Geological Quarterly, Vol. 39, No. 4, 1995, p. 489–512

Alicja KASPRZYK

Zechstein Anhydrites NW of the Holy Cross Mts. (Upper Permian, central Poland): facies and palaeogeography

The facies variety of the sulphate deposits in the Zechstein of the Holy Cross Mts. reflects distinct sedimentary conditions in the peripheral part of the evaporitic basin, where the cyclic sedimentation of PZ1, PZ2, PZ3, and PZ4 was largely affected by input of terrigenous material. In this area two sectors, southern and northern, may be distinguished on the basis of facies zonation. During the evaporite sedimentation, a major area north-west of the Holy Cross Mts. was exposed and affected by intense denudation at low sea level stands. In the marginal zone, evaporites are lacking and their facies equivalents are siliciclastic deposits. Palaeogeographic and facies patterns were controlled mainly by climatic and tectonic factors.

INTRODUCTION

Throughout geological history giant evaporitic accumulations have been formed under particular climatic and tectonic conditions that occurred in the past but do not exist today (P. Sonnenfeld, 1984). Although no modern analog exists as far as size is concerned, facies comparison has important implications for the interpretation of the sedimentary regime during evaporite deposition (J. K. Warren, C. G. S. C. Kendall, 1985; B. C. Schreiber, 1988). Consequently, the facies and sedimentary variety of evaporites are attributed to a wide range of depositional settings, as indicated by the study of modern evaporitic environments, all of which have the common attribute of aridity (e.g. A. V. Arakel, 1980; F. Orti Cabo *et al.*, 1984; B. W. Logan, 1987; B. H. Purser *et al.*, 1987; C. G. S. C. Kendall, J. K. Warren, 1988).

The facies succession and lateral distribution of the Zechstein (Upper Permian) deposits north-west of the Holy Cross Mts. (Fig. 1) are an expression of different basin configuration in the peripheral part of the Polish Basin (R. Wagner, 1994). In this area, shallow-water evaporites formed on the shelf whilst in the basin margin sabkha deposition took place (*op. cit.*). Along with sea-water ingressions, successive deposition of pelites, carbonates and

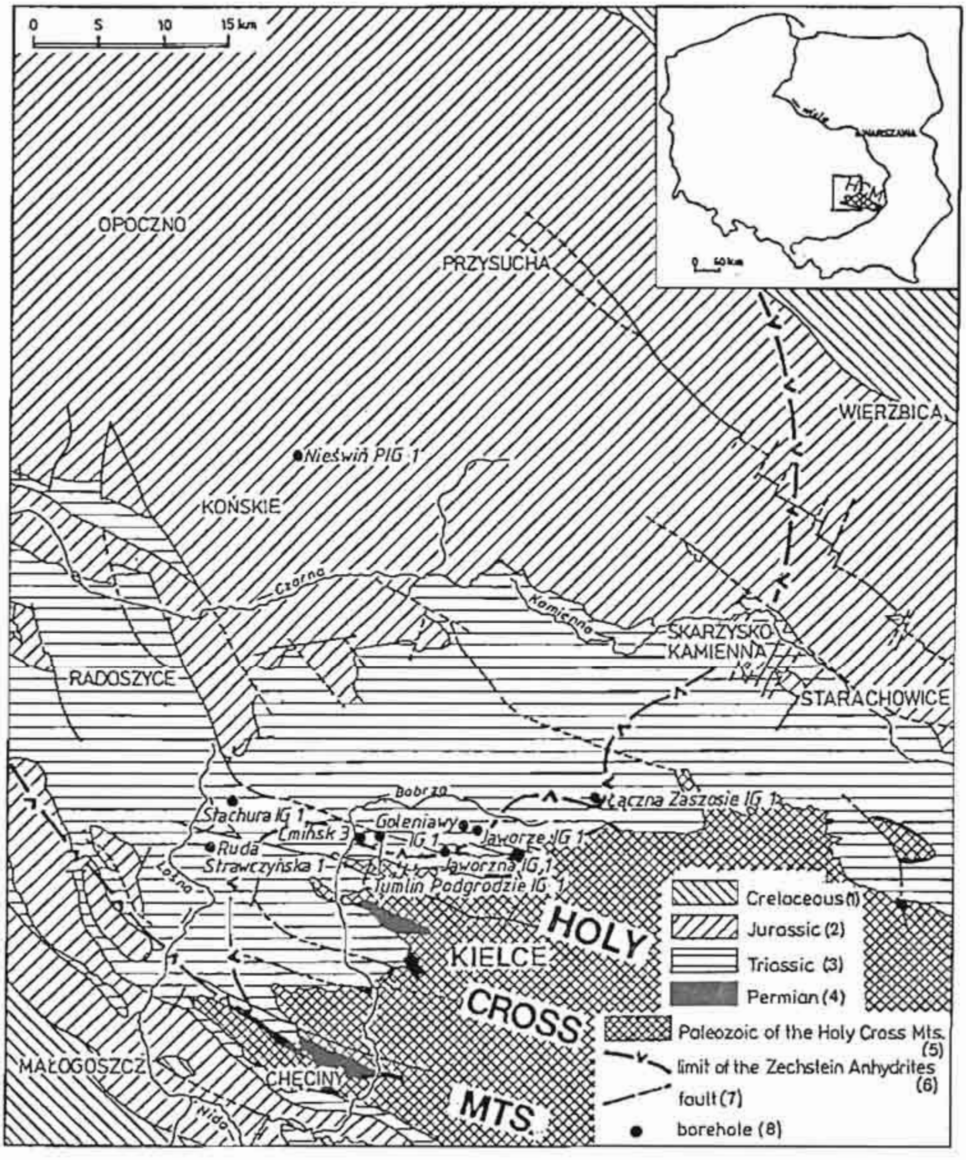


Fig. 1. Location of studied boreholes in the area north-west of the Holy Cross Mts.
Lokalizacja zbadanych otworów wiertniczych w północno-zachodnim obrzeżeniu Gór Świętokrzyskich
1 — kreda, 2 — jura, 3 — trias, 4 — perm, 5 — paleozoik Gór Świętokrzyskich, 6 — zasięg anhydrytów cechsztynu, 7 — uskok, 8 — otwór wiertniczy

evaporites resulted in evaporitic sedimentary cycles, which were largely incomplete in the marginal zone (Z. Kowalczewski, M. Rup, 1989; Z. Kowalczewski, S. Zbroja, in press). As a result, the lithostratigraphic correlation of sedimentary cycles between the marginal and basinal parts of the Zechstein basin is difficult and sometimes controversial in a more detailed approach (discussion in: Z. Kowalczewski, M. Rup, 1989; R. Wagner, 1994).

In this paper the facies and sedimentary pattern of sulphate deposits is discussed and used to reconstruct palaeoenvironmental conditions during cyclic evaporite deposition in the peripheral part of the Zechstein basin. For these purposes, several boreholes with sulphate deposits at depth between 275.0 and 2267.0 m, located north-west of the Holy Cross Mts. (Fig. 1) were chosen for detailed lithofacies and sedimentary studies. The results of this work provide implications for interpretation of sedimentary evolution in peripheral areas of the Polish Zechstein Basin.

GEOLOGICAL SETTING

During the latest Permian, laterally-extensive evaporite sedimentation took place in a shallow epicontinental basin which occupied large areas of central and eastern Europe, from the North Sea to Lithuania (R. Wagner, 1994). The resulting evaporite-bearing formation of the Zechstein locally exceeds 1000 m in thickness and comprises interbedded carbonates, anhydrites, halites, locally K-Mg salts, and terrigenous clastic deposits, which are strongly cyclic. In the lithostratigraphic division of the Zechstein formation distinct sulphate units are distinguished within each evaporite cycle (Table 1).

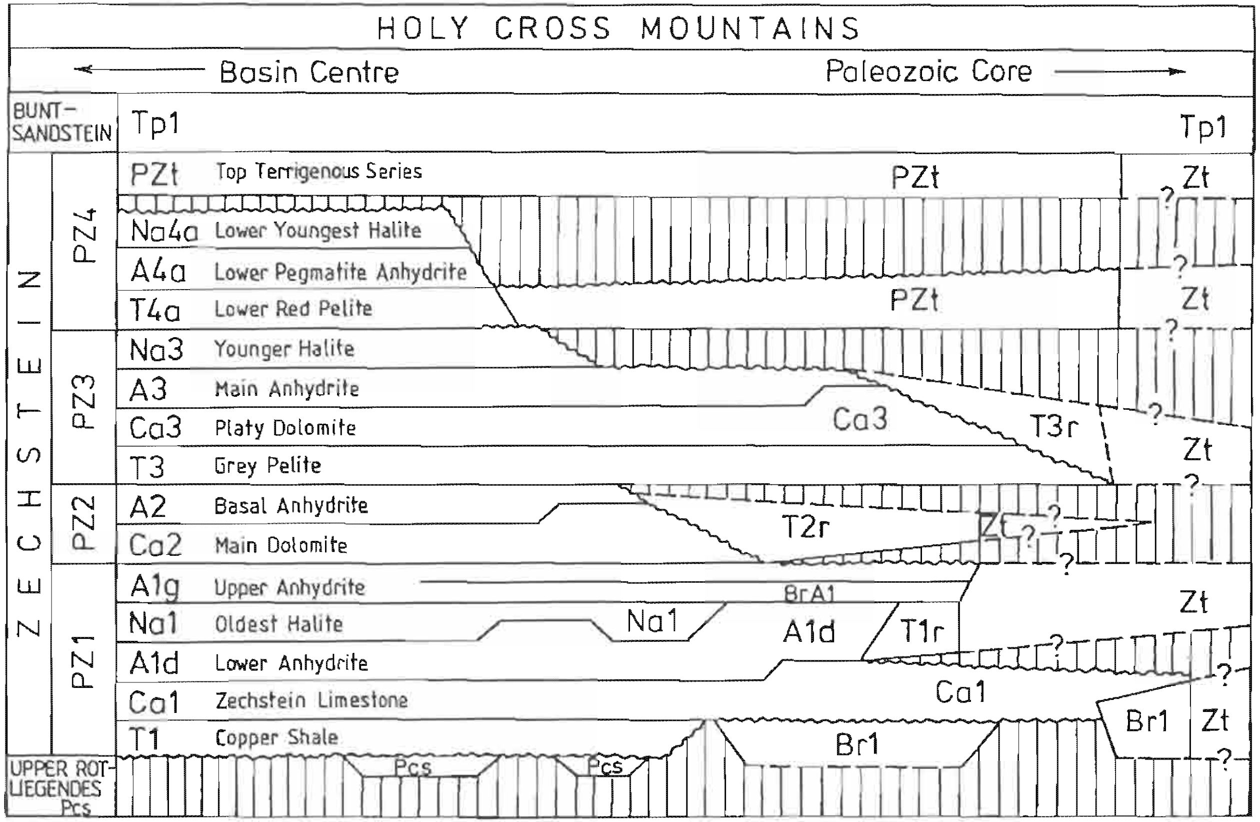
The Zechstein deposits north-west of the Holy Cross Mts. are from 3 to 760.6 m thick (the supposed original thickness is estimated from several tens to hundreds metres, S. Zbroja, personal communication 1995), and the major part is ascribed to the PZ1 cycle (Z. Kowalczewski, M. Rup, 1989). The oldest lithostratigraphic units are the Zechstein Limestone (Ca1) and the locally developed Copper Shale (T1) (Table 1). In the most complete section, two anhydrite units of the PZ1: the Lower Anhydrite (A1d) and the Upper Anhydrite (A1g) are separated by the Oldest Halite (Na1). The PZ2 deposits show limited extent and comprise the Main Dolomite (Ca2) and the Basal Anhydrite (A2) units. The succession of PZ3 contains the Grey Pelite at the base, which is overlain by the Platy Dolomite (Ca3), the Main Anhydrite (A3), and finally by the Younger Halite (Na3). The PZ4 cyclothem is made up of terrigenous-evaporitic sequences. In the extreme peripheral part of the basin, evaporite units are absent and replaced by siliciclastic deposits referred to as the Recessive Terrigenous Series T1r, T2r, and PZt in the lithostratigraphic division of the Zechstein (Table 1).

The Zechstein deposits developed in carbonate-siliciclastic facies, locally with sulphates, are exposed or occur in the shallow subsurface in the western part of the Holy Cross Mts. (Fig. 1). In distal peripheries the cyclic sequences of the PZ1, PZ2, PZ3, and PZ4 are more complete and well fitted to the lithostratigraphic division of the Zechstein in the Polish Basin (R. Wagner *et al.*, 1978; R. Wagner, 1988, 1994). The succession of facies throughout the cycle is transgressive-regressive, which reflects relative changes in sea level and in the physicochemical regime of sedimentation (Z. Kowalczewski, M. Rup, 1989; R. Wagner, 1994).

The regional tectonic framework of the study area is characterized by a dominant E–W and ESE–WNW fault system (Fig. 1), linked to late Variscan and Alpian diastrophism (Z. Kowalczewski *et al.*, 1990).

Table 1

Lithostratigraphic correlation of the Zechstein in the Holy Cross Mts. and their foreland (after R. Wagner, 1994)



Br1 – Basal Breccia; BrA1 – Anhydrite Breccia; T1r, T2r, T3r – Recessive Terrigenous Series PZ1, PZ2, PZ3; Zt – Terrigenous Zechstein

FACIES AND SEQUENCES

A general zonal distribution of sedimentary facies of the Zechstein Anhydrites north-west of the Holy Cross Mts. permits the distinction of two palaeogeographic regions, different in facies variation and sedimentary evolution (Figs. 2 and 3; Pl. I, Figs. 8–14). In the southern region (so-called "...proximal Permian-Mesozoic margin of the Holy Cross Mountains...", Z. Kowalczewski, S. Zbroja, in press), the following boreholes are located: Ruda Strawczyńska 1, Stachura IG 1, Ćmińsk 3, Tumlin Podgrodzie IG 1, Jaworzna IG 1, Goleniawy IG 1, Jaworze IG 1, Łączna Zaszosie IG 1 (Figs. 1 and 2). The northern region, represented by borehole Nieświń PIG 1, is part of the distal periphery of the Holy Cross Mts.

PZ1 ANHYDRITES

In the vertical section, sulphate deposits of the PZ1 cycle locally exhibit (Stachura IG 1, Tumlin Podgrodzie IG 1, Jaworze IG 1, Nieświń PIG 1) a distinct bipartition which comprises the Lower Anhydrite (A1d) and the Upper Anhydrite (A1g) units (Fig. 2). In other profiles studied, the only sulphate unit present is the Upper Anhydrite (S. Zbroja, 1990; A. Kasprzyk, 1994).

LOWER ANHYDRITE A1d

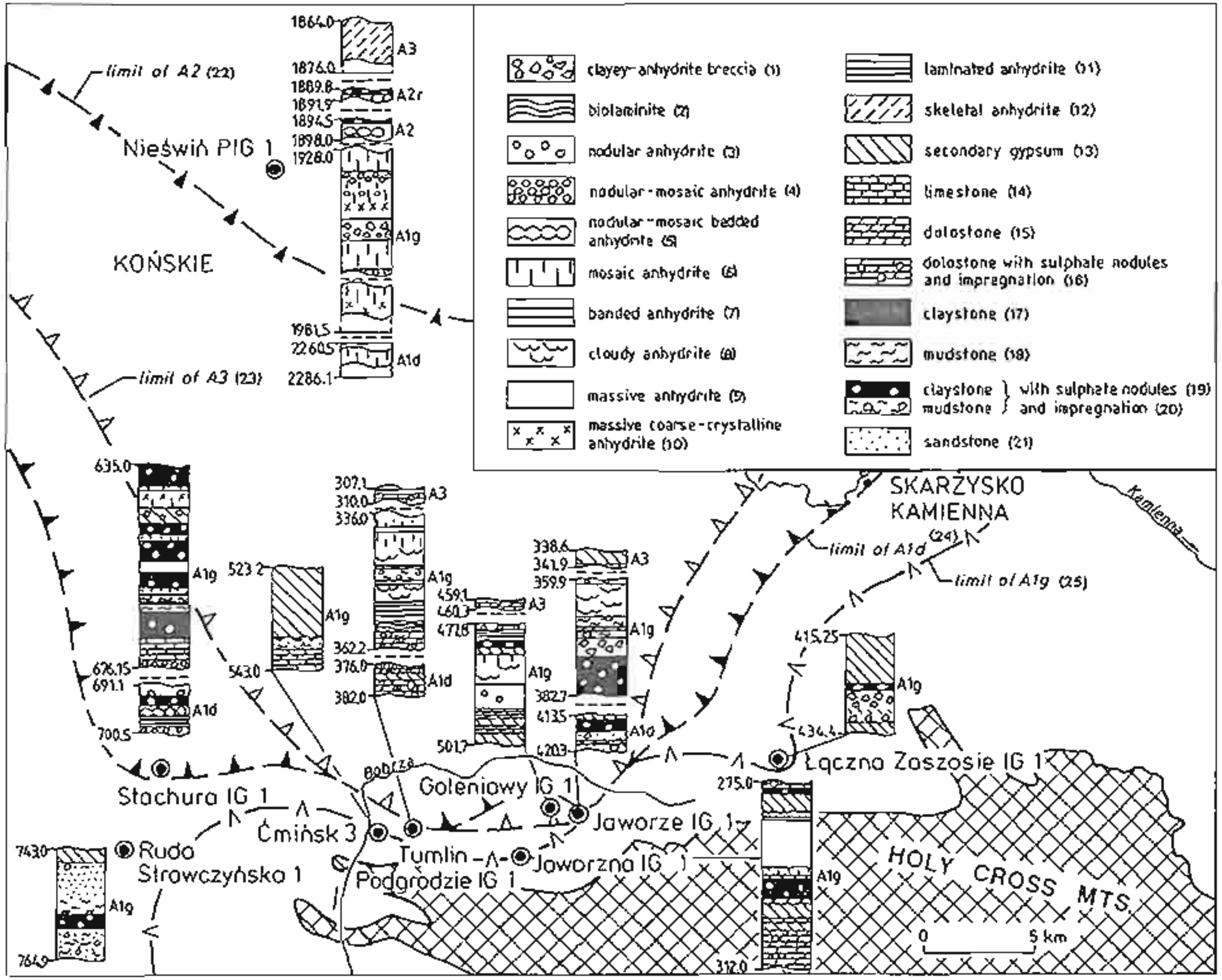
In the southern region, the Lower Anhydrite is 6.0–9.6 m thick (Fig. 2). It is composed of nodular, nodular-mosaic and mosaic sulphate facies (anhydrite and secondary gypsum) interbedded with red mudstones and (or) dolostones, which commonly show sulphate impregnation and nodules (Pl. I, Figs. 8 and 9). Nodules are millimetre-centimetre sized and occur isolated or aggregated into nodular layers, deforming the relict lamination of the host rock. They are connected with each other by a dense net of fibrous gypsum veins. Other characteristic sedimentary structures are lamination (planar, irregular and flaser), biolamination, grading, load structures, and brecciated layers. The transition to underlying deposits of the Zechstein Limestone and to overlying siliciclastics of the Terrigenous Series T1r is gradual and expressed as a relative decrease (< 50% on average) of the sulphate content (A. Kasprzyk, 1994).

In the Nieświń PIG 1 section, the Lower Anhydrite has been geophysically recognized at depth 2260.5–2286.1 m (Z. Kowalczewski *et al.*, 1991). The 3-metre long cored interval (depth 2264.0–2267.0 m) is composed of flaser anhydrites in the lower part, followed by massive and mosaic anhydrites with pseudomorphs after grass-like selenites; at the top, banded anhydrite with graded layers is present (Pl. I, Fig. 10).

UPPER ANHYDRITE A1g

In the studied area, the Upper Anhydrite is the best developed and the most extensive sulphate horizon which reaches 53.5 m in thickness (Nieświń PIG 1) (Fig. 2).

Based on a vertical set of lithofacies it is possible to distinguish four units (lithotypes), designated *A, B, C, D* (Fig. 4); each of them comprises a characteristic variety of facies which has palaeoenvironmental implications (A. Kasprzyk, 1994).


clayey-anhydrite breccia (1)
biolaminite (2)
nodular anhydrite (3)
nodular-mosaic anhydrite (4)
nodular-mosaic bedded anhydrite (5)
mosaic anhydrite (6)
banded anhydrite (7)
cloudy anhydrite (8)
massive anhydrite (9)
massive coarse-crystalline anhydrite (10)
laminated anhydrite (11)
skeletal anhydrite (12)
secondary gypsum (13)
limestone (14)
dolostone (15)
dolostone with sulphate nodules and impregnation (16)
claystone (17)
mudstone (18)
claystone } with sulphate nodules (19)
mudstone } and impregnation (20)
sandstone (21)
limit of A2 (22)
limit of A3 (23)
limit of A1d (24)
limit of A1g (25)
Nieświń PIG 1
KOŃSKIE
SKARŻYSKO KAMIENNA
Kamienna
Stachura IG 1
Rudo Strawczyńska 1
Ćmińsk 3
Tumlin
Podgrodzie IG 1
Goleniowy IG 1
Jaworze IG 1
Jaworzno IG 1
Łączna Zaszosie IG 1
Bobrza
HOLY CROSS MTS.
0 5 km
A3
A2r
A2
A1g
A1d
1864.0
1876.0
1889.8
1891.9
1894.5
1898.0
1928.0
1961.5
2260.5
2286.1
635.0
676.15
691.1
700.5
523.2
543.0
307.1
310.0
336.0
362.2
376.0
382.0
459.1
460.3
472.8
501.7
338.6
341.9
359.9
382.7
413.5
420.3
415.25
434.4
275.0
312.0
743.0
764.0

Unit *A* is composed of mixed siliciclastic-carbonate-sulphate facies which is transitional between T1r siliciclastics and overlying sulphate deposits (Fig. 4). Locally in the southern region (Tumlin Podgrodzie IG 1, Jaworzna IG 1, Goleniawy IG 1, Łączna Zaszosie IG 1) there is an alternation of layers, from some centimetres to decimetres thick, of carbonate and sulphate facies. Among them biolaminites as well as nodular and banded sulphate rocks (gypsum and anhydrite) contaminated with clay and carbonate material are dominant, and all display irregular clayey-organic lamination. In other sections (Ruda Strawczyńska 1, Stachura IG 1, Ćmińsk 3, Jaworze IG 1) unit *A* is composed of red mudstones, locally sandy, which commonly reveal sulphate impregnation and nodules (often calcified), and minor interbeds of carbonate rocks (limestones, dolostones, marls) (Fig. 2).

Unit *B* is distinctive in the sequence of the Upper Anhydrite by a presence of clayey-anhydrite breccias and conglomerates 0.45–8.70 m thick. Clasts are slightly abraded or angular fragments, millimetre-centimetre sized, of massive and laminated anhydrites and secondary gypsum, limestones, dolostones, claystones, and mudstones, embedded in a pelitic or clayey-carbonate-sulphate matrix (Pl. I, Fig. 11). Aligned, deformed and partly liquefied clasts are common. Locally, packets of sulphate-pelitic-carbonate laminae occur as interbeds within the thicker layers of breccias (Jaworze IG 1, Łączna Zaszosie IG 1). In the Ruda Strawczyńska 1 and Tumlin Podgrodzie IG 1 sections the local equivalents of breccias are sandy mudstones with sulphate nodules and impregnation, commonly showing distorted and deformation structures.

Breccias occur throughout the A1g section in different positions: in the middle or lower parts, just at the boundary with the Terrigenous Series T1r (southern region), or in the upper part (Nieświń PIG 1) (Fig. 2). It seems to be a rule that toward the north, with increasing burial, breccias displace upwards through the A1g section, and disappear in the central parts of the Zechstein basin (R. Wagner, 1994).

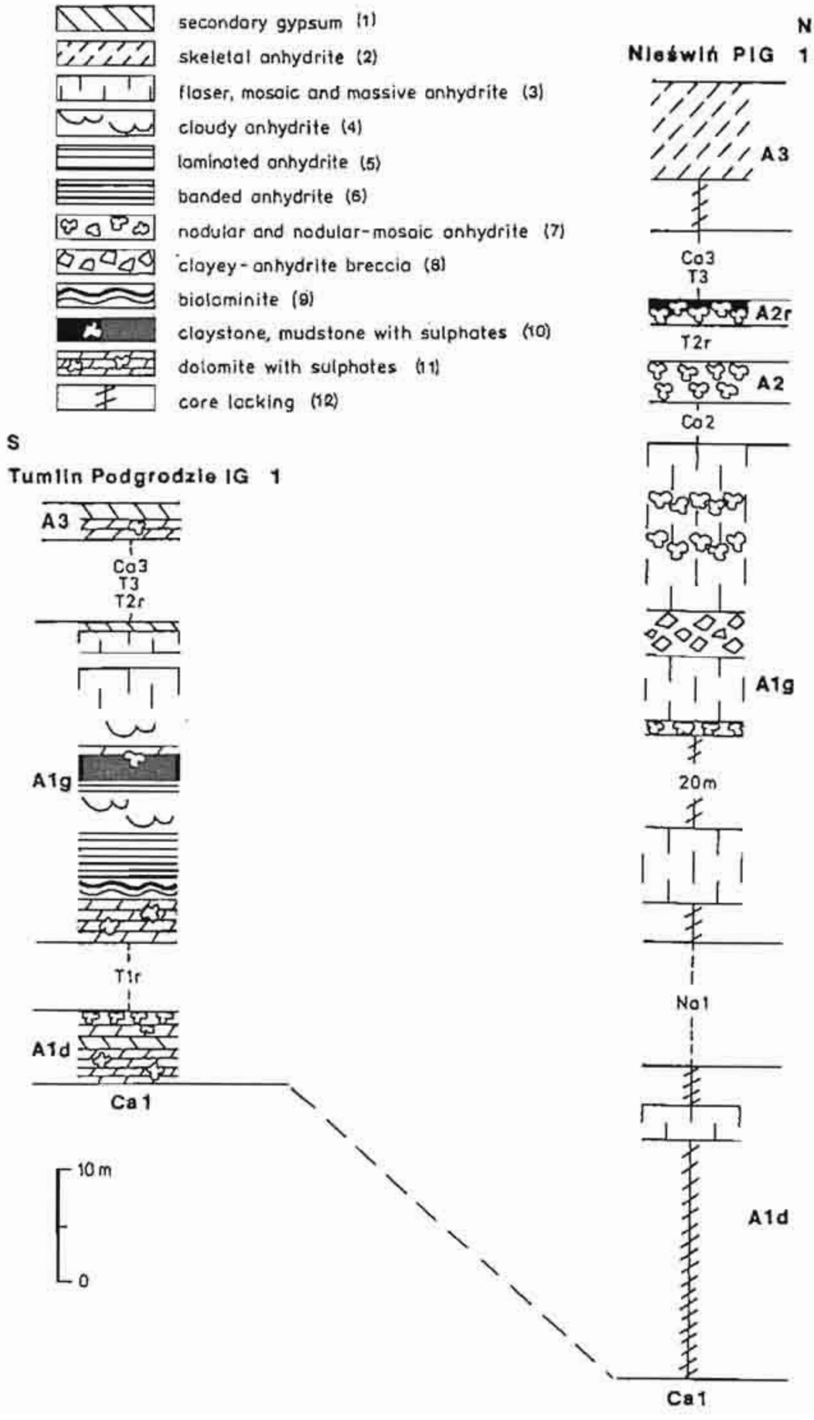
All features described allow the interpretation of unit *B* as an equivalent of the PZ1 Anhydrite Breccia (BrA1), distinguished by R. Wagner (1988) in the lithostratigraphic division of the peripheral parts of the Zechstein basin (Table 1).

In the middle section of the Upper Anhydrite — usually a thick (from 4.1 to 26.2 m) sulphate complex — unit *C* occurs (Fig. 4). It is composed of massive and mosaic gypsum and anhydrites with common pseudomorphs (up to 5 cm high) after grass-like and *cavoli* selenites (Pl. I, Fig. 12). Locally the transition to laminated, mosaic or bedded nodular-mosaic varieties, several decimetres thick, is observed. Massive and mosaic anhydrites are dominant lithologies of the Upper Anhydrite in the Nieświń PIG 1 section (Fig. 3). They are lacking in the extreme peripheral areas (Ruda Strawczyńska 1 — Fig. 4).

Fig. 2. Lithofacies of the Zechstein Anhydrites in studied boreholes

Wykształcenie litofacjalne poziomów anhydrytowych cechsztynu w badanych otworach wiertniczych

1 — brekcje anhydrytowo-ilaste, 2 — biolaminoidy, 3 — anhydryty gruzłowe, 4 — anhydryty gruzłowo-mozaikowe, 5 — anhydryty gruzłowo-mozaikowe warstwowane, 6 — anhydryty mozaikowe, 7 — anhydryty warstwowane, 8 — anhydryty chmurzyste, 9 — anhydryty masywne, 10 — anhydryty masywne grubokrystaliczne, 11 — anhydryty laminowane, 12 — anhydryty *szkieletowe*, 13 — gipsy wtórne, 14 — wapienie, 15 — dolomity, 16 — dolomity z gruzłami, 17 — iłowce, 18 — mułowce, 19 — iłowce z gruzłami i impregnacjami siarczanowymi, 20 — mułowce z gruzłami i impregnacjami siarczanowymi, 21 — piaskowce, 22 — zasięg anhydrytów A2, 23 — zasięg anhydrytu głównego A3, 24 — zasięg anhydrytu dolnego A1d, 25 — zasięg anhydrytu górnego A1g


secondary gypsum (1)
skeletal anhydrite (2)
flaser, mosaic and massive anhydrite (3)
cloudy anhydrite (4)
laminated anhydrite (5)
banded anhydrite (6)
nodular and nodular-mosaic anhydrite (7)
clayey-anhydrite breccia (8)
biolaminite (9)
claystone, mudstone with sulphates (10)
dolomite with sulphates (11)
core lacking (12)
S
Tumlin Podgrodzie IG 1
A3
Ca3
T3
T2r
A1g
T1r
A1d
Ca1
10 m
0
N
Nieświń PIG 1
A3
Ca3
T3
A2r
T2r
A2
Ca2
A1g
20m
Na1
A1d
Ca1

In the southern region, the A1g sequence is terminated by unit *D* (Fig. 4), which comprises different sulphate lithofacies greatly contaminated with clay and carbonate. The most common varieties are nodular and banded gypsum and anhydrite. They are intercalated with marls and claystones that abound in sulphate nodules and impregnation. This facies variety is transitional to the overlying Terrigenous Series of PZ2 (Fig. 4).

BASAL ANHYDRITE A2

In the northern region (Nieświń PIG 1), the facies association of the Basal Anhydrite is 3.5 m thick and consists of mosaic, nodular and nodular-mosaic bedded anhydrites (Pl. I, Fig. 13). Characteristic structures are: irregular biolamination, occasionally with preserved calcifield cyanobacterial filaments, fenestrae, deformation structures, and sulphate nodules — horizontally aligned, single or aggregated in layers. Nodules are several centimetres in diameter and show features typical of displacement growth within the laminated pelitic-carbonate matrix. These deposits grade upward into red mudstones of the Terrigenous Series T2r, which, in turn, are followed by a layer, 2.1 m thick, of intercalated mosaic, nodular-mosaic and nodular anhydrites referred to as the Screening Anhydrite of PZ2 (A2r) (Z. Kowalczewski *et al.*, 1991) (Fig. 3). The nodular lithologies are distinctive due to the presence of sulphate nodules, from some millimetres to a centimetre in diameter, commonly aggregated, deformed and embedded in the pelitic matrix, irregulary laminated with organic matter. Locally relict pseudomorphic structures after *cavoli* selenites and prismatic gypsum crystals (up to 3 cm long) may be seen, although recrystallization largely obliterated the original crystal morphologies. The transition to overlying dolomitic mudstones of the Grey Pelite (T3) is gradual.

In the southern region, the sulphate deposits of the PZ2 cycle are lacking (Figs. 2 and 4). A great diversity of siliciclastic facies, defined as the Terrigenous Series of the PZ2 cycle (S. Zbroja, 1990), comprises siltstone breccias with pelitic matrix in the extreme peripheries, and dolomitic sandstones, mudstones and claystones in more distal areas. Considering the palaeogeographic pattern in the peripheral parts of the Zechstein basin (e.g. R. Wagner, 1994), these deposits are interpreted as a facies equivalent of the PZ2 carbonates and anhydrites of the northern region (Z. Kowalczewski, S. Zbroja, in press) (Table 1).

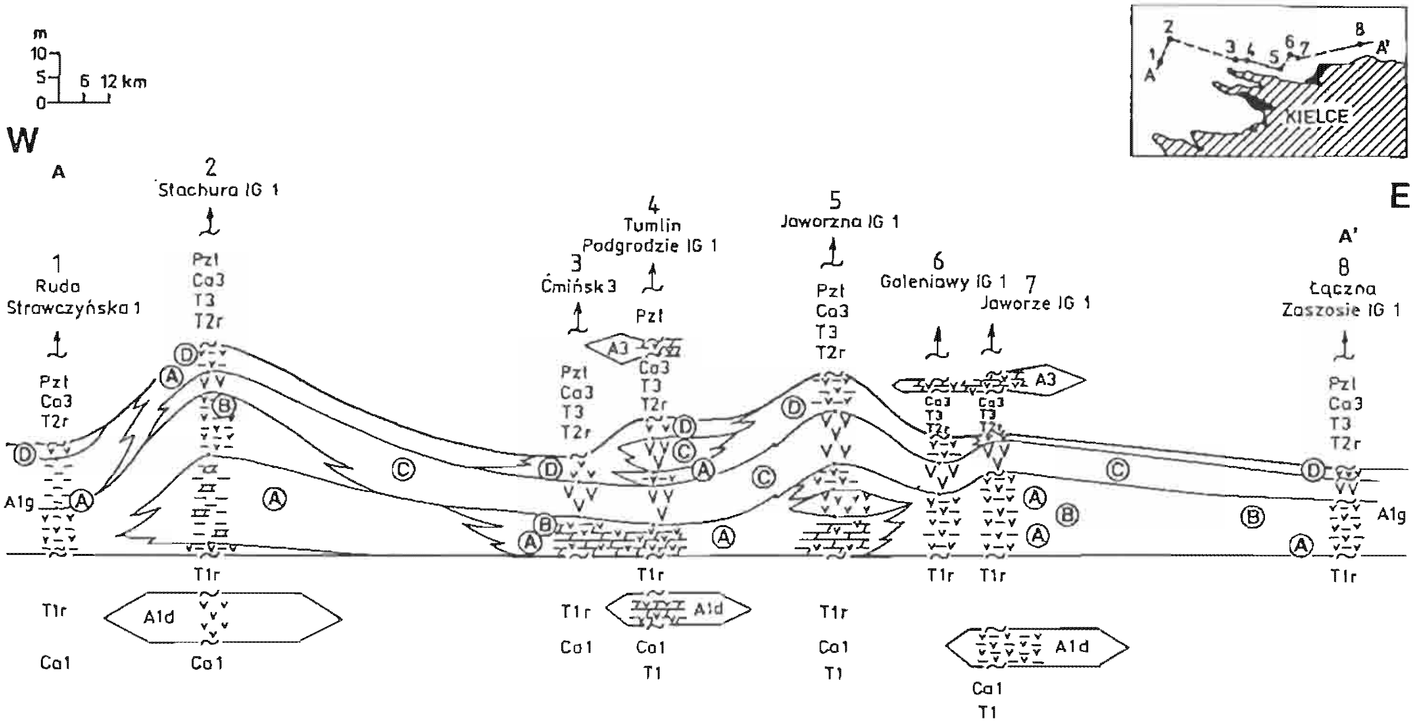
MAIN ANHYDRITE A3

The sulphate deposits of cycle PZ3 are widespread in the northern region (Fig. 5). In the profile of Nieświń PIG 1 they are 31.0 m thick. The 8-metre long cored interval (depth 1864–1872 m) from the upper part of the complex is completely composed of *skeletal*

Fig. 3. Correlation of the Zechstein Anhydrites in boreholes Tumlin Podgrodzie IG 1 and Nieświń PIG 1
Explanations in Table 1

Korelacja poziomów anhydrytowych w otworach: Tumlin Podgrodzie IG 1 i Nieświń PIG 1

1 — gipsy wtórne, 2 — anhydryty *szkieletowe*, 3 — anhydryty soczewowo-smużyste, mozaikowe i masywne, 4 — anhydryty chmurzyste, 5 — anhydryty laminowane, 6 — anhydryty warstwowane, 7 — anhydryty gruzłowe i gruzłowo-mozaikowe, 8 — brekcje anhydrytowo-ilaste, 9 — biolaminoidy, 10 — iłowce, mułowce z siarczanami, 11 — dolomity z siarczanami, 12 — interwał nierdzeniowany; pozostałe objaśnienia w tabeli 1



Sabkha facies: sulphate(1) carbonate-sulphate(2) siliciclastic-sulphate(3) carbonate-siliciclastic(4) siliciclastic(5)

Salina facies (6)

(A) – (D) lithotypes of the Upper Anhydrite anhydrites, which is a transitional facies between sulphate and halite rocks (cf. A. Kasprzyk, 1992). This variety is distinguished because of abundant halite cement and the importance of porosity due to dissolution (Pl. I, Fig. 14). The rock is fragile and crumbles when strongly impregnated with halite. Halite crystals are up to 2 cm in diameter, and aggregated into irregular clusters or bands within the anhydrite host rock contaminated with dolomicrite and organic matter. Fairly well preserved pseudomorphs after selenite crystals are typical (Pl. I, Fig. 14).

In the southern region, the Main Anhydrite does not exceed 3.3 m in thickness and appears only locally (Tumlin Podgrodzie IG 1, Goleniawy IG 1, Jaworze IG 1) above the microbialites of the Platy Dolomite (Ca3) (Fig. 4). It is composed of secondary gypsum largely contaminated with pelitic-dolomite-organic material which occurs dispersed or in streaks, diffuse bands, and interbeds. Characteristic structures of sulphates are: nodular, banded and nodular-mosaic. Grading, cross-lamination, load structures, deformation lamination, and biolamination are common features of the pelitic-dolomitic matrix and interbeds.

The top erosional surface of the Main Anhydrite is overlain by grey claystones and sandy mudstones, commonly cross-laminated, ascribed to the Top Terrigenous Series (PZt), which terminates the sequence of Zechstein deposits in the studied sections (Z. Kowalczewski, S. Zbroja, in press).

INTERPRETATION OF SEDIMENTARY ENVIRONMENT

A general zonal distribution of the sedimentary facies in the peripheral parts of the Zechstein basin was determined by complex interactions resulting from basin configuration, salt and water budgets, and the impact of local floods and sediment accretion, all affected by climatic and tectonic conditions (e. g. T. M. Peryt, 1984; Z. Kowalczewski, M. Rup, 1989; R. Wagner, 1994; A. Kasprzyk, 1994).

Basin morphology was one of the major controlling factors. In peripheral parts of the evaporitic basin the topographic configuration (inherited from the deposition of the Upper Rotliegendes) favoured continual free-flow water exchange between the shelf and the basin centre. In the area north-west of the Holy Cross Mts., the topographic pattern was related directly to three distinct structural elements: (1) the Palaeozoic core of the Holy Cross Mts. (the Holy Cross Mts. Land), (2) the Włoszczowa Elevation, and (3) the Radom–Kraśnik Upland, which separated Podlasie Bay from the Holy Cross Mts. Terrace (R. Wagner, 1988; A. Morawska, 1992). These structural elements restricted sea-water incursions and affected the facies distribution (Fig. 5). During Zechstein deposition, a system of widespread sulphate platforms and adjacent basins formed north-west of the Holy Cross Mts. The

Fig. 4. Stratigraphic-facies cross-section through the Zechstein Anhydrites along the line A — A'

Przekrój stratygraficzno-facjalny poziomów anhydrytowych cechsztynu wzdłuż linii A — A'

Kompleks sebhy — facje: 1 — siarczanowa, 2 — węglanowo-siarczanowa, 3 — silikoklastyczno-siarczanowa, 4 — węglanowo-silikoklastyczna, 5 — silikoklastyczna; 6 — salina; A–D — litotypy anhydrytu górnego

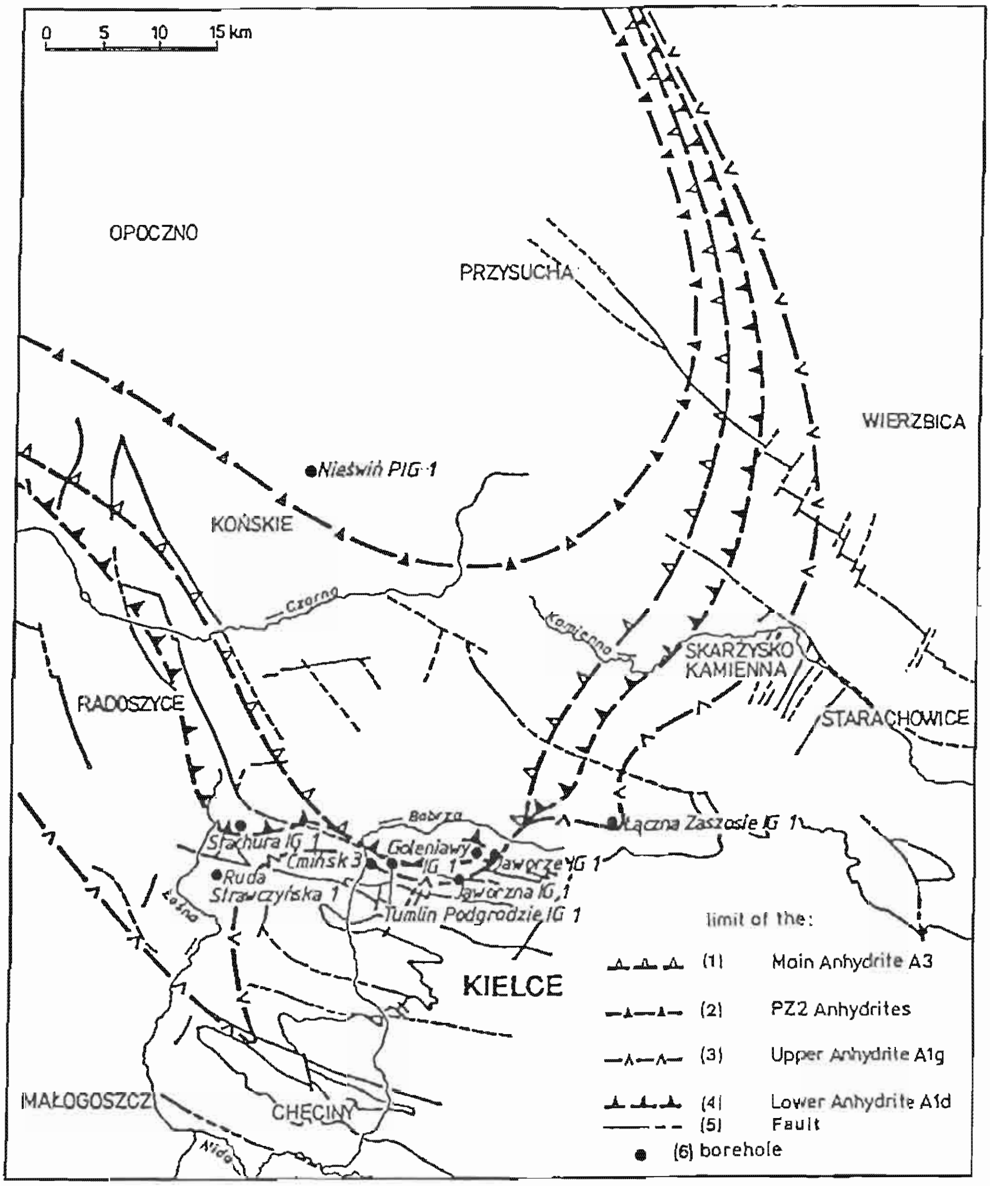


Fig. 5. Extent of the Zechstein Anhydrites in the area north-west of the Holy Cross Mts.

Zasięg poziomów anhydrytowych cechsztynu w północno-zachodnim obrzeżeniu Gór Świętokrzyskich

1 — zasięg anhydrytu głównego A3, 2 — zasięg anhydrytów PZ2, 3 — zasięg anhydrytu górnego A1g, 4 — zasięg anhydrytu dolnego A1d, 5 — uskok, 6 — otwór wiertniczy

topographic configuration of the basement was important for the formation of the Zechstein Anhydrites.

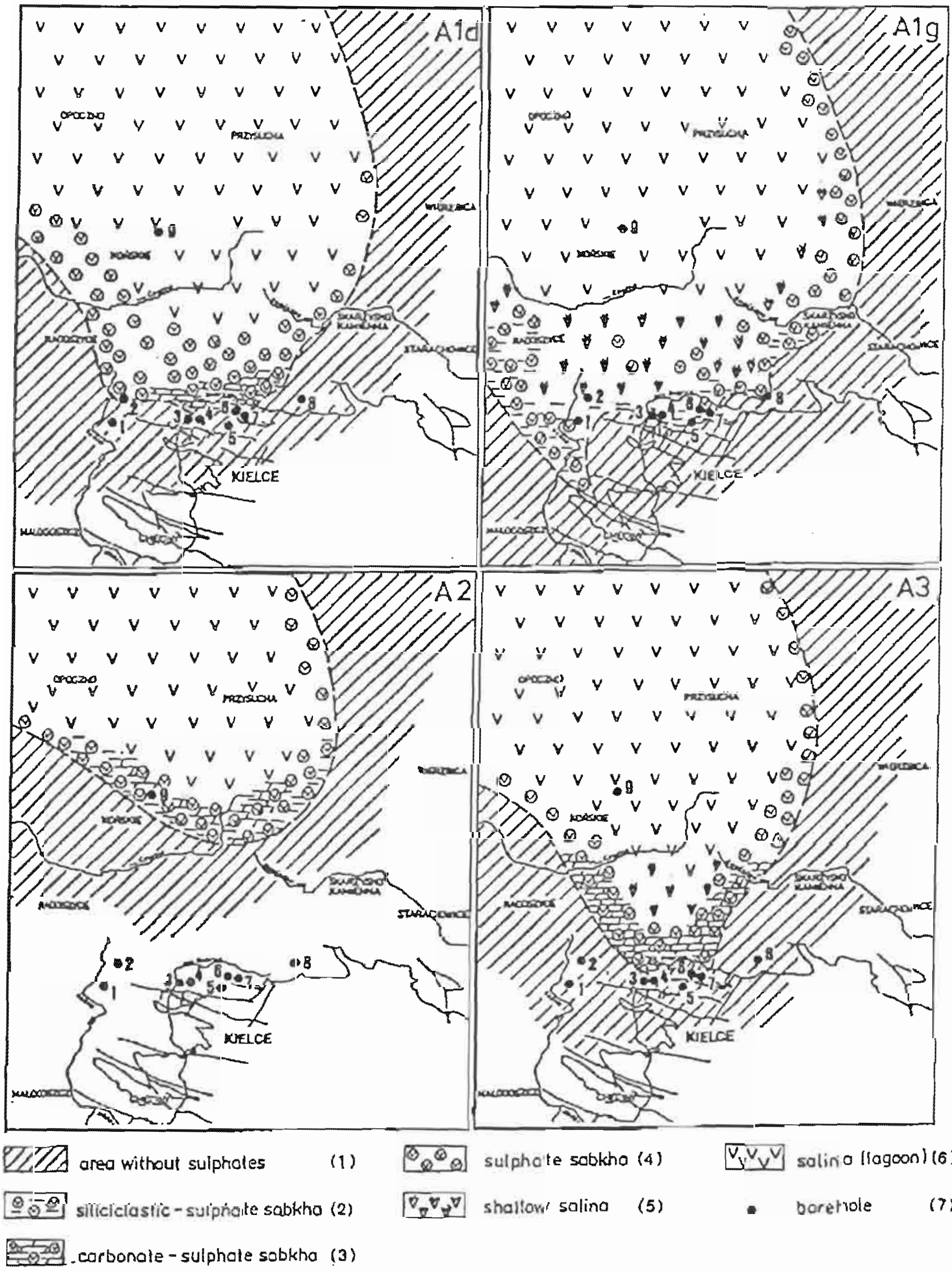
The facies variety of sulphate deposits (Figs. 2 and 3; Pl. I, Figs. 8–14) reflects distinct sedimentary conditions in the study area. They comprise subaqueous (relatively deep-water and shallow-water) as well as subaerial settings (Figs. 4, 6 and 7) as may be interpreted by comparing the facies with recent evaporitic environments.

Studies of coastal salinas and sabkhas (e.g. A. V. Arakel, 1980; F. Orti Cabo *et al.*, 1984; B. W. Logan, 1987; B. H. Purser *et al.*, 1987; C. G. S. C. Kendall, J. K. Warren, 1988) allow more detailed reconstruction of sedimentary conditions during the sulphate deposition in the peripheral areas of the Zechstein basin (Fig. 6). During low stands of sea level the sabkha complex developed in the peritidal zone of the basin margin (Fig. 7). The sabkha complex is defined by great facies diversity, that comprises siliciclastic, carbonate and sulphate deposits formed in subaerial settings and in ephemeral hypersaline ponds of the coastal flats. Characteristic sedimentary structures are: biolamination, stromatolites, sulphate nodules and enteroliths, erosional surfaces, dessication cracks. A stromatolitic and nodular facies developed in extremely shallow-water to subaerial environments, whereas bottom-nucleated selenites grew in stratified and high salinity lagoons (salinas) a few metres deep (Fig. 7). All these settings were episodically affected by incursions of sea-water as well as brackish-water inflow by runoff from the hinterland. Selenites developed characteristic morphological forms: grass-like and *cavoli* horizons, giant intergrowths, sabre-like crystals, all well known from recent salinas of southern and western Australia and south-eastern Spain (J. K. Warren, 1982; F. Orti Cabo *et al.*, 1984; B. W. Logan, 1987). Physical accretion of clastic deposits with a common assemblage of structures: cross-lamination, ripples, grading, prevailed in periods of high-water dynamics. Tectonic-eustatic activity, along with increased subsidence, promoted gravity-controlled basinward redistribution of clastic sulphate deposits by mass flows (T. M. Peryt *et al.*, 1993) (Fig. 7).

DIAGENESIS

Evaporites are easily affected by diagenetic alterations which lead to partial or complete obliteration of the original structure of the rocks (A. C. Kendall, 1992). The effects of these alterations, including dissolution-reprecipitation, displacement and replacement growth, are especially strongly manifested in the Zechstein section, where the only sulphates identified in the cores studied are anhydrite and secondary gypsum.

Preservation of sedimentary structures and pseudomorphs after crystalline fabrics of primary gypsum facies within the anhydrites (Pl. I, Figs. 9, 10, 12–14) indicate that gypsum was the main original sedimentary product, which was transformed to anhydrite during burial diagenesis. Alteration processes are attributed to high burial temperature and (or) pressure (cf. R. Langbein, 1979). Locally, anhydrites have been partly or completely hydrated (or rehydrated) owing to increased migration of meteoric waters, initiated by tectonic activity and (or) uplift and exhumation. Pseudomorphs after crystalline and sedimentary structures of original facies in anhydrites and secondary gypsum are useful for the interpretation of sedimentary evolution in the peripheral part of the Zechstein evaporitic basin.


A1d
A1g
A2
A3
KIELCE
area without sulphates (1)
siliciclastic - sulphaite sabkha (2)
carbonate - sulphate sabkha (3)
sulphate sabkha (4)
shallow salina (5)
salina (lagoon) (6)
borehole (7)

EVOLUTION OF SEDIMENTATION

A regional eustatic drop in sea level, which followed from synsedimentary tectonic movements and from increased evaporation in extreme arid climate, preceded the deposition of evaporites in the Zechstein basin (e.g. R. Wagner, 1994). Lithofacies and sedimentary studies show that the depositional pattern of Zechstein evaporites was complex and resulted from interaction of several factors. Among them the most important were rate of precipitation, sedimentary accretion, subsidence (both local and regional), and tectonic-eustatic fluctuations of sea level; all of these determined the sedimentary evolution in a basin system of physiographically differentiated palaeoenvironments.

PZ1 ANHYDRITES

A rapid sea-level drop at the end of deposition of the Zechstein Limestone (T. M. Peryt, L. Antonowicz, 1990; R. Wagner, 1994) led to the exposure and denudation of most of the peripheral areas. At the beginning of sulphate deposition, a system of widespread sabkha-like coastal flats was developed north-west of the Holy Cross Mts. (Fig. 6). Under variable sedimentary conditions physical and biogenic sediment accretion alternated with chemical precipitation. Resulting sulphate deposits of the Lower Anhydrite form onlapping associations of sulphate, sulphate-carbonate and sulphate-siliciclastic facies of the sabkha complex (Fig. 4). There was a distinct increase in the amount of terrigenous material toward the south, with a dominant continental sedimentary regime close to the Holy Cross Mts. Land. Accretion of siliciclastic deposits was the most intense on the landward side and gradually expanded over the entire area of the coastal plain. Resulting siliciclastic deposits compose the Terrigenous Series (T1r) (Fig. 4).

During sabkha deposition at the extreme peripheries of the basin, subaqueous sulphate sedimentation took place in the shallow-water lagoons (salinas) of more distal areas (Fig. 6). The progradation of sulphate deposits, along with the transgression, led to development of the sulphate platform attached to the carbonate platform of the Zechstein Limestone (R. Wagner, 1994). Consequently, a thick sulphate complex, now preserved as massive and mosaic anhydrites with pseudomorphs after selenites, formed in the northern area (Nieświń PIG 1) (Fig. 2). Flaser and banded anhydrites with graded laminae and layers in the upper A1d section (Pl. I, Fig. 10) are typical slope deposits of the deeper parts of the basin (cf. W. Schlager, H. Bolz, 1977; T. M. Peryt *et al.*, 1993; A. Kasprzyk, 1992). Accordingly, these facies may be used to interpret the local palaeogeographic pattern by distinguishing the

Fig. 6. Facies and palaeogeography of the Zechstein Anhydrites (A1d, A1g, A2, and A3) in the area north-west of the Holy Cross Mts.

1–9 — boreholes: *1* — Ruda Strawczyńska 1, *2* — Stachura IG 1, *3* — Ćmińsk 3, *4* — Tumlin Podgrodzie IG 1, *5* — Jaworzna IG 1, *6* — Goleniawy IG 1, *7* — Jaworze IG 1, *8* — Łączna Zaszosie IG 1, *9* — Nieświń PIG 1

Facje i paleogeografia poziomów anhydrytowych cechsztynu (A1d, A1g, A2 i A3) w północno-zachodnim obrzeżeniu Gór Świętokrzyskich

1 — obszary bez osadów siarczanowych, 2 — sebha silikoklastyczno-siarczanowa, 3 — sebha węglanowo-siarczanowa, 4 — sebha siarczanowa, 5 — płytka laguna, 6 — laguna, 7 — otwór wiertniczy; *1–9* — nazwy otworów wiertniczych — patrz tekst angielski

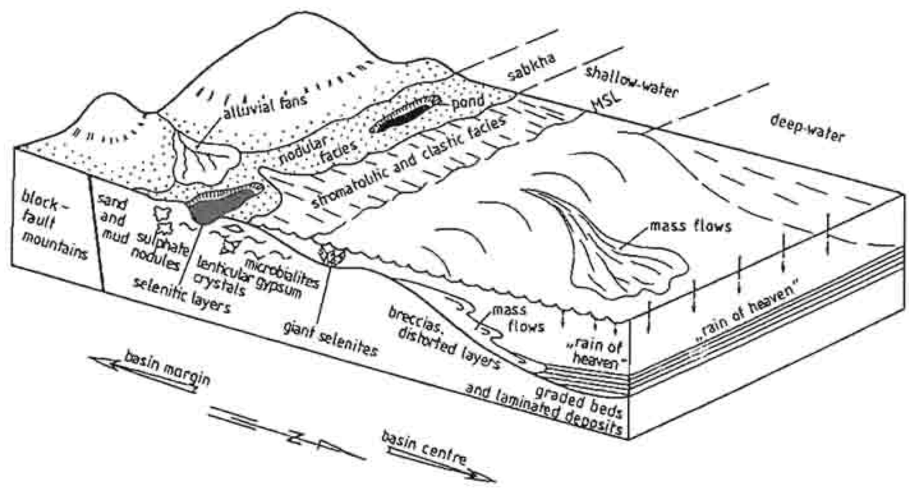


Fig. 7. Scheme of sedimentary environments of the Zechstein sulphate deposits in the area north-west of the Holy Cross Mts.

Schemat środowisk sedymentacyjnych utworów siarczanowych cechsztynu w północno-zachodnim obrzeżeniu Gór Świętokrzyskich

sulphate platforms and slopes in the peripheral parts of the Zechstein basin. Along with the progradation of sulphate platforms, formation of halite deposits of PZ1 started in rapidly subsiding local basins, presumably due to water-column stratification.

Further lowering of the sea level stopped the development of the sulphate platform and led to the exposure and intensive denudation of a large section of the southern region (Z. Kowalczewski, L. Lenartowicz, 1975). The increased input of terrigenous material by torrential floods and streams from the hinterland resulted in the formation of a thick siliciclastic complex (T1r) covering the sulphate deposits of the Lower Anhydrite or directly overlying the Zechstein Limestone (Fig. 4).

A marine transgression resulted in renewed evaporite accretion in the southern region, where a system of coastal flats developed early during the sulphate deposition of the Upper Anhydrite (Fig. 6). Only locally, in the extreme marginal areas, continuous siliciclastic deposition took place (M. Rup, 1985). The environmental system of the Upper Anhydrite comprised two main settings (Fig. 4): (1) sabkha-like coastal flats, where different siliciclastic, carbonate and sulphate facies display a distinct lateral distribution, and (2) lagoons or salinas with continuous subaqueous sulphate deposition.

The sequence of the Upper Anhydrite in the north-west of the Holy Cross Mts. is transgressive-regressive, similar to other areas in the peripheral parts of the Zechstein basin (T. M. Peryt, 1990, 1991; A. Kasprzyk, 1992; T. M. Peryt, A. Kasprzyk, 1992). In the southern region, breccias of BrA1 (Pl. I, Fig. 11) are thin or lacking. Where present they are overlain by a platform sulphate facies (unit *C*) (Fig. 4; Pl. I, Fig. 12). This succession evidences the progressive sulphate deposition which, in the peripheral part of the evaporite basin, took place along with transgression. Breccias formed during the flooding phase following the sea level low stands, according to the model presented by B. W. Sellwood and R. E. Netherwood (1984) for the Miocene evaporites of the Gulf of Suez. There are, however, alternative explanations for the breccia formation in the A1g section (discussion in: S. Lorenc, 1975; A. Kasprzyk, 1992, 1994); this will be the subject of a separate paper by the author.

Towards the end of the deposition of the Upper Anhydrite, a sea level drop led to the exposure of the major part of the southern region. Nodular and nodular-mosaic facies (unit *D*) of the upper A1g section formed under extremely shallow-water to subaerial conditions in a coastal sabkha (Fig. 4). Deposition of terrigenous clastic material in fluvial and lacustrine environments prevailed on the basin margin.

PZ2 ANHYDRITES

At the end of the deposition of the Main Dolomite, a regional eustatic drop in sea level favoured evaporite precipitation. During the formation of the Basal Anhydrite the southern region was exposed and intensively denudated, whilst in the northern region (Nieświń PIG 1) sedimentation took place in extremely shallow-water to subaerial settings (Fig. 6; Pl. I, Fig. 13). A facies association expresses an unstable sedimentary regime in a basin margin where a complex salina-sabkha system developed early during the evaporite sedimentation of the PZ2 cycle.

Fine differences in sedimentary accretion and subsidence rate between the marginal and more distal parts of the basin resulted in formation of a system of isolated hypersaline lagoons over a large area of the northern region where continuous subaqueous sulphate deposition created a vast sulphate platform (Fig. 6).

Intense siliciclastic deposition of the Terrigenous Series T2r started when changes in climate and (or) basin configuration, along with regression, resulted in a brackish-water inflow by runoff from the hinterland. The occurrence of sulphate facies of the Screening Anhydrite (A2r), overlying the Terrigenous Series (T2r) in the upper PZ2 section (Fig. 3), indicates renewed sea-water influx related with the initial episode of the PZ3 transgression.

PZ3 ANHYDRITES

In the southern region, deposition of the Main Anhydrite was limited to particular areas, where microbial and nodular facies developed in extremely shallow-water to subaerial environments of the carbonate-sulphate sabkha system (Figs. 4–6). Perhaps deposition expanded over a larger area but later denudation resulted in the complete removal of sediments. Sulphate deposition in shallow-water hypersaline lagoons prevailed in the northern region (Fig. 6), where bottom-nucleated selenitic facies developed characteristic crystalline structures, now perfectly preserved as pseudomorphs within the anhydrites (Pl. I, Fig. 14). In the deeper, more subsided parts of the basin, halite started to precipitate in local salt pans, along with continuous deposition of sulphates.

At the end of sulphate deposition, sea level fell again. Intense redeposition of siliciclastic material by floods and streams led to formation of the Top Terrigenous Series PZt, which terminates the sequence of the Zechstein in the basin margin north-west of the Holy Cross Mts. (Fig. 4).

Further sediment progradation of the PZ4 cycle was limited to the extreme distal areas where a system of playa-like coastal flats and ephemeral hypersaline ponds formed (Z. Kowalczewski *et al.*, 1993; R. Wagner, 1994). In an unstable physicochemical regime, owing to changes in climate, physical accretion was accompanied by chemical precipitation of sulphates and halites.

CONCLUSIONS

The main factors controlling palaeoenvironmental conditions of evaporite deposition in the peripheral parts of the Zechstein basin were: subsidence, tectonic and eustatic activity, evaporite drawdown and sedimentary overburden — all influencing the short-term evolution of the basin system (cf. T. M. Peryt, 1984; R. Wagner, 1988, 1994; Z. Kowalczewski, M. Rup, 1989). Of these, synsedimentary tectonic movements were the determining agent in the area north-west of the Holy Cross Mts., where the facies distribution reflects physiographically differentiated palaeoenvironments.

One response to the tectonic activity, accompanied by regional, eustatic fluctuations of sea level and changes in climate (cf. T. M. Peryt, 1984; Z. Kowalczewski, M. Rup, 1989; R. Wagner, 1994), was major cyclicity during Zechstein deposition. On the basis of interpreted sedimentary evolution it is shown that sea level fell several times during evaporite formation. In peripheral areas of the basin even slight sea level fluctuations resulted in important changes in the sedimentary regime that are expressed in facies variations. These phenomena were the main causes of cyclic sedimentation of evaporites in the peripheral areas of the Zechstein basin.

Acknowledgements. I wish to express my gratitude to Doc. Dr. hab. Zbigniew Kowalczewski and Dr. hab. Ryszard Wagner for inspiring comments and remarks on earlier versions of this paper. I also thank Stanisława Zbroja and Maria Kuleta M. Sc., for helpful discussion, Hanna Stec for making the drawings and Janina Modrzejewska for hand specimen photographs.

This study was carried out within project no. 6.20.1511.00.0.

Oddział Świętokrzyski
Państwowego Instytutu Geologicznego
Kielce, ul. Zgoda 21
Received: 24.05.1995

REFERENCES

ARAKEL A. V. (1980) — Genesis and diagenesis of Holocene sediments in Hutt and Leeman lagoons, Western Australia. J. Sed. Petrol., 50, p. 1305–1326, no. 4.

KASPRZYK A. (1992) — Charakterystyka litofacjalna poziomów anhydrytowych cechsztynu perykliny Żar. Prz. Geol., 40, p. 233–241, no. 4.

KASPRZYK A. (1994) — Charakterystyka litofacjalna poziomów anhydrytowych cechsztynu północnego obrzeżenia Gór Świętokrzyskich (otwory: Tumlin Podgrodzie IG 1, Nieświń PIG 1). Arch. Państw. Inst. Geol. Kielce.
KENDALL A. C. (1992) — Evaporites and diagenesis: Quantitative diagenesis: Recent developments and applications to reservoir geology — abstracts, North Atlantic Treaty Organization (NATO), Advanced Study Institute, University of Reading.
KENDALL C. G. S. C., WARREN J. K. (1988) — Peritidal evaporites and their sedimentary assemblages. In: Evaporites and hydrocarbons (ed. B. C. Schreiber), p. 66–138. Columbia Univ. Press. New York.
KOWALCZEWSKI Z., LENARTOWICZ L. (1975) — The Permian sequence in the north-western part of the Świętokrzyskie Mountains (in Polish with English summary). Kwart. Geol., 19, p. 597–622, no. 3.
KOWALCZEWSKI Z., RUP M. (1989) — Zechstein rocks of the Góry Świętokrzyskie (in Polish with English summary). Biul. Państw. Inst. Geol., 362, p. 5–39.
KOWALCZEWSKI Z., ZBROJA S. (in press) — Góry Świętokrzyskie (Holy Cross) Mountains. In: The Permian system in Poland (ed. R. Wagner). Państw. Inst. Geol. Warszawa.
KOWALCZEWSKI Z., LENARTOWICZ L., ZBROJA S., KULETA M., HERMAN G., FIJAŁKOWSKA A., MALEC J. (1990) — Badania geologiczne permu w północno-zachodniej części Gór Świętokrzyskich w aspekcie poszukiwań rud Cu, Pb, Zn, Fe i V. Arch. Państw. Inst. Geol. Kielce.
KOWALCZEWSKI Z., WAGNER R., WOIŃSKI J. i in. (1991) — Dokumentacja wynikowa otworu Nieświń PIG 1. Arch. Państw. Inst. Geol. Kielce.
KOWALCZEWSKI Z., WAGNER R., WOIŃSKI J. i in. (1993) — Dokumentacja wynikowa otworu Opoczno PIG 2. Arch. Państw. Inst. Geol. Kielce.
LANGBEIN R. (1979) — The Zechstein sulphates: the state of the art. Lect. Notes Earth Sc., 10, p. 143–188.
LOGAN B. W. (1987) — The MacLeod Evaporite Basin. Western Australia. Am. Ass. Petrol. Geol. Mem., 44, Tulsa, Oklahoma.
LORENC S. (1975) — Petrography and facies differentiation in the Werra limestones and anhydrite rocks, Fore-Sudetic Monocline, SW Poland (in Polish with English summary). Geol. Sudet., 10, p. 59–103, no. 1.
MORAWSKA A. (1992) — Permian north of the Holy Cross Mts. (Central Poland) (in Polish with English summary). Prz. Geol., 40, p. 216–223, no. 4.
ORTI CABO F., PUEYO MUR J. J., GEISLER-CUSSEY D., DULAU N. (1984) — Evaporitic sedimentation in the coastal salinas of Santa Pola (Alicante, Spain). Rev. Inst. Inv. Geol., 38/39, p. 164–220.
PERYT T. M. (1984) — Sedimentation and early diagenesis of the Zechstein Limestone in Western Poland (in Polish with English summary). Pr. Państw. Inst. Geol., 109, p. 1–80.
PERYT T. M. (1990) — The Zechstein Upper Anhydrite (A1g) of the Polish part of the Peri-Baltic syneclise. Biul. Państw. Inst. Geol., 364, p. 5–29.
PERYT T. M. (1991) — Lower and Upper Werra Anhydrite in the Leba elevation area (northern Poland): Lithofacies and paleogeography. Zbl. Geol. Paläont., Teil I, p. 1189–1200, no. 4.
PERYT T. M., ANTONOWICZ L. (1990) — Facies and paleogeography of the Zechstein Lower Werra Anhydrite (A1d) in Poland (in Polish with English summary). Prz. Geol., 38, p. 173–180, no. 4.
PERYT T. M., KASPRZYK A. (1992) — Stratigraphy and sedimentary history of the Zechstein (Upper Permian) of the North Sudetic Trough (SW Poland) (in Polish with English summary). Prz. Geol., 40, p. 457–467, no. 8.
PERYT T. M., ORTI F., ROSELL L. (1993) — Sulfate platform-basin transition of the lower Werra Anhydrite (Zechstein, Upper Permian), western Poland: facies and petrography. J. Sed. Petrol., 63, p. 646–658, no. 4.
PURSER B. H., SOLIMAN M., M'RABET A. (1987) — Carbonate, evaporite, siliciclastic transitions in Quaternary rift sediments of the northwestern Red Sea. Sed. Geol., 53, p. 247–267
RUP M. (1985) — Korelacja osadów permu górnego w regionie świętokrzyskim. Arch. Państw. Inst. Geol. Kielce.
SCHLAGER W., BOLZ H. (1977) — Clastic accumulation of sulfate evaporites in deep water. J. Sed. Petrol., 47, p. 600–609, no. 2.
SCHREIBER B. C. (1988) — Subaqueous evaporite deposition. In: Evaporites and hydrocarbons (ed. B. C. Schreiber), p. 182–255. Columbia Univ. Press. New York.
SELLWOOD B. W., NETHERWOOD R. E. (1984) — Facies evolution in the Gulf of Suez area: sedimentation history as an indicator of rift initiation and development. Mod. Geol., 9, p. 41–68.
SONNENFELD P. (1984) — Brines and evaporites. Academic Press. Orlando.
WAGNER R. (1988) — The evolution of the Zechstein Basin in Poland (in Polish with English summary). Kwart. Geol., 32, p. 33–52, no. 1.
WAGNER R. (1994) — Stratigraphy and evolution of the Zechstein Basin in the Polish Lowland. Pr. Państw. Inst. Geol., 146.

WAGNER R., PERYT T. M., PIĄTKOWSKI T. (1978) — Ewolucja cechsztyńskiego basenu sedymentacyjnego w Polsce. In: Atlas litofacjalno-paleogeograficzny permu obszarów platformowych Polski. Inst. Geol. Warszawa.
WARREN J. K. (1982) — The hydrological setting, occurrence and significance of gypsum in late Quaternary salt lakes in South Australia. Sedimentology, 29, p. 609–637.
WARREN J. K., KENDALL C. G. S. C. (1985) — Comparision of sequences formed in marine sabkha (subaerial) and saline (subaqueous) setting — modern and ancient. Am. Ass. Petrol. Geol. Bull., 69, p. 1013–1023.
ZBROJA S. (1990) — Wykształcenie litologiczne osadów cechsztynu. In: Badania geologiczne permu w północno-zachodniej części Gór Świętokrzyskich. Arch. Państw. Inst. Geol. Kielce.

Alicja KASPRZYK

POZIOMY ANHYDRYTOWE CECHSZTYNU W NW OBRZEŻENIU GÓR ŚWIĘTOKRZYSKICH (GÓRNY PERM, CENTRALNA POLSKA): FACJE I PALEOGEOGRAFIA

Streszczenie

Obszar północno-zachodniego obrzeżenia Gór Świętokrzyskich wchodzi w skład peryferyjnej części zbiornika cechsztyńskiego (fig. 1), co znajduje odzwierciedlenie w niepełnym rozwoju sedymentacji cyklicznej utworów ewaporatowych cyklotemów PZ1, PZ2, PZ3 i PZ4 oraz dużym udziale skał klastycznych (fig. 2, tab. 1). Analiza wykształcenia litofacjalnego poziomów anhydrytowych w wybranych otworach wiertniczych pozwala wyróżnić dwa rejony o nieco odmiennym wykształceniu utworów cechsztyńskich i odrębnie przebiegającym procesie sedymentacji: południowy (tzw. bliskie obrzeżenie permsko-mezozoiczne Gór Świętokrzyskich) i północny (tzw. obrzeżenie dalekie) (fig. 2, 3).

W obrzeżeniu bliskim anhydryt dolny jest wykształcony jedynie lokalnie jako anhydryty gruzłowe i gruzłowo-mozaikowe, powstałe w środowisku sebhy. Sekwencja anhydrytu górnego obejmuje cztery litotypy (fig. 4). Rozpoczynają ją iłowce i mułowce, lokalnie skały węglanowe z siarczanami, lub utwory siarczanowe silnie zanieczyszczone. Ich rozwój, związany z nową transgresją morza, objął strefę brzeżną zbiornika. Wyżej w profilu występują brekcje anhydrytowo-ilaste, a ponad nimi gruby kompleks anhydrytów i gipsów wtórnych masywnych i mozaikowych. Utwory te powstały w środowisku płytkich, połączonych lagun (salin), tworzących system platformy siarczanowej. Sekwencję anhydrytu górnego kończą osady siarczanowo-węglanowo-silikoklastyczne o teksturach gruzłowych. Rozwój ich zachodził w warunkach częstych zmian reżimu fizykochemicznego, charakteryzujących zróżnicowane środowiska okołopływowe systemu sebhy paralicznej. Tym samym sekwencja anhydrytu górnego w północno-zachodnim obrzeżeniu Gór Świętokrzyskich ma charakter transgresywno-regresywny.

Na obszarze dalekiego obrzeżenia permsko-mezozoicznego Gór Świętokrzyskich utwory siarczanowe PZ1 reprezentują facje platformy siarczanowej i jej skłonu. W czasie rozwoju anhydrytów gruzłowo-mozaikowych cyklu PZ2 w środowisku przybrzeżnej sebhy, rozwiniętej w dalekim obrzeżeniu Gór Świętokrzyskich, strefa brzeżna — obejmująca obszar obrzeżenia bliskiego — była wynurzona i poddana intensywnej denudacji. Utwory siarczanowe poziomu A2r to osady inicjalnej transgresji cyklu PZ3, która objęła swym zasięgiem jedynie obrzeżenie dalekie (fig. 5). Na obszarze tym utwory siarczanowe anhydrytu głównego są wykształcone jako anhydryty gruzłowe — w części dolnej, oraz utwory siarczanowe laminowane i gruzłowo-mozaikowe — wyżej. Utwory te powstały w środowisku skrajnie płytkowodnym i subaeralnym systemu sebhy węglanowo-siarczanowej (fig. 6). W tym czasie w dalekim obrzeżeniu Gór Świętokrzyskich tworzyły się w zbiorniku typu laguny facje selenitowe, których charakterystyczne struktury krystaliczne dziś są zachowane w anhydrytach szkieletowych w formie pseudomorfoz.

Najpełniejsze wykształcenie i najszerszy zasięg mają utwory anhydrytu górnego (fig. 2, 5). Duże zróżnicowanie litofacjalne oraz bogaty inwentarz struktur sedymentacyjnych sekwencji siarczanowych (tabl. I, fig. 8–14) wskazują na zmienne warunki sedymentacji. Warunki te, zrekonstruowane na podstawie analogii do współczesnych środowisk ewaporacyjnych, reprezentują środowiska zarówno subakwalne (względnie głębokowodne i płytkowodne), jak i subaeralne (fig. 4, 6, 7).

PLATE I

Fig. 8. Nodular-mosaic anhydrite with dolomite matrix and a dense net of fibrous-gypsum veins; Lower Anhydrite; depth 376.8–377.0 m

Anhydryt gruzłowo-mozaikowy o matriks dolomitowym, gęsto żyłkowany gipsem włóknistym; anhydryt dolny; głęb. 376,8–377,0 m

Fig. 9. Dolomite (biopelmicrosparite) irregularly laminated, with sulphate nodules and impregnations, and with gypsum veins; clayey-organic laminae (dark) are distorted by sulphate nodules resembling pseudomorphs after lenticular and prismatic gypsum crystals (arrows); Lower Anhydrite; depth 379.65–379.80 m

Biopelmikrosparyt nieregularnie laminowany z gruzłami i impregnacjami siarczanowymi, gęsto żyłkowany gipsem; laminy ilasto-organiczne (ciemne) nieciągłe, lokalnie o przebiegu zaburzonym przez gruzły siarczanowe przypominające pseudomorfozy po soczewkowych i pryzmatycznych kryształach gipsu (strzałki); anhydryt dolny; głęb. 379,65–379,80 m

Fig. 10. Graded-bedded anhydrite with erosional base at the contact with mosaic anhydrite (lower part); Lower Anhydrite; depth 2264.35-2264.60 m

Anhydryt frakcjonalnie warstwowany, w dole ostro kontaktujący z anhydrytem mozaikowym; anhydryt dolny; głęb. 2264,35–2264,60 m

Fig. 11. Anhydrite-clayey breccia with lithoclasts of anhydrites (A), dolomites — laminated biopelmicrosparites (D), and claystones in clayey-carbonate-anhydrite matrix contaminated with organic matter; aligned components are oriented uniformly; note porosity within carbonate clasts; Upper Anhydrite, unit B; depth 1943.4–1943.5 m

Brekcja anhydrytowo-ilasta z litoklastami: anhydrytów (*A*), dolomitów — laminowanych biopelmikrosparytów (*D*) i iłowców w matriks dolomitowo-ilasto-anhydrytowym, zanieczyszczonym materią organiczną; wydłużone składniki wykazują jednokierunkową orientację; okruchy węglanów porowate; anhydryt górny, litotyp *B*; głęb. 1943,4–1943,5 m

Fig. 12. Mosaic anhydrite with pseudomorphs after *cavoli* selenites; note relicts of regular growth bands of former gypsum prisms (arrows); Upper Anhydrite, unit *C*; depth 343.20–343.35 m

Anhydryt mozaikowy z pseudomorfozami po wiązkach selenitowych typu *cavoli*; miejscowo czytelne relikty stref przyrostu pierwotnych kryształów pryzmatycznych gipsu (strzałki); anhydryt górny, litotyp *C*; głęb. 343,20–343,35 m

Fig. 13. Nodular-mosaic bedded anhydrite with alternation of layers: anhydrite (*A*) and dolomitic siltstone (*D*); small arcuate-shaped nodules are anhydrite pseudomorphs after prismatic gypsum crystals; Basal Anhydrite; depth 1894.65 m

Anhydryt gruzłowo-mozaikowy warstwowany z naprzemianległymi warstwami anhydrytu (*A*) i mułowca dolomitowego (*D*); drobne gruzły o zarysach ostrokrawędzistych to pseudomorfozy anhydrytu po kryształach pryzmatycznych gipsu; anhydryt podstawowy; głęb. 1894,65 m

Fig. 14. *Skeletal* anhydrite; pseudomorphs after selenite crystals outlined by dolomite-organic material; note dissolution pores after halite; Main Anhydrite; depth 1868.40–1868.55 m

Anhydryt szkieletowy; zarysy pseudomorfoz po kryształach selenitowych podkreślone ciemnymi smugami dolomitowo-organicznymi; liczne pory z rozpuszczania halitu; anhydryt główny; głęb. 1868,40–1868,55 m

Figs. 8, 9, 12 — Tumlin Podgrodzie IG 1 borehole; Figs. 10, 11, 13, 14 — Nieświń PIG 1 borehole

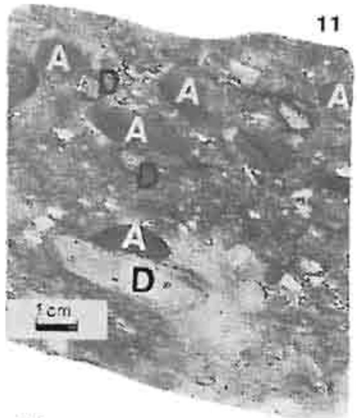
Fig. 8, 9, 12 — otwór wiertniczy Tumlin Podgrodzie IG 1; fig. 10, 11, 13, 14 — otwór wiertniczy Nieświń PIG 1

8

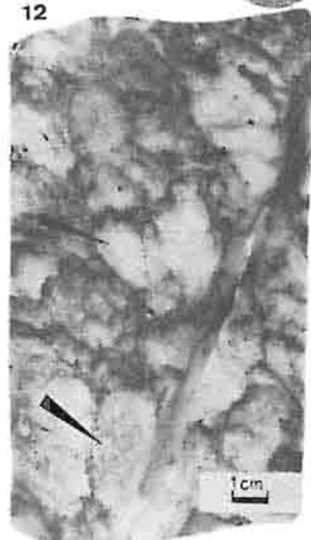
9

10

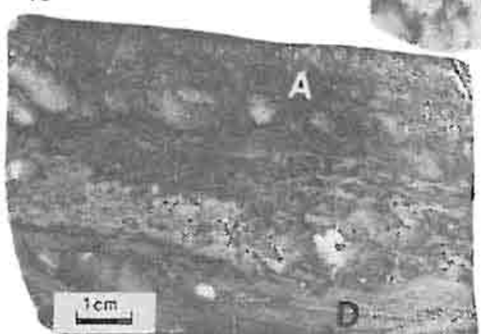
11



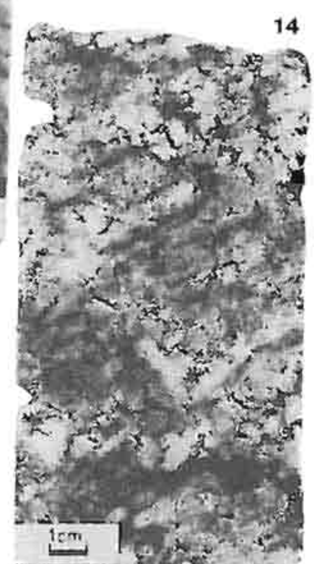
12



13



14



Alicja KASPRZYK — Zechstein Anhydrites NW of the Holy Cross Mts. (Upper Permian, central Poland): facies and palaeogeography