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The Middle Badenian rock salts in the Carpathian Foredeep — characteristics, origin and economic value

The salt deposits are a very significant (in volume, extent and economic value) compound of the Middle Miocene (Badenian) evaporitic formation in southern Poland. They occur in the axial part of the Carpathian Foredeep and are characterized by a complicated geological structure, resulting from varied sedimentary conditions and later tectonic deformations. This paper presents the general characteristics of these deposits and some current hypotheses on their origin and reasons for such varied development. Also the main rock salt deposits, documented within the foredeep, are described, and perspectives of their future exploitation and others ways of management discussed.

INTRODUCTION

The rock salt deposits, composing a significant part of the Middle Miocene (Badenian) evaporitic sulphur-bearing formation in southern Poland, is the second most important salt complex — in volume and extent — in Poland after the Upper Permian (Zechstein) evaporites. They originated within a forearc trough (the Carpathian Foredeep), one of the marginal basins of the Tethys Ocean during the Tertiary. This basin, the most northerly, comprised — with others — the Paratethys zone. It was separated from the southern basins by the active Carpathian arc, but from the North was bordered by uplifted older mountain chains and uplands of southern Poland. The basin evolution, controlled mainly by the orogenic activity of the Carpathians, determined the deposition style and extent of the evaporitic facies.

The aim of this paper is to present the general characteristics of these deposits, within which are located important mineral resources, a discussion on their origin, economic value and also on the perspectives of further exploitation and management.

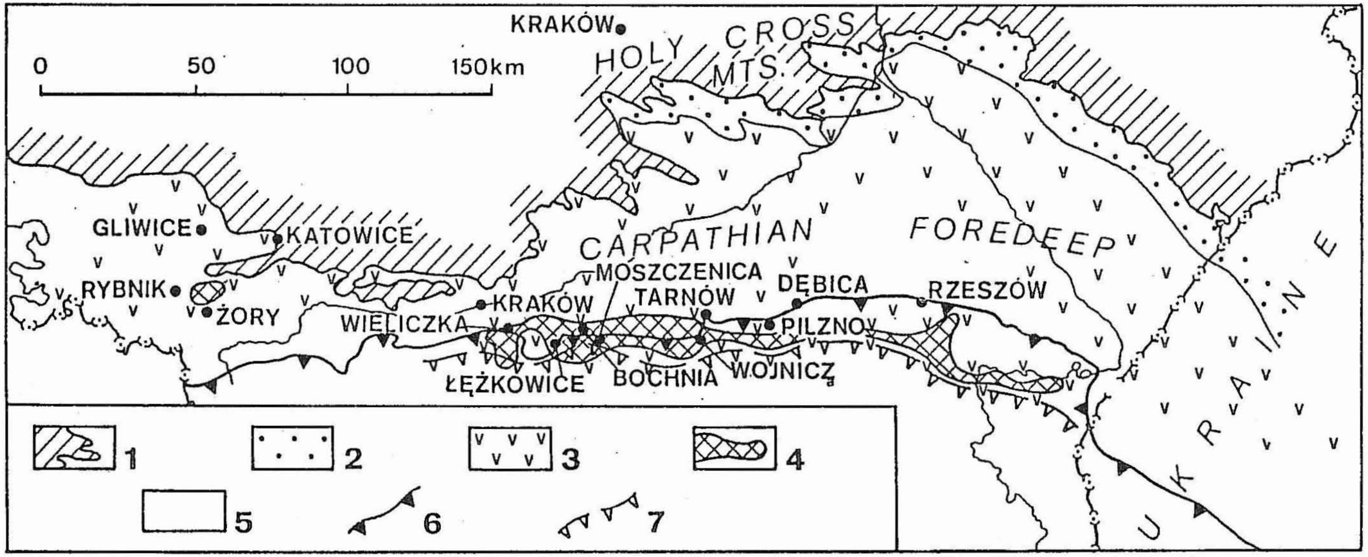

Fig. 1. Distribution of the Middle Badenian evaporites in the Carpathian Foredeep (after A. Garlicki, 1979, changed)

1 — under-Badenian deposits, 2 — carbonates of littoral facies, 3 — sulphates, 4 — chlorides, 5 — area without Badenian evaporites, 6 — recent Carpathian margin, 7 — position of the Carpathian margin during Middle Badenian

Rozmieszczenie ewaporatów środkowobadeńskich w zapadlisku przedkarpackim (według A. Garlickiego, 1979, zmienione)

1 — utwory podbadeńskie, 2 — węglany facji litoralnej, 3 — siarczany, 4 — chlorki, 5 — obszar pozbawiony ewaporatów badeńskich, 6 — obecne położenie brzegu Karpat, 7 — położenie brzegu Karpat w środkowym badenie

GEOLOGICAL PATTERN OF SALT DEPOSITS

Data about the geology of the Badenian salt formation in the Carpathian Foredeep come from boreholes, underground salt mines (Bochnia, Wieliczka, Moszczenica – Siedlec) and seismic sections.

The salt deposits occur over a distance of more than 200 km (Fig. 1), from the vicinity of Rybnik in the Upper Silesia area to Rzeszów in the Eastern Carpathians, occupying an area of 1500 km^2 (A. Garlicki, 1979). Salt thickness increases eastward, from 40 m nearby Wieliczka to over 200 m in the surroundings of Tarnów (A. Garlicki, 1974). The whole evaporitic series, including the intercalating sulphates and clastics, is 600 m thick in the central part (the Wieliczka – Dębica region) of the Carpathian Foredeep (R. Ney *et al.*, 1974).

Palaeontological findings date the origin of this evaporitic series at Middle Badenian, called "Wielician Substage" (A. Papp *et al.*, 1978), earlier defined as the "Bochenian Substage" (R. Ney *et al.*, 1974) or the "Opolian Substage" (A. Garlicki, 1970), both were included in the old Tortonian stage (A. Garlicki, 1974). The evaporites are underlain by clayey-sandy deposits of euxinic type (Figs. 2, 3), called the Skawina and Przemyśl Beds, with fauna and plant remains (A. Garlicki, 1979). The marly-sandy series overlying the evaporites are named the Chodenice Beds in the axial part of the foredeep (between Bochnia and Tarnów) and they are of a similar character (Figs. 2, 3). The salt deposits are now formally described as a lithostratigraphic unit of the Badenian stage in Poland (A. Garlicki, 1994) called the Wieliczka Formation and belong to the Wielician substage (see — the Table in *Preface*, this volume).

Most of the Miocene deposits from the southern part of the foredeep were thrust over the sediments from its northern side, due to the Upper Badenian and Sarmatian foldings in the Carpathians compressing the trough. This resulted in two tectonic units: the "autochthonous series", being formed *in situ*, and the "allochthonous series", which were moved from the South and overthrusted (A. Garlicki, 1968a, b, 1970, 1974, 1979; A. Gaweł, 1962; R. Ney et al., 1974; J. Poborski, K. Skoczylas-Ciszewska, 1963). Moreover, in the central and eastern parts of the foredeep the older flysch deposits of the Carpathians were thrusted over the folded Miocene sediments. The folding zone of evaporites varies in width, from 8–10 km between Siedlec and Tarnów up to several kilometres further eastward (between Tarnów and Dębica). The present southern boundary of the Carpathian Foredeep is of tectonic nature, which induces many difficulties in reconstructions of the primary extent of the Miocene deposits and facies (P. Karnkowski, 1994).

The studies of facies distribution of the Badenian evaporites (A. Garlicki, 1968*a, b*, 1970, 1973, 1974, 1979; R. Ney *et al.,* 1974) indicated (Fig. 1) that the chloride facies occupied the central, axial part of the Carpathian Foredeep, a characteristc feature for all fore-mountain troughs (A. C. Kendall, 1984). These deposits are bordered to the North and South by sulphate and carbonate facies. To the South the active slope of the folding Carpathian chain supplied large amounts of clastics that controlled evaporitic sedimentation. The influx of marine water into the foredeep came both from the SW (western Paratethys) and the SE (eastern Paratethys). Salt deposition took place at almost the same time over the whole area of the foredeep (A. Garlicki, 1968*a, b*, 1979). At that time the foredeep was divided into 3 minor basins (Fig. 4), partly separated by perpendicular

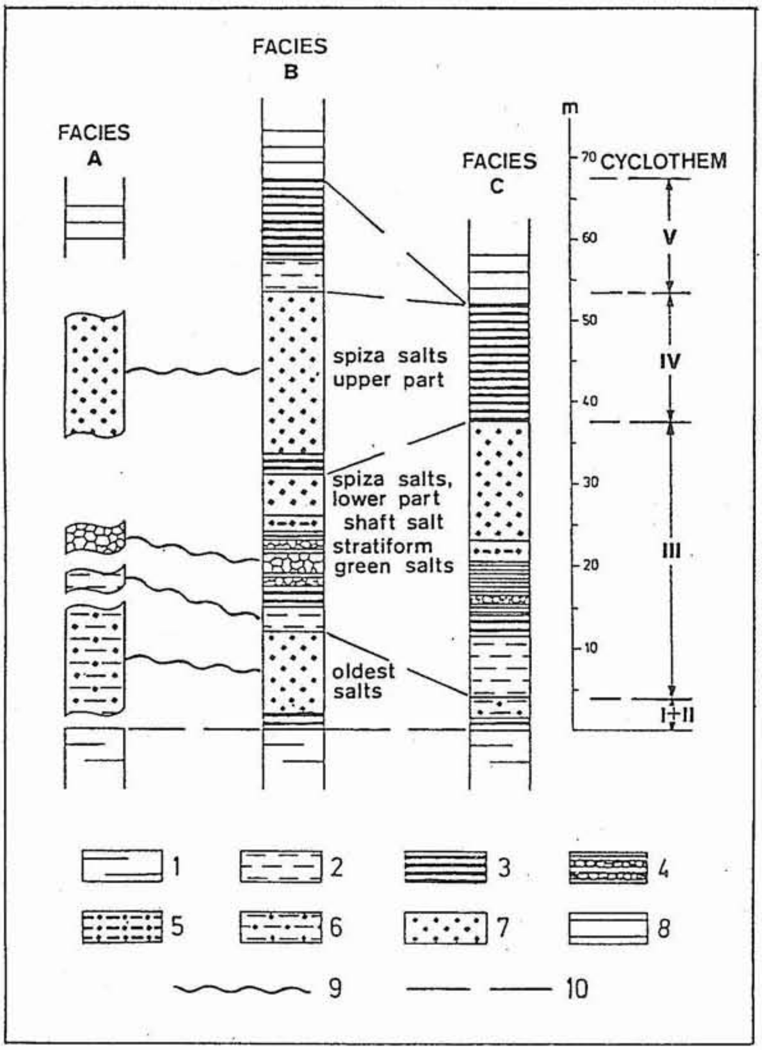

Fig. 2. Synthetic profiles of the salt deposits at Wieliczka (after A. Garlicki, 1979)
1 — underlying sediments (the Skawina Beds), 2 — claystones, siltstones and sandstones, 3 — claystones, siltstones and anhydritic (gypsum) sandstones, clayey-anhydritic shales, 4 — index horizon of clayey— anhydritic shales with huge salt crystals, 5 — anhydritic-salt shale, 6 — salt clay (zuber), 7 — rock salt, 8 — overlying sediments (the Chodenice Beds), 9 — probable unit correlation, 10 — correlation of cyclothems

Profile syntetyczne osadów solnych w Wieliczce (według A. Garlickiego, 1979)
1 — utwory spągowe (warstwy skawińskie), 2 — iłowce, mułowce i piaskowce, 3 — iłowce, mułowce i piaskowce anhydrytowe (gipsowe), łupki iłowo-anhydrytowe, 4 — poziom przewodni łupków iłowo-anhydrytowych z solą kryształową, 5 — łupek anhydrytowo-solny, 6 — ił solny (zuber), 7 — sól kamienna, 8 — utwory stropowe (warstwy chodenickie), 9 — przypuszczalna korelacja jednostek litologicznych, 10 — korelacja cyklotemów

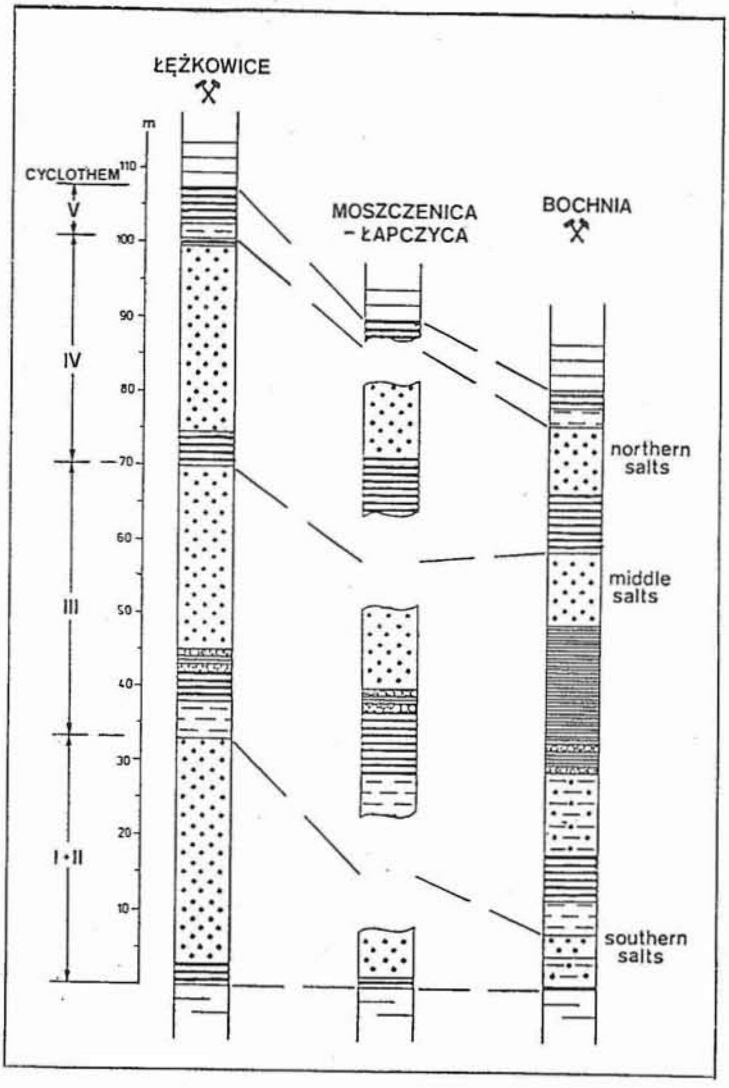

Fig. 3. Synthetic profiles of the salt series from the salt deposits at Łężkowice, Moszczenica – Łapczyca and Bochnia (after A. Garlicki, 1979)
Explanations as on Fig. 2
Syntetyczne profile serii solnej ze złóż soli Łężkowice, Moszczenica – Łapczyca, Bochnia (według A. Garlickiego, 1979)
Objaśnienia jak na fig. 2

basement elevations named: the Kraków sill, the Rzeszotary uplift, and the Lower San Anticlinorium. These subbasins had free and continuous water/brine exchange and are called: the Upper Silesia Basin (Rybnik – Żory region), the Wieliczka – Bochnia – Rzeszów

Basin, and the basin located eastward from Rzeszów, widely connected with the giant Ukrainian Basin. These basins were of varied depth: from 100–200 m in the Upper Silesia Basin up to 600–800 m in the area between Bochnia and Tarnów (A. Garlicki, 1979). Within them sulphates were accumulated on basin margins and/or sills/uplifts, and chlorides — in basin centres due to gravitational downflow of heavy salt brines.

Tectonic movements in the Carpathians significantly influenced evaporitic sedimentation (A. Garlicki, 1968*a, b*, 1979), involving variable subsidence rates of individual basin bottoms, changing basin shape and morphology (gradual basin compression and movement of the subsidence axis northward, closing and opening of the straits) and controlling the clastic supply from the emerged basin margins. All these factors determined the accumulation of salt sediments with varied contents of pelitic/clastic material (from "pure rock salt" to clayey salt and salty clay) and frequent interbeds of clastics and sulphates (Figs. 2, 3). The last ones, occurring within the salt deposits of the "autochthonous series", are 10–20 m thick and contain intercalations of claystone and siltstone (A. Garlicki, 1980). In the central part of the Carpathian Foredeep, in the lower part of the evaporitic series, these sulphates are developed as finely laminated anhydrites, but in the top — as nodular anhydrites. The sulphates known from the "allochthonous series" are strongly disturbed, with enterolithic and nodular structures.

Tectonically linked sea level changes were the main reason for the origin of 5 evaporitic depositional cycles (Figs. 2, 3), distinguished in the Badenian evaporitic formation in the foredeep centre (A. Garlicki, 1968*a*, *b*, 1979). These cycles, consist of such lithological units as: clastic-pelitic, sulphate and chloride members, having different extents and thicknesses, determined by contemporary palaeogeographic conditions. The third cycle has the maximum extent. The total time of the deposition of all cycles, including the periods of accumulation of clastic interbeds, was calculated as over 20 000 years (A. Garlicki, 1968*a*). Lastly, the same transgressive-regressive cycles were described within the marginal Badenian sulphates (A. Kasprzyk, 1994), suggesting tectonically induced eustatic sea level variations over the whole Carpathian Foredeep.

ORIGIN OF THE SALT DEPOSITS — A REVIEW OF HYPOTHESES

Some general geochemical and palaeontological data identify on the conditions of the Badenian salt deposition.

The determination of bromine content (20–67 ppm) in halites from the Wieliczka salt mine (A. Garlicki, J. Wiewiórka, 1981; A. Garlicki *et al.*, 1991) confirm the marine character and low concentration of primary Badenian salt brines (comp. data of A. G. Herrmann *et al.*, 1973). Rare higher values (221 ppm), noted in the salts of the oldest cycle from Wieliczka, document only a momentarily higher brine concentration. Bromine values of about 30 ppm, found in the salts from the Upper Silesia area (A. Garlicki *et al.*, 1991) indicate a significant brine dilution in this shallow basin. Generally the brine concentrations in the Badenian basin were to a low to induce the precipitation of K-Mg salts (potassium content in the Badenian salts is quite low, 70–84 ppm — A. Garlicki *et al.*, *op. cit.*).

The palaeobotanical data (A. Garlicki, 1979, with references) indicates that the climate throughout the Miocene was warm and dry, with mean annual temperature about 19°C.

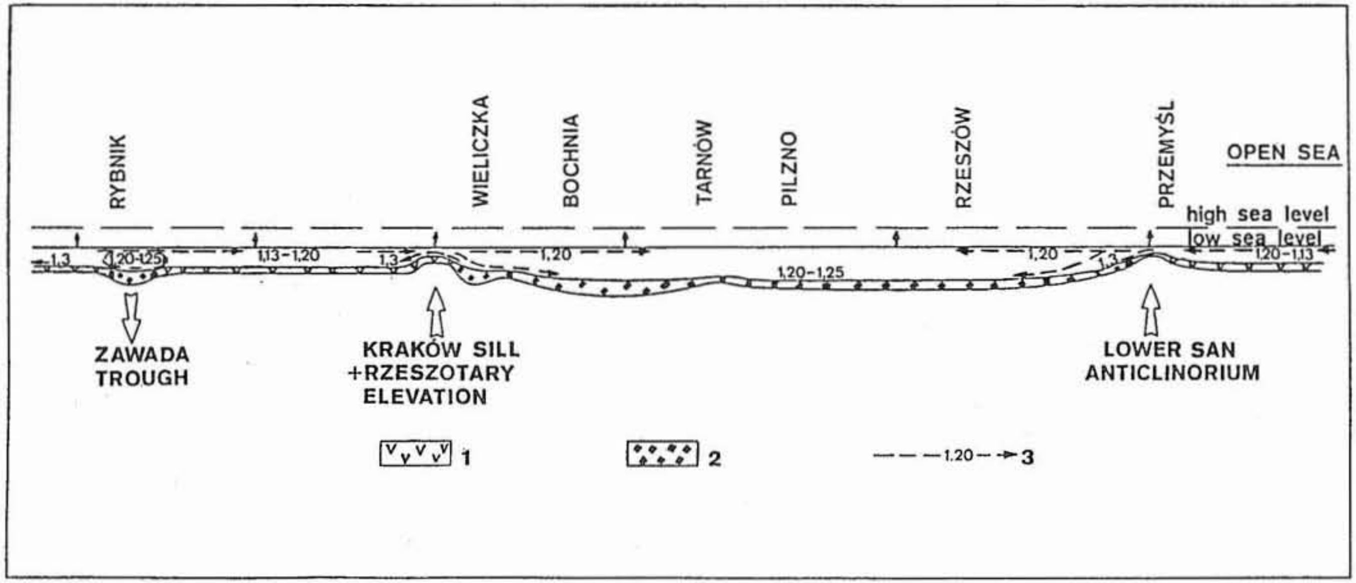

Fig. 4. Model of the evaporitic sedimentation in the Carpathian Foredeep during Middle Badenian (after A. Garlicki, 1979)
1 — sulphates, 2 — chlorides, 3 — calculated value of brine specific weight and flow direction
Model sedymentacji ewaporatowej w zapadlisku przedkarpackim w środkowym badenie (według A. Garlickiego, 1979)
1 — siarczany, 2 — chlorki, 3 — przypuszczalna wartość ciężaru właściwego solanek i kierunek przepływu

During the Middle Badenian it could have been humid (J. Liszkowski, 1989), but some cooling and aridization could have take place in the Upper Badenian and Sarmatian stages.

Most genetic interpretations are based on data from the best recognized profiles of Badenian salts at the historical Wieliczka salt mine, located in the western part of the central salt subbasin (Wieliczka – Bochnia – Rzeszów Basin — Figs. 1, 4). Evaporites there have high lithological variability (Fig. 2): from "pure" halites to salty clays; sandy-pelitic and sulphate interbeds; abundant sedimentary structures such as cross-beddings, ripples, graded bedding, scours, chevron and hopper halites; faunal and floral remains; numerous tectonic structures. These features involve many different interpretations of the origin of these sediments. In general, the profile of the Badenian evaporites at Wieliczka is subdivided into two units (A. Garlicki, 1968*a*; A. Gaweł, 1962; J. Poborski, K. Skoczylas-Ciszewska, 1963; J. Wiewiórka, 1974): the so-called "stratiform deposit", and the "boulder deposit", consisting of several lithological compounds such as oldest salt, spiza salt and schaft salt (Fig. 2). Three distinguished sequences of evaporites in the Wieliczka area (Fig. 2) are regarded as individual facies, deposited in various parts of the primary Wieliczka subbasin.

The rocks, composing the "stratiform deposit", accumulated in the northern, deeper and more distal part of the salt subbasin (W. Charysz, J. Wiewiórka, 1977; A. Gaweł, 1962; J. Poborski, K. Skoczylas-Ciszewska, 1963). The sediments of the "boulder deposit" originated in the southern, shallow and marginal part, strongly influenced by tectonics and clastic input (K. Bukowski, 1992; J. Rolewicz, 1987). Some authors (A. Garlicki, 1968*a*; J. Poborski, K. Skoczylas-Ciszewska, 1963; R. Tarka, 1992) assumed that the present character of the "boulder deposit" resulted from tectonic brecciation of primary stratiform evaporites, their overthrusting on the "stratiform deposit", and later folding of both units together. Other scientists (K. Kolasa, A. Ślączka, 1984, 1985*a, b*) stated that the "boulder deposit" was formed due to submarine gravitational (olistostrome) slumps/flows, developed on a tectonically active basin slope. Studies of the clastic interbeds within the evaporites as well as of the clayey salts ("green salts" and "zubers") confirmed (K. Bukowski, 1992) that they were deposited in a basin with differentiated depth and high seismic activity of the margins, involving frequent turbiditic flows and slumps. Part of the salts, with chevron and secondary transparent halite, were defined as shallow deposits, originating in periodically flooded and dried basins and they are quite similar to the "chaotic-mudstone-halite" sediments known from the mudflats of the playa. The clay minerals were studied from the clayey salts of the "boulder deposit" at Wieliczka (M. Pawlikowski, A. Skowroński, 1975; A. Szybist, 1975) indicating their mixed terrigenous-marine origin. In the "stratiform deposit" local concentrations of strontium and boron (K. Prochazka *et al.*, 1969) were found, but without economic value.

Studies of idiomorphic halite crystals with zonal structure from rock salt at Wieliczka (M. Pawlikowski, 1975; M. Pawlikowski, E. Książek, 1975) documented their formation on the basin bottom in conditions of changing brine concentration, pH and Eh values and a varied supply of terrigenous material. The analysis of inclusions within halites (K. Bukowski, 1992) indicated the occurrence of inclusions with 1–3 phases but the studies of homogenization temperatures suggested a temperature of primary salt brines below 20°C. Much evidence of diagentic transformations of halite at higher temperatures (in overburden conditions) were also noted, as well as more frequent occurrences of inclusions in active tectonic zones (R. Tarka, 1992).

A particular problem is the occurrence of rhythmic fine lamination (dark and light bands) in some types of salts (so-called "spiza salt") in Wieliczka (Fig. 2). This feature was related to climatic cycles, reflecting 11-years periods of storm activity in a steppe climate (A. Gaweł, 1962). The rhythmic salt/sulphate interbeds were regarded as annual or solar cycles and based on such assumptions the total time of accumulation of the Badenian salt was calculated as 11 400–13 500 years (A. Garlicki, 1968*a*).

Some general studies on the geology and stratigraphy of the Badenian salts were carried out in the Bochnia salt mine (J. Poborski, 1952; A. M. A. Wali, 1986) and in the Moszczenica – Łapczyca deposit (A. Garlicki, 1970). They enabled the distinction of similar cycles and lithological units to those observed at Wieliczka (Fig. 3).

In the last few years a quite new, controversial theory was presented on the origin of all Miocene evaporitic formations in the Central Paratethys (J. Liszkowski, 1989). This theory assumed that the main sources of brine in these Miocene evaporitic basins were pore waters, existing within the flysch rocks. These highly mineralized waters were — according to this author — expelled from the flysch during folding movements in the Carpathians. J. Liszkowski strictly correlated the periods of salt deposition during the Miocene with the phases of tectonic activity. He estimated the total time of the brine expulsion and salt accumulation during the Badenian as 10^5–10^4 years. The local increase in brine concentration, inducing the chloride precipitation, resulted from a "negative filtration effect" and a mixing of brine bodies of different chemistry and concentration. The results of studies of the decrepitation temperatures of inclusions in the Miocene halites indicated the temperature of crystal generation was 35–45°C, typical — after the author — for brines warmed geothermally during their migration through the sedimentary cover. In the proposed model the main factors, determining evaporitic deposition, were the compressive tectonic movements and the volume and chemistry of pore brines existing within rocks of the orogene.

This short review of actual hypotheses on the origin of the Badenian salts illustrates a wide spectrum of opinions about environments and factors controlling their deposition. Such variability results from the highly differentiated development of these rocks with evidence of deep water (gravity slump/flow structures) and very shallow, nearly subaerial (sabkha/playa pans) conditions. The comparison of these data, coming from a narrow forearc basin, with those of the well recognized salts of the Upper Permian "salt giant" from the area of the Polish Lowland, could enable the elaboration of a model of deep-water chlorides, now being questioned in literature (A. C. Kendall, 1993). Such comparative studies may also explain some other detailed problems such as: characteristics and origin of salt facies, evolution of chloride brines in various depth conditions, influence of tectonic and eustatic factors on salt sequences, mechanism and reasons of observed rhythmites (salt/sulphate bands) within salt units, etc.

ECONOMIC VALUE OF THE BADENIAN ROCK SALTS IN THE CARPATHIAN FOREDEEP AND THEIR MANAGEMENT

The Badenian rocks salts of the foredeep were discovered very early — archeological findings of relicts of equipment for salt production from natural brine outflows were dated as Neolithic, i.e. 3500 years B.P. (*Wieliczka...*, 1981). Mining works were started at

Wieliczka at the end of XIIIth century, but earlier at Bochnia. During the next 500 years the largest and most famous salt mining district in the whole Polish historical territory developed there. The discovery of large deposits of Upper Permian salts within diapirs in the Polish Lowland during the mid XIX century, and their subsequent intensive exploitation, slowly decreased the role of this former historical salt region.

Recently the total prognostic resources of the Badenian rock salt in the area between Wieliczka and Dębica (calculated for salt seam depth up to 1000 m) are estimated at 2140 mln t, and the theoretical resources (a salt seam depth over 1000 m) — at 200 mln t (B. Bąk, S. Przeniosło, 1993). Hitherto, 6 main rock salt deposits have been contoured and documented within the Carpathian Foredeep. Their general economic parameters are as follows (after E. Konstantynowicz, 1989):

— the stratiform salt deposit Rybnik – Żory, located at the western edge of the foredeep (Fig. 1); the salt seam, 5–40 m thick, occurs at a depth of 200–300 m, the content of NaCl varies from 68 up to 98% and the economic resources are calculated at 2100 mln t;

— the Wieliczka salt deposit, southward from Kraków (Fig. 1), with an active underground mine and famous museum in the older abandoned parts of the mine; in this deposit is located the drill mine Barycz; this deposit is characterized by complicated geological structure, described earlier, the salt sequence thickness is up to 400 m; NaCl content changes from 40 up to 99% and the salt resources are estimated at 45 mln t;

— the Bochnia salt deposit, eastward from Wieliczka (Fig. 1), with an active and very old (there are some evidences of mining works from IX–X centuries) underground mine; the strongly folded and inclined salt horizon is recognized up to a depth of 450 m, the average content of NaCl is 96% and the economic resources are calculated at 4.5 mln t;

— the Łężkowice – Siedlec deposit, southward from Bochnia (Fig. 1), with the drill mine Łężkowice; the salt horizon, from decimetres up to several tens of metres thick, is intensively folded and overthrusted and it is noted at varied depths of 40–500 m; the average content of NaCl is 81.3% and the economic resources are 38 mln t;

— the Moszczenica – Łapczyca deposit, located eastward from the Łężkowice – Siedlec deposit (Fig. 1) and being its eastern prolongation with the same internal structure; the new underground mine Moszczenica – Siedlec is located there; the average NaCl content in the deposit is 86.5% and the economical resources are estimated at 246 mln t;

— the Wojnicz deposit, southward from Tarnów (Fig. 1); the folded salt horizon occurs at a depth over 1500 m, the average NaCl content is 75% and calculated salt resources are about 200 mln t (B. Bąk, S. Przeniosło, 1993).

All salt production from the Badenian salts now comes from 5 salt mines: three underground mines (old ones: Wieliczka and Bochnia, and the new one — Moszczenica – Siedlec) and two drill mines (Barycz and Łężkowice). In all mines salt is obtained from brines, coming from artificial or natural disolution of salt series.

The economic value of the Badenian rock salts from the Carpathian Foredeep is gradually decreasing due to the negative tendencies in the world salt market, a decrease of national salt production in recent years, as well as to the exploitation of giant salt resources within the Upper Permian deposits in the Polish Lowland. Also the complicated geological structure, the highly variable NaCl content within salt series and difficult hydrogeological conditions make these deposits very unfavourable for exploitation. The existing mines will in future be abandoned or converted into underground sanatoriums or museums, as for instance the part of the Wieliczka mine, from 1976 a national museum and from 1978 included in the world list of human culture monuments (*Wieliczka...*, 1981).

The proposals for further management of active mines and documented deposits of Badenian rock salts as underground depositories for oil/gasoline and wastes (A. Grabania, 1992; B. Nielubowicz, 1992) were excluded due to tectonic activity within the Carpathian Foredeep, very complicated geological structure of deposits and related varied salt thickness, lack of larger underground excavations and high water menace, newly evidenced by the catastrophic brine inflow into the Wieliczka salt mine in 1992 (A. Garlicki, Z. Wilk, 1993).

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ŚRODKOWOBADEŃSKIE SOLE KAMIENNE W ZAPADLISKU PRZEDKARPACKIM — CHARAKTERYSTYKA, GENEZA I WARTOŚĆ SUROWCOWA

Streszczenie

Sole kamienne stanowią znaczący pod względem objętości osadów, rozprzestrzenienia i wartości surowcowej (oprócz siarczanów i węglanów z mineralizacją siarkową) składnik środkowomioceńskiej (badeńskiej) formacji ewaporatowej w południowej Polsce. Zajmują osiową część zapadliska przedkarpackiego i cechuje je zróżnicowane wykształcenie i skomplikowana budowa tektoniczna, wynikające ze zmiennych warunków depozycji i późniejszych deformacji tektonicznych, będących odbiciem ruchów fałdowych w Karpatach. W artykule przedstawiono ogólną charakterystykę utworów solnych, ich zróżnicowanie miąższościowe i facjalne, będące wynikiem różnych warunków depozycji. Omówiono szereg aktualnych koncepcji powstawania soli badeńskich, szczególnie licznych (ze względu na ilość poczynionych obserwacji) dla utworów z Wieliczki. Według tych koncepcji depozycja chlorków odbywała się w zmiennych, skrajnie różnych warunkach — od głębokowodnych (K. Kolasa, A. Ślączka, 1984, 1985*a, b*) po niemal subarealne (K. Bukowski, 1992). Innymi źródłami depozycji soli w zasilaniu wód basenu ewaporacyjnego były też solanki porowe, wyciśnięte ze skał fliszu karpackiego (J. Liszkowski, 1989).

Dla ukazania surowcowego znaczenia soli badeńskich scharakteryzowano ogólnie 6 głównych złóż soli kamiennej, udokumentowanych na obszarze zapadliska. Całkowite zasoby perspektywiczne soli kamiennej na obszarze od Wieliczki po Dębicę oceniane są na 2140 mln t, zaś teoretyczne — na 200 mln t (B. Bąk, S. Przeniosło, 1993). Ze względu na niekorzystną koniunkturę gospodarczą i zagospodarowywanie ogromnych złóż soli cechsztyńskich na Niżu Polskim, jak również na skomplikowaną budowę geologiczną i trudne warunki hydrogeologiczne wydobycie złóż soli badeńskich jest stopniowo ograniczane, a istniejące kopalnie (3 podziemne i 2 otworowe) zostaną w przyszłości zlikwidowane. Trudne warunki geologiczne złóż soli w zapadlisku, duże zagrożenia wodne i brak rozległych wyrobisk nie pozwalają na inne formy ich zagospodarowania, np. jako zbiorników ciekłych paliw czy składowisk szkodliwych odpadów (A. Grabania, 1992; B. Nielubowicz, 1992).