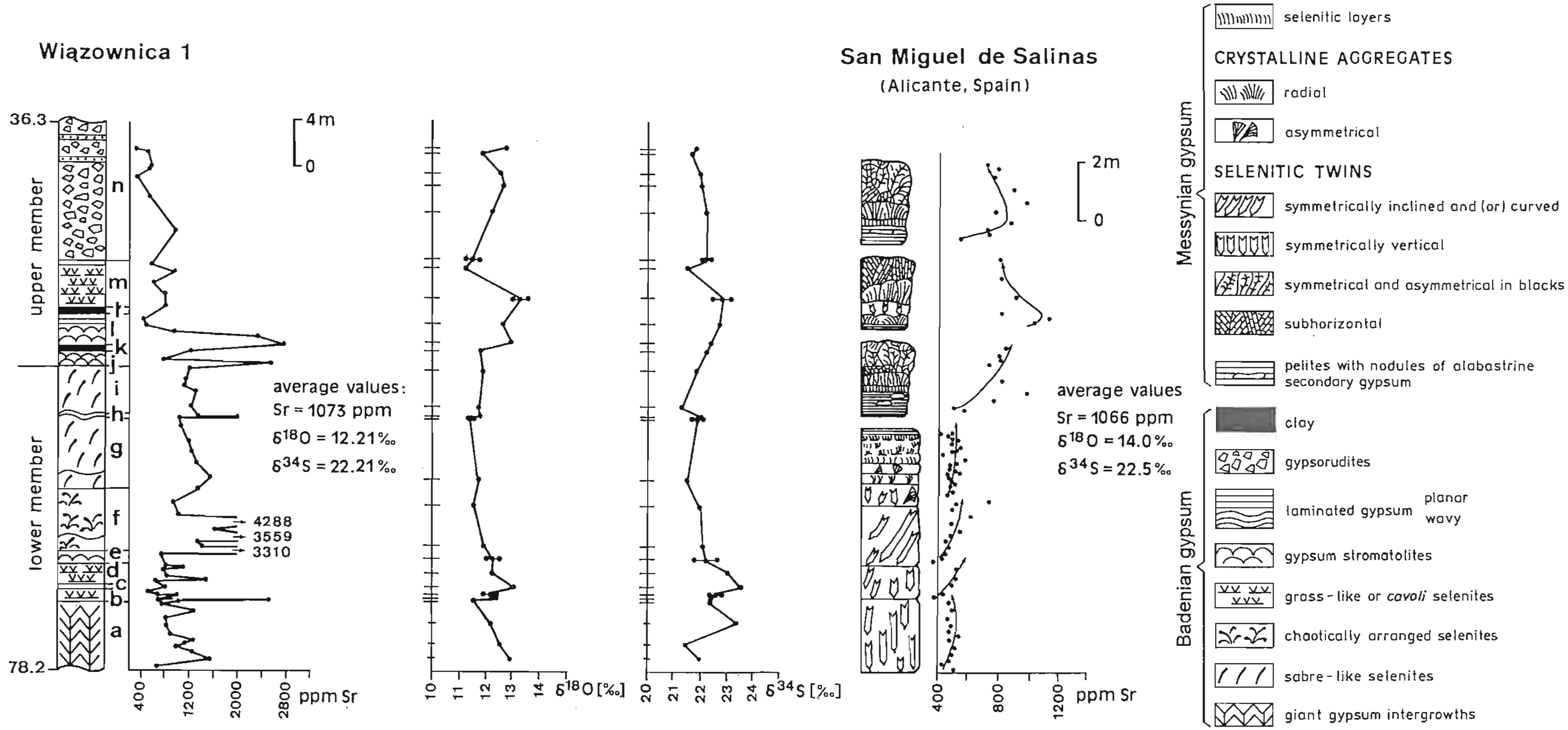

Fig. 5. Comparison of Sr distribution and isotopic composition in the gypsum sections: the Badenian gypsum south of the Holy Cross Mountains (borehole Wiązownica 1) and the Messinian gypsum in south-east Spain (San Miguel de Salinas, Alicante; after F. J. García Veigas *et al.*, 1990); facies changes and depositional discontinuities are reflected in the strontium content; for Badenian gypsum the Sr contents and isotopic data of sulphur and oxygen in sulphate ion are after L. Rosell *et al.* (1998) and A. Kasprzyk (1997), respectively

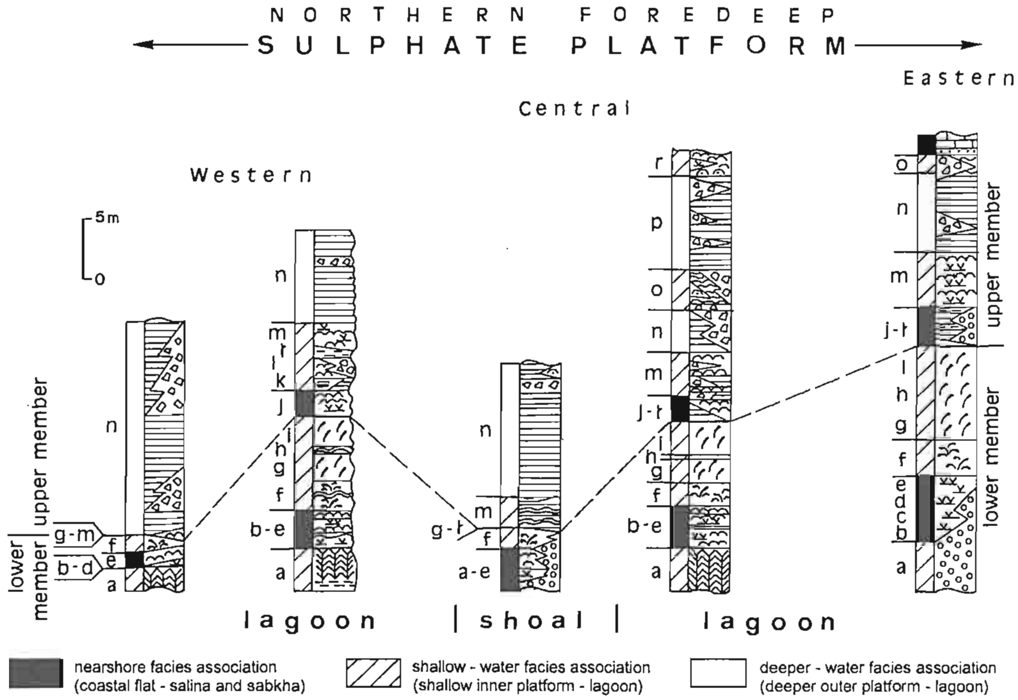

Fig. 6. Stratigraphic-facies cross-section through the Badenian gypsum deposits

Explanations of lithofacies as in Fig. 4

have been grouped into three facies associations: a nearshore facies association (NFA); a shallow-water facies association (SFA); and a deeper-water facies association (DFA). These record a range of depositional environments from subaerial to subaqueous. Descriptive data for each of the component lithofacies and examples of the vertical and lateral distribution of the platform sulphate facies are shown in Figures 2–4 and 6.

The nearshore facies association (NFA) comprises units *b* to *e* and *j* to *t* in the Badenian gypsum section, as well as the uppermost siliciclastic-carbonate-sulphate deposits at the landward margins of the platform (Figs. 2 and 6). The component lithofacies are characterized by common cryptmicrobial and nodular structures, and a large content of terrigenous material deposited at the shoreline by runoff. This association is very similar to that formed recently in sabkhas along the Persian Gulf, the Red Sea and the Mediterranean coasts, and associated with salt lakes of Western Australia (E. Gavish, 1980; G. P. Butler *et al.*, 1982; B. W. Logan, 1987; A. C. Kendall, G. M. Harwood, 1996). The shallow-water facies association (SFA) consists predominantly of autochthonous selenitic gypsum lithofacies, some of which resemble crusts of vertically-oriented gypsum crystals grown on the bottoms of modern salinas in South and Western Australia and southeast Spain (J. K. Warren, 1982; F. Ortí Cabo *et al.*, 1984; B. W. Logan, 1987). This association is representative of the lower member (units *a*, *f* to *i*) and units *m*, *o*, *r* (Figs. 2 and 6). The deeper-water facies association (DFA) characterizes the upper member (units *n* and *p*). The main lithofacies that compose this association, laminated clastic gypsum and gypsorudites showing common redeposition features and fine-grained cumulate deposits (Figs. 2 and 4), are interpreted to have been formed in the distal parts of the platform, although they do not have a modern analogue. These three associations represent the main sulphate-platform depositional systems: (1) sabkha-like coastal flats and salinas; (2) shallow inner platform-lagoons and inferred islands or shoals without evaporitic deposition; and (3) deeper outer platform-lagoons (a broad intermediate zone between the basin centre and its margin). The environmental settings for Badenian gypsum have been identified by comparison of facies associations with modern evaporitic environments. Comparable facies associations and depositional settings have been also recognized in other ancient evaporitic formations (reviews in B. C. Schreiber, 1986, 1988; J. K. Warren, 1989; A. C. Kendall, G. M. Harwood, 1996).

The basin morphology was one of the major controlling factors for Badenian evaporite deposition. In the basin margin the topographic configuration maintained a continuous free-flowing water exchange between the platform and the adjacent deep basin. Islands and shoals were related to prexisting topographic highs. The coastal sabkha-like system developed early during sulphate deposition along the shoreline and on the slopes of a local shoal developed on a NW elongated feature (the central elevation, Fig. 1B). During sulphate deposition, a marginal complex of shoals, sabkhas and ephemeral salinas could occupy the broad shoreline zone at a low see level stand. These environments were characterized by the nearshore facies association with dominant nodular and stromatolitic lithofacies. The inner platform-lagoons were occupied by the shallow-water facies association. A relatively deeper-water facies association (redeposited clastic gypsum and cumulate deposits) composing the upper member formed in the outer platform-lagoon (Fig. 6).

BATHYMETRY

On the basis of the dominant gypsum facies, the initial water depth for the inner-platform lagoons at the onset of gypsum formation must have been at least a few metres. On the other hand, there is evidence of shallower conditions from the sedimentary record (e.g. stromatolitic, alabastrine and nodular facies, gypsoolites, desiccation cracks, ripples) throughout the gypsum section, and modern analogues suggest extremely shallow-water to subaerial sulphate deposition (*cf.* A. Kasprzyk, 1993*a*). Considering the facies stratigraphic relationships of the gypsum and the underlying and overlying sediments, as well as bathymetrical differentiations of the latter (respectively, 30–120 and 20–50 m; E. Łuczkowska, 1967; W. Studencki, 1987), the maximum depth of gypsum deposition in the basin margin may be estimated as a few tens of metres.

Selenitic gypsum — the main component of the lower member, grew on the bottom of lagoons or perennial salinas several metres deep at most. In these shallow-water environments, relative changes in brine depth and fluctuations of pycnocline, perhaps as a response to the interplay of evaporative drawdown and water influxes, were common and resulted in frequent facies changes and dissolution and/or erosion events (A. Kasprzyk, 1993*b*; M. Bąbel, 1996). The latter caused interruption of gypsum growth and local fragmentation (brecciation) and redeposition of the early sediment. Thin intercalations of laminated gypsum within selenitic facies display cross-lamination and ripples suggesting redeposition of the clastic gypsum material in the shallow subaqueous environment. The major variations of sedimentary conditions from subaerial and very shallow-water to relatively deeper-water resulted in the succession of sulphate facies in the vertical section, and in some discontinuities between successive facies sequences (Figs. 2 and 4). The most significant change in the gypsum facies and sedimentary environments at the boundary of selenitic (autochthonous) and clastic (allochthonous) members reflects the overall deepening owing to an apparent change in the basin morphology, although these events were diachronous across the platform (A. Kasprzyk, 1991, 1993*b*; T. M. Peryt, M. Jasionowski, 1994; T. M. Peryt, 1996). These variations express repeated deepening-shallowing episodes of evaporite deposition in the northern peripheral part of the Badenian basin (Fig. 6).

BRINE COMPOSITION

Isotopic studies of primary gypsum facies have been used as a tool for palaeoenvironmental interpretations of sulphate deposition in the peripheral part of the Badenian basin (S. Hałas *et al.*, 1996; A. Kasprzyk, 1997). The oxygen and sulphur isotope composition of gypsum is homogeneous throughout the major part of the section. The average values (12.21 and 22.21‰ for oxygen and sulphur, respectively) are close to data found for the Messinian (Upper Miocene) primary gypsum in SE Spain ($\delta^{18}O$ = 13.7‰ and $\delta^{34}S$ = 21.5‰) (discussion in: A. Kasprzyk, 1997), as well as to other Tertiary sulphate evaporites (G. E. Claypool *et al.*, 1980), and thus provide arguments for the marine origin of these deposits (Fig. 5). A slight depletion (of about 1.5‰) in O^{18} of Badenian gypsum in comparison to the Messinian example might reflect an input of low-salinity waters (e.g. continental ones) related to palaeogeographic control on sulphate deposition in the northernmost part of the Central Paratethys. In the vertical section of Badenian gypsum, isotopic indicators show an apparent anomaly in the lowermost part of the clastic gypsum member (Fig. 5), which may reflect active bacterial sulphate reduction or dissolution-precipitation processes (S. Hałas *et al.*, 1996; A. Kasprzyk, 1997). These results combined with the sedimentological data discussed above support the opinion that sedimentary conditions in the peripheral part of the evaporite basin changed drastically, most probably as a response to increased inflow of fresh marine waters enriched in heavy sulphate ions at the transition from the autochthonous to allochthonous gypsum members.

Detailed analyses of the strontium content, which is commonly regarded as a good geochemical indicator of salinity in the stage of sulphate precipitation (e.g. G. P. Butler, 1970; E. Usdowski, 1973; F. Ortí Cabo *et al.*, 1984; H. Dronkert, 1985), document unstable salinity conditions during gypsum deposition in the peripheral part of the Badenian basin (A. Kasprzyk, 1993*d*, 1994; L. Rosell *et al.*, 1998). A distinct change in Sr values (of about 1000 ppm, in average) implies an increase in salinity at the transition from bedded and stromatolitic gypsum to skeletal and sabre-like varieties within the lower (selenitic) member (Fig. 5). In the upper member, a general decrease in the Sr content (mean < 1000 ppm, Fig. 5; also L. Rosell *et al.*, 1998) records relatively lower-salinity brines for the clastic gypsum components, and argues against the hypothesis of M. Bąbel (1996) which suggested an increase in salinity within the brine column during deposition of the upper gypsum member. In general, higher and more variable values are recorded for the selenitic member in the marginal zones, and lower and more homogeneous Sr contents in deeper parts of the shelf. Thus, the distribution of strontium within the gypsum deposits may reflect a relationship between the Sr content and the palaeogeographic location on the platform (discussion in L. Rosell *et al.*, 1998). This relationship indicates the lateral, physiographically controlled gradient in salinity: more variable salinity conditions (with episodes of higher concentration) were confined to the landward part of the platform (at the margins) or shoals (e.g. Przyborów 1 borehole; L. Rosell *et al.*, 1998), and relatively stable brines in local depocentres were probably protected by a permanent pycnocline. For the selenitic gypsum, the average Sr content is higher (more than twice) in comparison with its facies equivalents from modern salinas, which may reflect either an originally elevated strontium content or the salinity of mother brines at the Badenian basin margin.

Studies of inclusions (mineral, fluid and micro-organic) in selenitic crystals and chemical analyses of extracted water (O. I. Petryczenko *et al.*, 1995; O. I. Petrichenko *et al.*, 1997) showed that brines at the time of gypsum deposition had sulphate composition defined by the content: 0.25–0.30% $CaSO_4$; 0.12–0.15% NaCl; 0.09–0.11% Na_2SO_4; 0.04–0.06% $MgSO_4$; 0.005–0.01% K_2SO_4, which cannot be obtained from simple equilibrium evaporation of seawater (*cf.* A. C. Kendall, G. M. Harwood, 1996 and references therein). Moreover, it was found that the total mineralization during deposition of skeletal and sabre-like gypsum in the local sub-basin south of the Holy Cross Mountains did not exceed 0.5% (O. I. Petryczenko *et al.*, 1995). The relatively higher mineralization (1.6–6.5%) was recorded in other parts of the Badenian basin in West Ukraine (O. I. Petrichenko *et al.*, 1997). Based on these results, the total mineralization in the Badenian basin could be a few times lower than that characteristic for the stage of gypsum precipitation from marine-derived waters (i.e. 11–12%), which clearly contradicts data on the isotopic composition and the strontium content of the Badenian gypsum, summarized above and accepted by the present author (Fig. 5), indicating a marine origin and relatively high salinity for the mother brines.

Results of lithofacies and geochemical studies as well as comparison with facies analogues from modern evaporitic environments, e.g. from the coastal salinas of SE Spain (F. Ortí Cabo *et al.*, 1984; H. Dronkert, 1985), provide arguments for the interpretation of salinity evolution in the peripheral part of the Badenian basin. Variations in brine concentration, chemistry and impurities content could determine the type of the precipitating minerals, evaporite crystal size and morphology (e.g. P. Sonnenfeld, 1984; A. C. Kendall, G. M. Harwood, 1996). A lack of gypsum in sediments underlying giant selenitic intergrowths of the lower gypsum section over most of the area of the platform peripheries argues for a rapid rise in salinity through a continuous feed of new, preconcentrated waters. Based on the concentrations of brines favouring the growth of bottom selenitic crusts in the modern coastal salinas, it can be supposed that the salinity was above 250 g/l but did not exceed 300 g/l during the development of Badenian selenitic gypsum. Dissolution surfaces (Pl. I, Fig. 1) reflect episodic drops in the brine concentration and suggest shallow subaqueous deposition. The internal zonation (120) of crystals record successive growth stages of selenites. In modern salinas of South Australia similar surfaces of successive crystal growth are marked by cyanobacterial-peloidal laminae and reflect seasonal fluctuations of the halocline, which, however, did not interrupt the syntaxial crystal growth (J. K. Warren, 1982; H. Dronkert, 1985). These fluctuations, although not necessary seasonally controlled, may also be a possible cause of the zonation in Badenian selenitic crystals.

The thick complex of clastic gypsum deposits showing redeposition features (upper member) originated in less concentrated waters within a stratified brine column, when physical accretion dominated. The salinity of dense bottom waters could episodically exceed 320 g/l favouring the precipitation of halite on or within the bottom sediment, as indicated by well preserved pseudomorphs and moulds after halite crystals. The halite itself had a low preservation potential due to frequent fluctuations in salinity around halite saturation. The sedimentary regime at the end of sulphate deposition was probably controlled by frequent changes in the brine concentration, related to fluctuating water balance, which led to marked facies variation.

EVOLUTION OF SEDIMENTATION

In this section, general facies patterns and stratigraphical relations are used to infer a history of sulphate deposition. Cyclic successions of facies associations from subaerial (nearshore) to subaqueous (shallow-water to deeper-water) are identified throughout the gypsum section on the basis of dominant facies and sedimentary structures (Fig. 6), that have been discussed in greater detail elsewhere (A. Kasprzyk, 1993*a–c*; M. Bąbel, 1996). Two distinct depositional stages are involved in each succession (Fig. 6): (I) a sabkha-like coastal flat and salina stage, represented by the nearshore facies association, and (II) a shallow inner platform-lagoon stage, characterized by the shallow-water facies association. The stage (III) of an outer platform-lagoon represented by the deeper-water facies association is distinguished within the uppermost succession. Thus, each succession records major changes in depositional environments on the platform. One possible explanation is that the cyclic facies successions correspond with basin margin flooding (transgressive phase) and progressive evaporative drawdown (regressive phase).

LOWER MEMBER

An eustatic sea-level fall, which must have been greatly magnified by evaporative drawdown in an arid climate, preceded the deposition of evaporites in the Badenian basin at about 13.7 Myr BP (N. Oszczypko, 1996). Climatic and tectonic changes were the most important controlling factors affecting the ratio between input and output of water, and thus for evaporite precipitation and sedimentary evolution at the basin margin. In this area, sulphate deposition started in partly isolated, shallow-water sub-basins (lagoons) several metres deep during the late regressive phase. Black bituminous clays with bottom-nucleated gypsum crystals were deposited in the deepest parts of lagoons on the platform, while in the starved, deep central basin probably no sulphate initially formed. In stratified, high-salinity lagoons giant gypsum intergrowths (unit *a*) grew on the bottom. Their growth was periodically interrupted by influxes of less-saline waters from the hinterland and by major drops in salinity due to water mixing. Facies analogues are known from the Quaternary salt lakes in South Australia, where large elongate selenitic crystals (up to 50 cm long) have grown in shallow waters (less than 10 m deep) with their long axes perpendicular to the bedding (M. Goto, 1968; J. K. Warren, 1982; C. G. St. C. Kendall, J. K. Warren, 1988). Similarly, the Badenian giant intergrowths, although showing different crystallographic features, originated by continual precipitation from brine and the bottom upright growth was controlled by pycnocline fluctuations. A further change in the facies association was probably related with intense drawdown that resulted in the exposure of a large area of the inner platform. This is indicated by a dissolution contacts between giant gypsum intergrowths and overlying bedded selenites (Fig. 6). The facies succession apparently records initially subaerial conditions with prolonged periods of dilution by freshwater (gypsum karst), that became subaqueous upon marine flooding.

A sudden marine influx caused partial reworking and/or dissolution of pre-existing gypsum. The initial facies association including gypsum stromatolites and cryptmicrobial laminites of extremely shallow-water to intermittently submerged subaerial settings, and subaqueous selenites (units *b–e*) reflects varied sedimentary conditions. Using modern coastal salinas and sabkhas (reviews in A. C. Kendall, G. M. Harwood, 1996) as analogues for the Badenian example, it is supposed that microbial mats developed during dilution of brines by freshwater flowing in from the hinterland, and could have been completely gypsified in periods of increased brine concentration, resulting in the formation of alabastrine gypsum (*cf.* A. Kasprzyk, 1993*c*). The diagenetic origin of alabastrine gypsum *via* phase transformations of gypsum to anhydrite and anhydrite back to gypsum (secondary gypsum) has been recently proposed by T. M. Peryt *et al.* (1997), though this is not supported by petrographic evidence: no anhydrite relicts and crystalline fabrics typical of secondary gypsum (e.g. F. Ortí, 1977; A. Kasprzyk, F. Ortí, 1998) have been recognized. The presence of remnant films of organic matter and gypsum domal stromatolites atop the unit *c* implies its microbial origin. Gypsification of microbial mats might occur in extreme shallow-water environments subjected intermittently to subaerial exposure (J. M. Rouchy, C. L. V. Monty, 1981; H. Dronkert, 1985; J. M. Rouchy *et al.*, 1994).

A progressive deepening across the platform peripheries is indicated by a succession from nearshore facies to shallow-water selenites deposited in inner platform-lagoons (Fig. 6). The return to subaqueous conditions resulted in development of the thick selenitic gypsum complex (units *f–i*). The water depth was probably a few metres less but salinity higher than those in which giant gypsum intergrowths formed, as indicated by geochemistry and evidences of frequent fluctuations of the pycnocline (Fig. 5). Wind, the density gradient, brine chemistry, and the impact of freshwater and/or seawater floods were the main factors which affected sulphate deposition on the inner platform. During high water agitation by wave action, mechanical processes caused reworking and redeposition of clastic gypsum detritus (e.g. unit *h*).

Different sedimentary evolution in the central study area (the central elevation) was controlled by basin configuration and morphology. At the onset of sulphate deposition, the central shoal was largely exposed subaerially, as indicated by the lateral facies distribution and relationships (Figs. 4 and 6). Much of the basal nodular sulphate is developed as poorly preserved pseudomorphs after upright-growth gypsum crystals in a dolomitic mudstone matrix, but these have been largely modified by synsedimentary growth of displacive anhydrite nodules, related to phreatic processes (sabkhatization) when lagoon or salinas were infilled or desiccated and converted to a sabkha-like system (discussion in: A. Kasprzyk, F. Ortí, 1998). Modern facies analogues are known from coastal sabkhas of the Persian Gulf and the Red Sea (E. Gavish, 1980; G. P. Butler *et al.*, 1982). The lateral and vertical continuum of Badenian sulphate lithofacies from nodular to stromatolitic and selenitic gypsum reflects changes in a palaeoenvironment from subaerial to subaqueous during deposition of the lower gypsum member (Fig. 6).

UPPER MEMBER

At the boundary of the lower and upper gypsum members, changes in the basin configuration, in the water budget and in dynamics resulted in dominantly clastic gypsum accretion. Coastal salinas of Western Australia, where clastic gypsum facies have formed in periodically agitated waters (A. V. Arakel, 1980; B. W. Logan, 1987), provide a basis for the interpretation of the processes which initiated the facies succession of the upper member on the margins of the Badenian basin. In the landward side, the main forcing mechanism was wind and wave action. Storm-driven marine waters periodically flooded coastal flats and ephemeral salinas. Incursions of brackish water from runoff accelerated the mechanical transfer of gypsum detritus. Each flood deposited a thin bed or laminae of reworked detrital gypsum and terrigenous material. Redeposition processes were most intensive in the west of the area, whereas the central elevation was subaerially exposed (A. Kasprzyk, 1991, fig. 8 therein). In this unstable physicochemical regime, the varied facies association (units *j–m*) formed at the extreme peripheries of the platform, probably during progressive transgression.

Tectonic activity and related local subsidence and uplift resulted in high relief, which favoured reworking of basin-marginal sediments and dominant slope-controlled, basinward redeposition of clastic materials by mass flows, slumps and density currents, accompanied by cumulate gypsum precipitation in density stratified waters (units *n–p*) (Fig. 6). Gypsorudites and laminated gypsum showing slump features in the north and west of the study area are interpreted to have formed in proximal slope settings, while graded bedded deposits recognized in the south and south-east developed on the distal slope (T. M. Peryt, A. Kasprzyk, 1992*a*). Synsedimentary tectonic movements and local intense subsidence and/or uplift created a relative morphological gradient between the eastern and western parts of the basin, and resulted in the shifting of depocentres eastward.

A rapid sea-level fall (a possible combined effect of eustasy and tectonic movements) terminated sulphate deposition and led to almost complete desiccation of the northernmost part of the basin. Evaporite deposition probably continued in distal parts of the platform (e.g. in the east-central study area) occupied by shallow-water environments (unit *r*) during the low sea-level stand. Carbonate microbial facies associated with evaporites developed in local ponds of coastal flats (T. M. Peryt, A. Kasprzyk, 1992*b*). In south-east Poland and West Ukraine, deposition of the Ratyń Limestone overlying the erosional gypsum surface has been related to early transgression — the initial episode of the next depositional cycle (T. M. Peryt, D. Peryt, 1994).

CONCLUSIONS

The facies succession and lateral relationships reflect differentiated palaeoenvironmental conditions during the gypsum deposition in the northern peripheral part of the Badenian basin within the Carpathian Foredeep area, as shown by comparing the facies with modern evaporitic environments.

Three distinct facies associations identified throughout the gypsum section represent the main sulphate-platform depositional systems: (1) sabkha-like coastal flats and salinas, (2) shallow inner platform-lagoons, and (3) deeper outer platform-lagoons. The nearshore facies association is characterized by nodular and stromatolitic lithofacies as well as mixed siliciclastic-carbonate-sulphate deposits developed in extremely shallow-water to subaerial environments, that occupied landward margins of the platform and local shoals during low sea-level stands. The shallow-water association is predominantly composed of bottom-grown selenites originated in partly isolated inner-platform lagoons a few metres deep. In shallow water, remobilization and redeposition of the clastic gypsum sediment were caused by the wind and wave action. The deeper-water facies association formed when synsedimentary tectonic activity and related local subsidence and uplift created areas of a distinct morphology, and this promoted the gravity-controlled, basinward redeposition of clastic gypsum by mass movement.

At the margins of this Badenian basin within the foredeep, facies relationships are largely diachronous. The major variations in depositional environments are expressed in cyclic successions of the facies associations.

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ROZWÓJ SEDYMENTACJI BADEŃSKICH OSADÓW GIPSOWYCH W PÓŁNOCNEJ CZĘŚCI ZAPADLISKA PRZEDKARPACKIEGO

S t r e s z c z e n i e

Gipsy badeńskie są szeroko rozprzestrzenione w północnej, peryferyjnej części zapadliska przedkarpackiego, gdzie są znane z licznych odsłonięć powierzchniowych i otworów wiertniczych (fig. 1). Osady te wykazują duże zróżnicowanie litofacjalne i tworzą w profilu stałą sekwencję warstw (od *a* do *r*) składających się na dwa podstawowe kompleksy: dolny (głównie gipsy autochtoniczne, selenitowe) i górny (głównie gipsy allochtoniczne, klastyczne i drobnokrystaliczne) (fig. 2). Ku południowi, wraz ze wzrostem głębokości występowania (powyżej 250 m), gipsy są częściowo lub całkowicie zastąpione przez anhydryty zachowujące wiele struktur pierwotnych skał gipsowych.

Zmienność facji i ich następstwo, a także skład geochemiczny (fig. 3–5; tabl. I–V) odzwierciedlają zmienne warunki sedymentacji w brzeżnej strefie zbiornika badeńskiego. Warunki te zrekonstruowano na podstawie podobieństwa litofacji do osadów współczesnych środowisk ewaporacyjnych. Gipsy selenitowe tworzyły się w środowiskach płytkowodnych poddanych okresowym wynurzeniom, natomiast depozycja grubego kompleksu gipsów klastycznych miała miejsce w środowisku głębszym.

Gipsy powstawały na platformie w rozległych, płytkowodnych lagunach (salinach, subbasenach). Rozdzielały je lokalne wyspy lub płycizny o kierunku NW–SE, mające założenia tektoniczne. Wyróżnione asocjacje facjalne gipsów: przybrzeżna (NFA), płytkowodna (SFA) i głębokowodna (DFA) reprezentują główne systemy depozycyjne platformy siarczanowej: (1) strefy brzegowej (sebha — salina przybrzeżna), (2) płytkiej, wewnętrznej części platformy, i (3) głębszej, zewnętrznej części platformy (fig. 6). W strefie peryferyjnej zbiornika depozycja gipsów miała miejsce w zróżnicowanych środowiskach. Osady sebhy wykształciły się na równiach przybrzeżnych, które okresowo pokrywały znaczną część platformy wewnętrznej w czasie niskiego stanu wód. Facje stromatolitowe tworzyły się w środowiskach od skrajnie płytkowodnych do subaeralnych, natomiast gipsy selenitowe rozwijały się na dnie płytkich (o głębokości do kilku metrów) lagun, częściowo izolowanych od wpływu otwartego morza. W warunkach płytkowodnych osad gipsowy był łatwo redeponowany w okresach zwiększonej dynamiki wód. W wodach głębszych, gęstościowo rozwarstwionych, depozycji gipsów klastycznych towarzyszyło wytrącanie gipsu w toni wodnej.

Stwierdzone cykliczne następstwo asocjacji facjalnych w profilach gipsów badeńskich (fig. 2, 6) odzwierciedla zasadnicze zmiany środowiska sedymentacji w peryferyjnej części zbiornika. Głównymi czynnikami determinującymi charakter i sukcesję osadów były względne zmiany głębokości, dynamiki i zasolenia wód. Najbardziej drastyczne zmiany środowiska sedymentacji, które można wiązać z większymi zmianami poziomu morza, zaznaczyły się na granicy depozycji kompleksu gipsów selenitowych i kompleksu gipsów klastycznych, a także pod koniec depozycji gipsów.

EXPLANATIONS OF PLATES

PLATE I

Fig. 1. *Szklica* gypsum. Asymmetrical chaotic giant intergrowths of crystalline aggregates oriented along vertical or slightly inclined compositional surfaces (cs), showing features of competitive growth; in the upper part — a dissolution surface (arrows) partly obliterated by syntaxial crystal growth. Unit *a*. Leszcze quarry, locality Gacki. The head of the hammer is 17 cm long

Fig. 2. Lower part of gypsum section composed of bedded selenite (units *b* and *d*), alabastrine gypsum (unit *c*), stromatolitic gypsum (unit *e*), and skeletal gypsum (lower part of unit *f*). Note differential thickness of unit *d* and domal arrangement of component selenitic layers. Locality Chotel Czerwony–Zagórze

Fig. 3. Stromatolitic gypsum composed of gypsum domal stromatolites with *cavoli* selenites detailed in B. Unit e. A — Locality Chwałowice; the pointer (central part) is 15 cm long. B — Borehole Suchowola 81, depth 88.4–88.5 m

PLATE II

Fig. 1. Gradual transition between skeletal gypsum (unit *f*) and sabre-like gypsum (unit *g*). Note splits of uniformly oriented, elongated selenitic crystals (arrowheads). Locality Gartatowice. The exposure is 3.5 m high

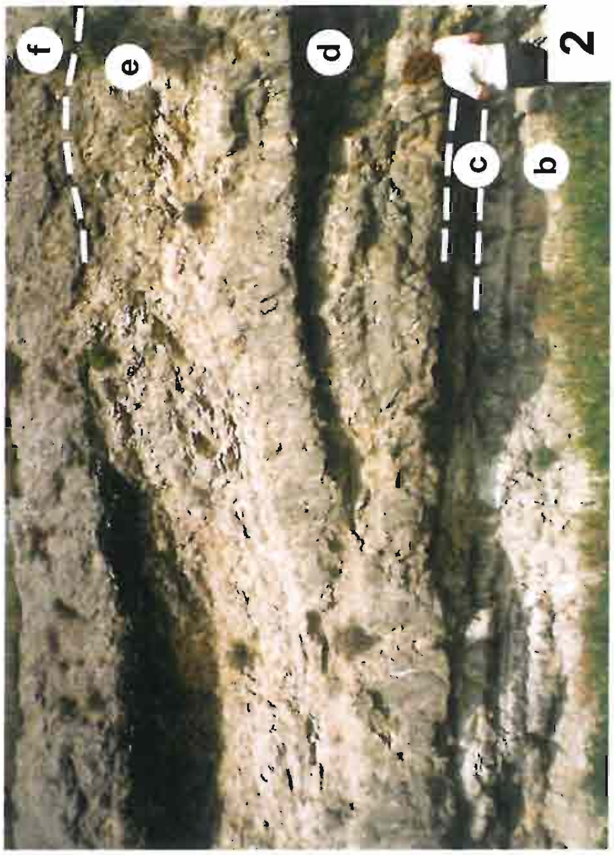
Fig. 2. Upper part of the lower (selenitic gypsum) member composed of sabre-like gypsum (units *g* and *i*) and the laminated gypsum intercalation (unit *h*). Note bedding in the upper unit *g* and uniform, subhorizontal orientation of sabre crystals in unit *i*. Locality Chwałowice. The height of the exposed section is 6 m

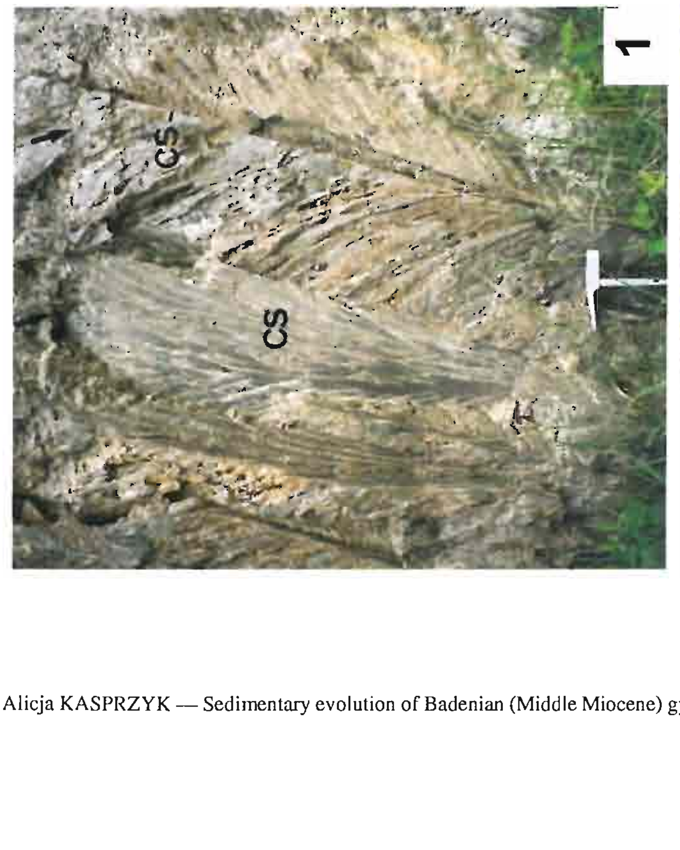
Fig. 3. Parallel laminated gypsarenites with redepositional features: brecciated and/or contorted layers (arrowhead), convoluted laminae, and fragments of reworked gypsum (o). Unit *k*(?). Locality Górki

PLATE III

Fig. 1. A — Upper gypsum member exposed in the SE wall of Borków quarry. The succession comprises gypsum breccia (unit *l*), claystone (unit *t*), stromatolitic gypsum with crystalline aggregates and selenitic cones (unit *m*), and laminated gypsarenites (unit *n*). Note the irregular bottom surface distinctive of the unit *m*. Locality Szarbków. The exposure is 12 m high. B — Close-up of the transition between units *l* and *m*. Note a vertical pit filled with a chaotic *in situ* gypsum breccia in unit *l*. The width of the photo is 6 m

Fig. 2. Laminated gypsarenites and gypsum-marly breccias with a thick, *in situ* broken interbed (central part), interpreted as slumped deposits. The upper gypsum member. Locality Gniazdowice





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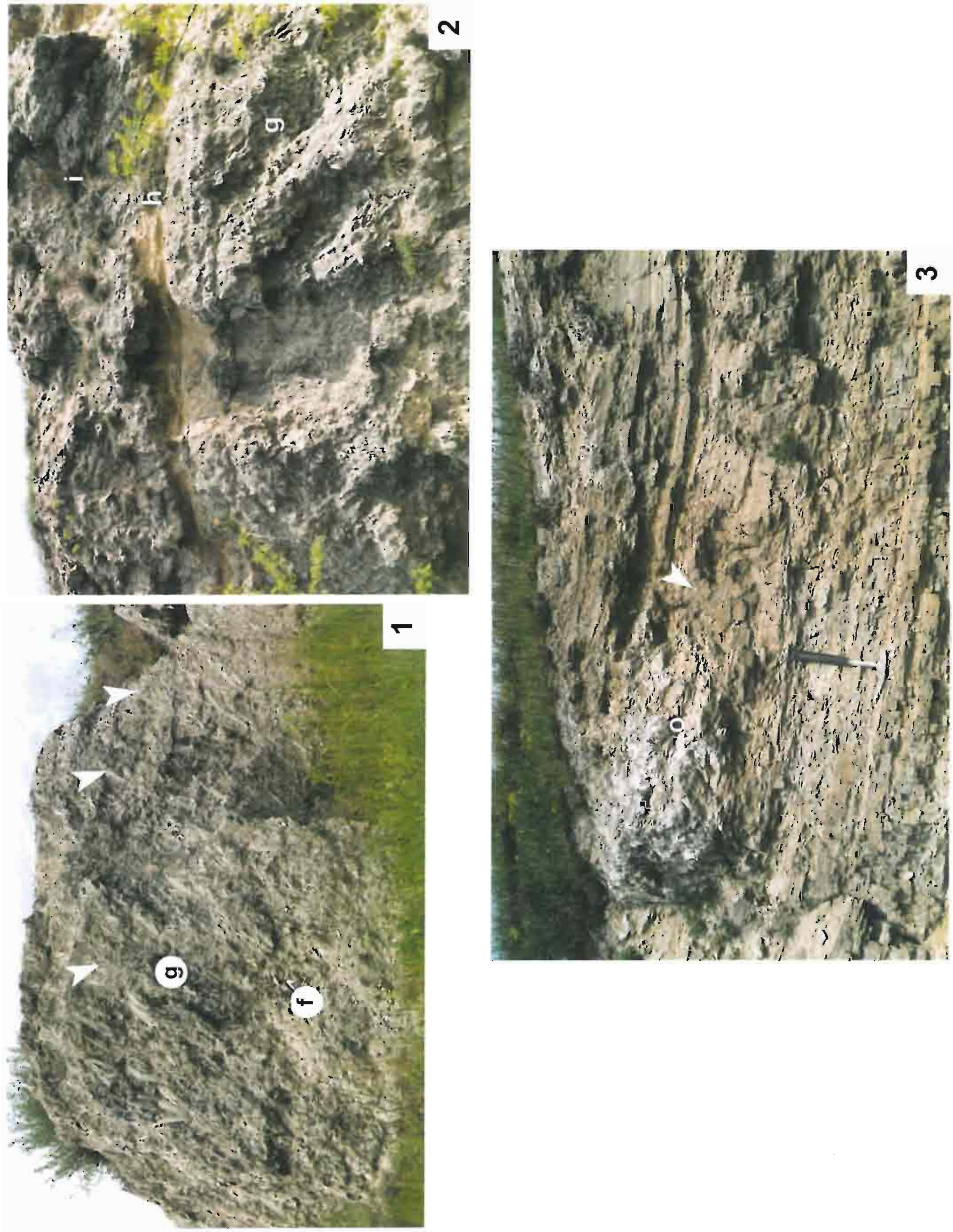

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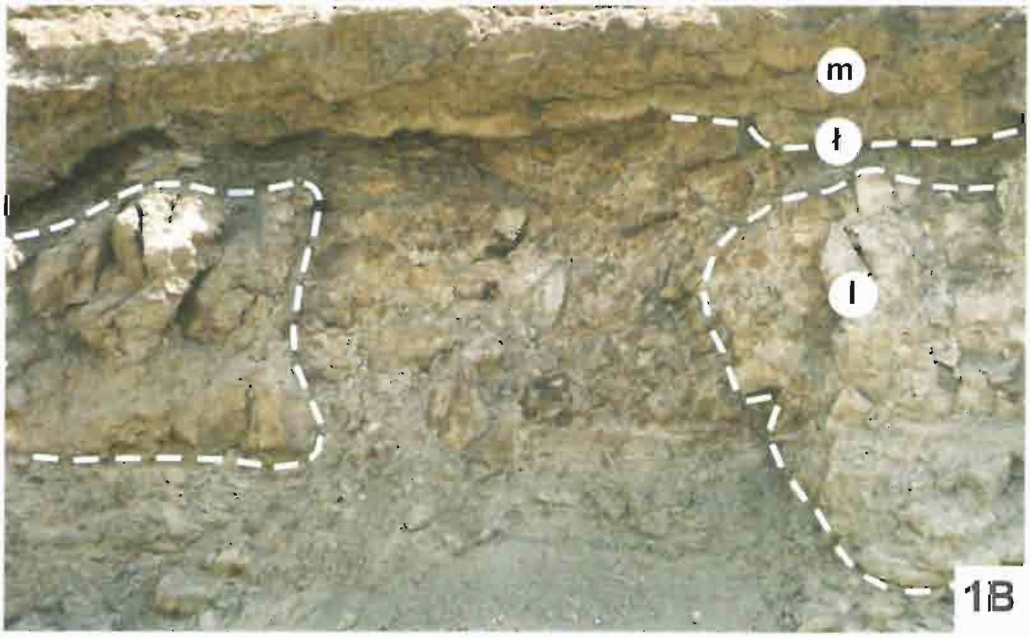

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