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Geology and resources of salt deposits in Poland: the state of the art

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Rock salt occurs in Poland (Central Europe) in two salt-bearing formations of upper Permian (Zechstein) and Neogene (Middle Miocene, Badenian Stage) age, while potash salts are only of Permian age. The total resources of rock salt are $>106 \times 10^9$ Mg, predominantly from the Zechstein ($>81 \times 10^9$ Mg of anticipated economic resources in 15 documented salt deposits of both stratiform and diapir types). They are now exploited in two underground salt mines and two solution mines that produced in 2008 over 3×10^6 Mg of rock salt, mainly from the diapirs. The most perspective future management of these rock salt deposits are as safe underground cavern stores for oil and gas (currently two of these exist, and one is in progress) and depositories. The Badenian deposits (stratiform and stratiform-folded), exploited in the past millennium, occur in a limited area of Southern Poland and are now only of historical-touristic value. Potash salts, quite common within the Zechstein evaporite complexes, are documented in a single salt diapir in Central Poland (resources of over 72×10^6 Mg, with minimal and accidental exploitation of carnallite and kieserite) and in sulfate horizons accompanying the rock salt in Northern Poland (four deposits of polyhalite with resources of *ca*. 0.67×10^9 Mg). Because of low market prices of potash products offered by neighbouring countries the future management of national potash salt resources seems to be non-economic.

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INTRODUCTION

Rock salts occur in Poland in two evaporite formations: an Middle Miocene (Badenian Stage) one in Southern Poland (Carpathian Foredeep area) and an upper Permian (Zechstein) one in Northern and Central Poland area (Fig. 1; Czapowski *et al.*, 2008*a*; Czapowski and Bukowski, 2009; with references therein). This paper is a synthetic review of updated data (included in thematic papers, deposit documentations and periodic anticipated economic resources – see: *op. cit.* with references herein) on geology, estimated resources and the management status of salt deposits in Poland, last published twenty years ago (Osika, 1990).

The Badenian salts were exploited in prehistoric times though records of salt mining date from the 11th century and the mines there were finally abandoned in the 1990's. Resources of three (those listed in statistical summaries) from seven documented salt deposits are equal to 5.1% of national rock salt resources.

The Zechstein salts occur within four thick evaporite successions at depths from several hundreds metres (Northern and SW Poland with five stratiform salt deposits) to several kilometres (Polish Lowland area in Central Poland). Numerous salt domes and diapirs (up to 7 km high) occur in the Polish Lowland and during the last 150 years rock salt deposits were documented in some of them. Deposits resources are estimated at 56×10^9 Mg (i.e. 65.6% of national salt reserves) and salt produced from three managed structures in 2008 dominated the national salt production. Only Zechstein rock salts are exploited (in three diapir salt deposits and seasonally in a single stratiform one) and two diapirs are managed for gas and oil products storages (Fig. 1).

Salt production in 2008 in Poland was 3.27×10^6 Mg , including: 2.58×10^6 Mg from the solution mines (Góra, Mogilno I, Mogilno II; data calculated from brine volume; Table 1) and from the underground mines (Table 2 and Fig. 1): 0.448×10^6 Mg from the Kłodawa mine and 0.166×10^6 Mg from the Sieroszowice/Kazimierzów mine. Also 0.08×10^6 Mg of evaporated salt was produced in the saltworks,

Fig. 1. Salt deposits in Poland

using salt brines from coal mines. In 2007 the volume of rock salt produced in Poland (3.1×10^6 Mg) was 1.3% of global salt production (Fig. 2).

In 2008 the balance geological resources of rock salt in Poland, estimated for 19 salt deposits were calculated at *ca*. 85.4×10^9 Mg, and the anticipated subeconomic resources ones – *ca*. 20.7×10^9 Mg (Table 1). Resources in five managed deposits were 12.6×10^9 Mg, three deposits of Badenian salt (resources of *ca*. 188×10^6 Mg) were closed (and removed from the statistics list) and the remaining documented unmanaged 12 deposits (both of Badenian and Zechstein salts) contain *ca*. 72.6×10^9 Mg of rock salt (Table 1).

The actual resources, annual production and state management of the documented rock salt deposits in Poland are shown in Table 2.

ZECHSTEIN ROCK SALTS

Fourteen documented deposits of Zechstein rock salts (Table 2 and Figs. 1, 3), with anticipated economic resources of over 81×10^9 Mg, include: four stratiform deposits (resources of *ca*. 25×10^9 Mg) and ten deposits in seven salt diapirs (resources $>56 \times 10^9$ Mg). The active underground mines are located in one stratiform deposit (Sieroszowice/Kazimierzów) and in one diapir (Kłodawa), and two 2 salt diapirs are exploited with leaching wells (Mogilno and Góra – Table 2 and Fig. 3), functioning also as gas and oil storages (Karnkowski and Czapowski, 2007; Czapowski *et al*., 2008*a*, *b*; with references therein).

The stratiform deposits of Zechstein salts are characterized by relatively simple geological structure. The largest such de-

Table 1

Number, resources and management of rock salt deposits in Poland (after Wołkowicz *et al.*, 2009; resources calculated outside protection pillars)

Resources	Number of deposits	Geological resources [10^6 Mg]		Salt production [10^6 Mg]
		Anticipated economic resources (categories: A+B+C1+C2)	anticipated subeconomic resources	
Total resources	19	85392	20678	3.19
Resources of managed deposits				
Total	5	12562	8	3.19
Mined deposits	4	6864	8	3.09
Seasonally exploited deposits (cavern storage)	1	5698	–	0.1
Resources of unmanaged deposits				
Total	12	72641	20483	–
Deposits documented in details	5	28445	10018	–
Deposits preliminary recognized	7	44196	10465	–
Resources of abandoned deposits				
Total	2	188	187	–

category C2 – deposit with preliminary recognized resources, categories A+B+C1 – deposit documented in detail

posits were found in Northern Poland, west of Gdańsk Bay (Fig. 3), and are located within a single thick (up to 220 m) layer of rock salt (Na1). This layer, inclined slightly to the SE, is located at a depth of 490.5 to 1285.3 m and its variable thickness (0–225.5 m, average – 127.4 m) is a result of palaeofacies variability (Czapowski *et al.*, 2008*b*). Three large rock salt deposits (with total resources of over 22×10^9 Mg, 25% of total national salt reserves) were discovered and documented there in 1975–2008 (Table 2):

– the Mechelinki deposit (area 9 km^2, resources of up to 3×10^9 Mg);

– the Puck Bay deposit (area 101 km^2, resources of *ca*. 16.3×10^9 Mg);

– the Łeba deposit (area 50 km^2, resources of *ca*. 2.7×10^9 Mg).

All these deposits are built of almost homogenous rock salt (average NaCl content varies from 96.7 to 97.8%, insolubles up to 2.9%), with rare, thin and impersistent interbeds of K-Mg salts (mostly syn- and early diagenetic polyhalite – Peryt *et al*., 1998) and sulfates, with a few fault zones cutting the salt. The salt layer is under- and overlain by two (several to 200 m-thick) beds of anhydrite (A1d and A1g – Fig. 4), these being the isolating horizons. To date these deposits have not been exploited but their structural features suggest possible deposit management as underground stores and radioactive waste depositories (Czapowski *et al.*, 2008*b*; with references therein). The leaching for gas caverns within the Mechelinki deposit started in September 2010 and is planned to finish in 2013 (Laskowska *et al.*, 2009).

In SW Poland (the Fore-Sudetic Monocline area; Figs. 1 and 3), in the region of copper mining, two stratiform salt deposits have been documented. The first one, the Sieroszowice/Kazimierzów deposit documented in 1990–2006 (2.9×10^9 Mg of resources), is placed in a rock salt unit (Na1) located above the copper-bearing horizon, at depths of 827.0–1270.0 m. The varied seam thickness (several to 200 m) reflects the palaeofacies pattern and numerous faults. Anhydrite interbeds and locally the salt are highly tectonized. As in Northern Poland, two anhydrite units underlie and overlie the salt seam. The NaCl content is 75.5–99.8% (98% dominant), the sulfates content being up to 6%. The salt is mechanically exploited in the galleries and chambers, using the power-air supply of the copper mines as well as their shafts for salt transport.

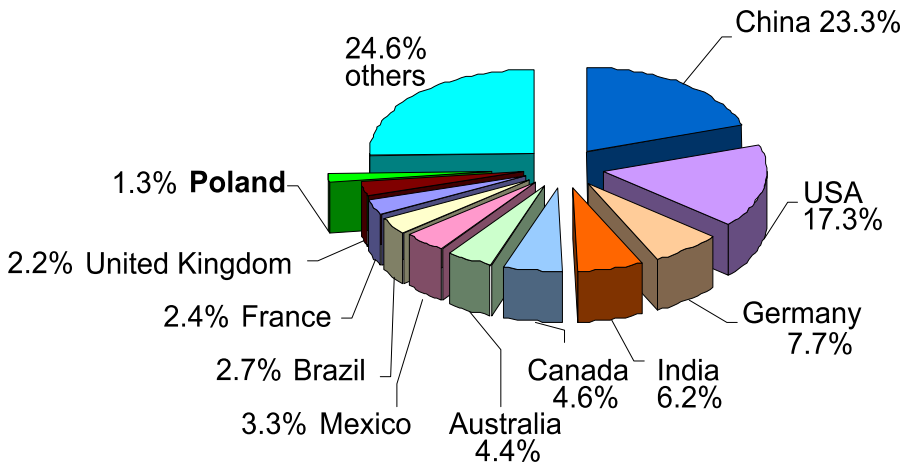

Fig. 2. Structure of the global production of salt in 2007 (after www.saltinsitute.org)

Table 2

Actual resources, production and management stage of rock salt deposits in Poland (data in part from Wołkowicz *et al.*, 2009)

Deposit name and age	Deposit management/onset of mining works	Geological resources [10^6 Mg]	Salt production [10^6 Mg]
I. Stratiform deposits			
Łeba (PZ)	P	2751	–
Mechelinki (PZ)	R, CS (in progress)	2975	–
Puck Bay (PZ)	R	16336	–
Sieroszowice/Kazimierzów (PZ)	E/1991	2936	0.166
Rybnik–Żory–Orzesze (Ne)	P	2099	–
II. Stratiform-folded deposits			
Siedlec–Moszczenica (Ne)	Z	188	–
Wojnicz (Ne)	P	2083	–
III. Deposits in salt diapirs			
Damasławek (PZ)	P	17690	–
Góra (PZ)	E/1965; CS/1998	2325	1.06
Mogilno I (PZ)	E/1978	3631	1.41
Mogilno II (PZ)	CS/1992	5697	0.1
Lubień (PZ)	R	4071	–
Łanięta (PZ)	R	2127	–
Kłodawa North (PZ)	P	6888	–
Kłodawa Center (PZ)	E/1949	904	0.448
Kłodawa South (PZ)	P	4072	–
Rogóźno (PZ)	P	8612	–

P – deposit with preliminary recognized resources (category C2), R – deposit documented in detail (categories A+B+C1), E – deposit actually exploited (date of starting exploitation), CS – deposit managed as a cavern storage (date of starting storage), Z – deposit with finished exploitation, Ne – Badenian (Neogene) deposit, PZ – Zechstein (Permian) deposit

The second, unmanaged, stratiform deposit Bytom Odrzański, north-west of the Sieroszowice/Kazimierzów deposit (Fig. 3), contains four salt layers, lying one above other at depths from 1039.5 m to over 1450 m, with thicknesses from several metres to 300 m. Sulfate, carbonate and claystone beds separate the salt bodies and the NaCl content varies (88–98%) with a high clay amount (5–8%). The preliminary calculated whole salt resources are 48.76×10^9 Mg (not included in the statistics). Because of widespread tectonic deformation (faulting, fracturing) and salt thickness variations these salt deposits may create more geological problems for future mining.

Hitherto salt deposits have been documented in nine of the numerous diapirs that occur in Central Poland (Fig. 3) but two of these (Wapno and Inowrocław) were closed in 1970–1980. Nine salt deposits, documented to depths of 1000 and 1800 m in seven diapirs, are listed in Table 2; in the Kłodawa diapir, three salt deposits with total resources of over 11.8×10^9 Mg occur (the central deposit with resources of 0.9×10^9 Mg is exploited using explosives in the underground mine) and two deposits have been distinguished in the Mogilno diapir (total resources of over 9.3×10^9 Mg; the Mogilno I deposit works as a solution mine, and the Mogilno II deposit functioned from 1992 as a cavern gas storage).

The last managed Góra salt diapir (Table 2 and Figs. 1, 3), with resources of 2.3×10^9 Mg, has been exploited since 1968 via leaching wells, and from 2002 several leached caverns were adapted for oil and oil products storage. Other four unmanaged salt deposits in four diapirs (Damasławek, Lubień, Łanięta and Rogóźno – Fig. 3) offer total anticipated economic resources of 30.75×10^9 Mg.

Salt deposits in diapirs are characterized by a very complicated internal structure (e.g., Kłodawa diapir – Fig. 5), resulting from varied lithology and highly complicated tectonics. These features make it difficult to interpret properly the diapir internal structure and consequently to calculate salt resources and plan safe and economic mine excavations (both as underground mines and as leaching caverns). Most recognized salt diapirs in Poland have the younger Zechstein salt units (beloning to the Z3 and Z4 cyclothems) in the upper part of the salt trunk. Because they contain interbeds and a high admixture of potash salts, sulfates and clay matter, they are difficult to realize as proper storage caverns and mine chambers for salt excavation. The older Zechstein salt units (representing the Z1 and Z2 cyclothems) with lower potash and sulphate-clay admixture commonly build the lower part of diapir trunks so the most economic salt exploitation takes place at the lower levels.

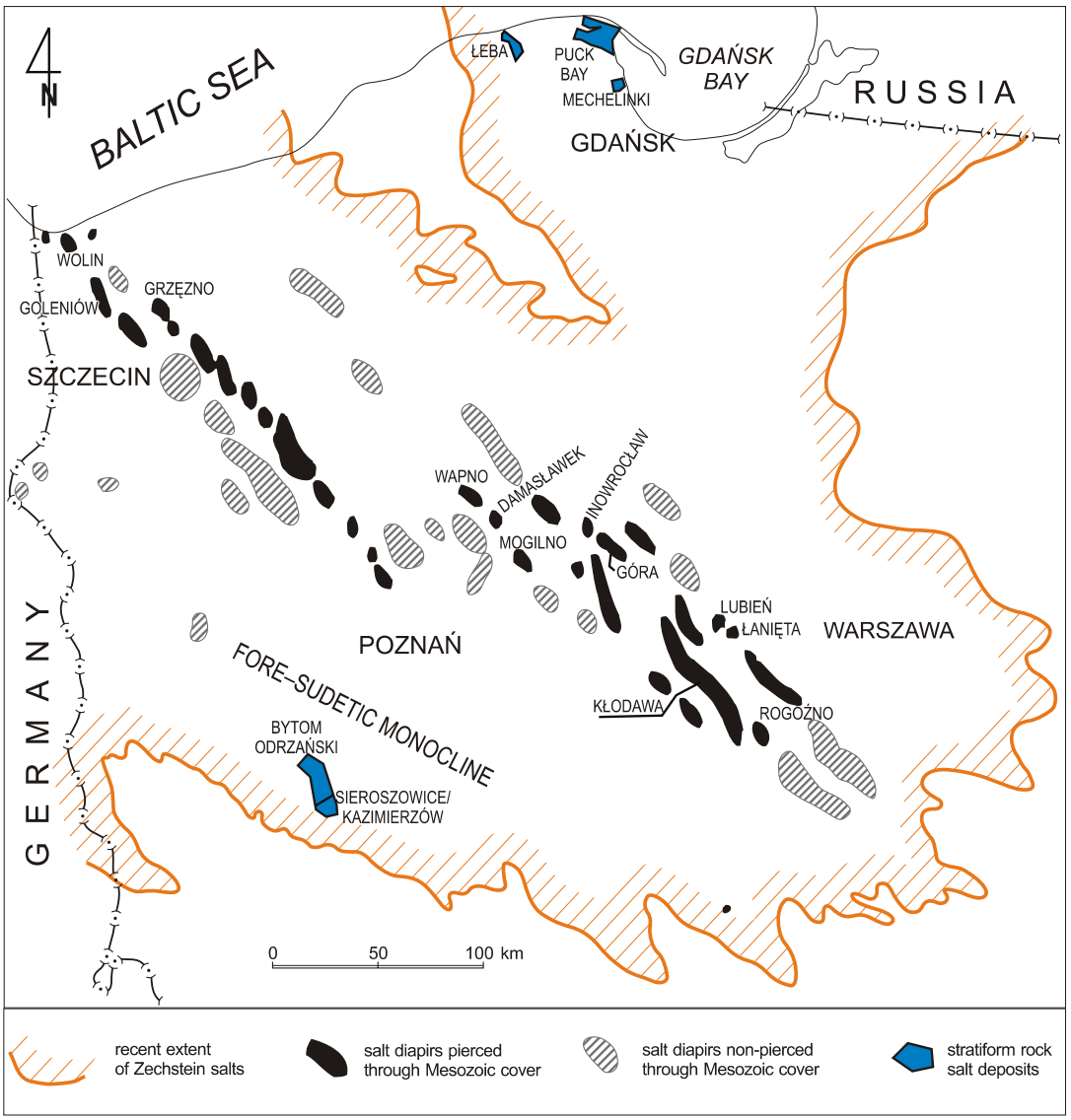

Fig. 3. Location of salt diapirs and stratiform rock salt deposits in Poland (after Karnkowski and Czapowski, 2007, modified)

The salt mirror in the most salt diapirs in Poland is located at depths below 1500 m, assumed as the common technical-economical limit for location of storage caverns. In five diapirs (Goleniów, Damasławek, Lubień, Łanięta and Rogoźno – Fig. 3) this mirror is placed at a depth of less than 1 km, in three others (two in the Wolin diapir and one in the Grzęzno diapir in NW Poland) at depth intervals between 1–1.5 km, so they may be managed in future as cavern stores, after more detail geological recognition and reinterpretation of older data (Karnkowski and Czapowski, 2007; Czapowski *et al.*, 2008*a*).

Potential (prognostic and theoretical) rock salt reserves, located in the Zechstein strata in Poland, were calculated (in the depth interval 0.7–2.0 km) at 2.25×10^{12} Mg, including reserves of stratiform deposits (2.18×10^{12} Mg) and of salt diapirs (73.86×10^{9} Mg; Czapowski *et al.*, 2008*a*).

BADENIAN (MIDDLE MIOCENE) ROCK SALTS

The Badenian salt deposits are located in the Carpathian Foredeep in the southern part of Poland (Fig. 1). Most of these deposits were folded (except for the single stratiform Rybnik–Żory–Orzesze deposit in the tectonic depression of Upper Silesia region) in front of the Carpathian nappes and were overthrusted from the south onto the autochthonous succession infilling the foredeep (Andreyeva-Grigorovich *et al.*, 2008). Deposits of the salt-bearing formation, which are intensively folded and imbricated, occur at a depth from 50 to 800 m (Fig. 6). The salt layers are from several to several hundred (via tectonic duplication) metres thick and contain a considerable admixture of clay and anhydrite.

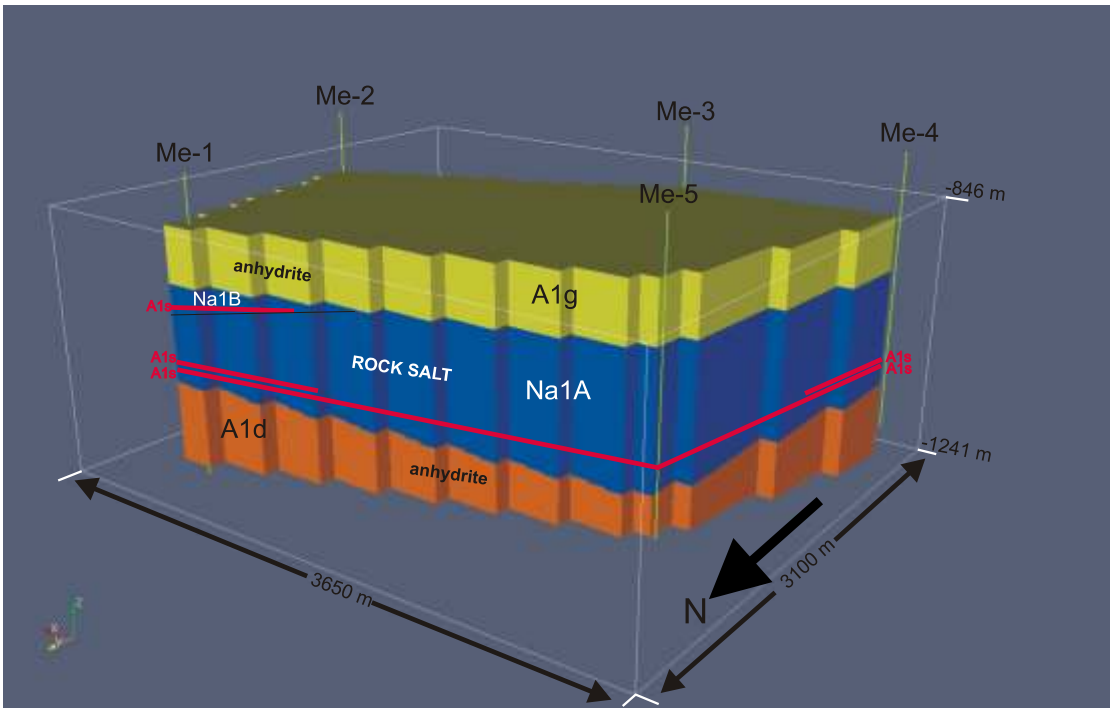

Fig. 4. Geological model of stratiform salt deposit Mechelinki in Northern Poland (after Czapowski *et al.*, 2008*b*)

Explanations of geological units in text

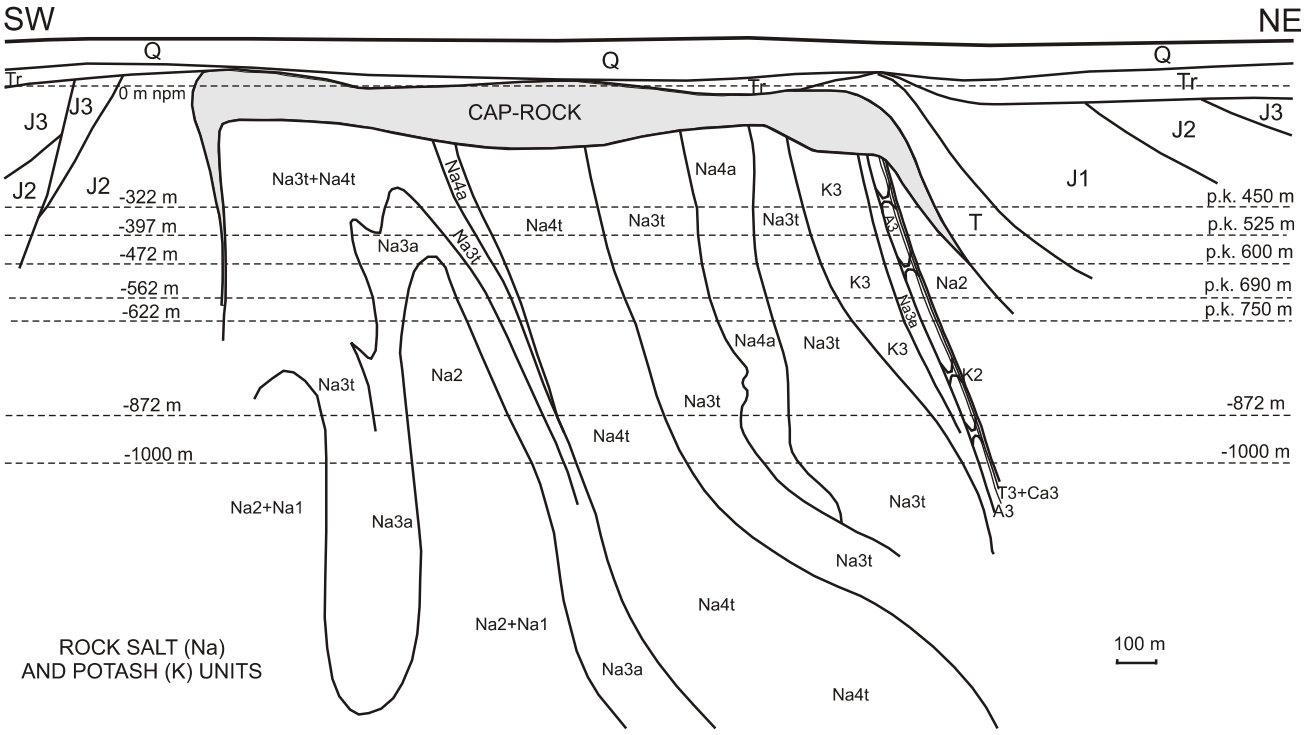

Fig. 5. Schematic geological section of the Kłodawa salt diapir in Central Poland (after Burliga, 1996) Badenian (Middle Miocene) rock salts

p.k. – mine level, Q – Quaternary, Tr – Tertiary, J (1, 2, 3) – Jurassic, T – Triassic; Zechstein lithostratigraphic units: Na1 – Oldest Halite, Na2 – Older Halite, K2 – Older Potash, T3 – Grey Pelite, Ca3 – Platy Dolomite, A3 – Main Anydrite, Na3 – Younger Halite (a – lower), K3 Younger Potash, Na3t – Brown Zuber, Na4a – Underlying Halite, Na4t – Red Zuber

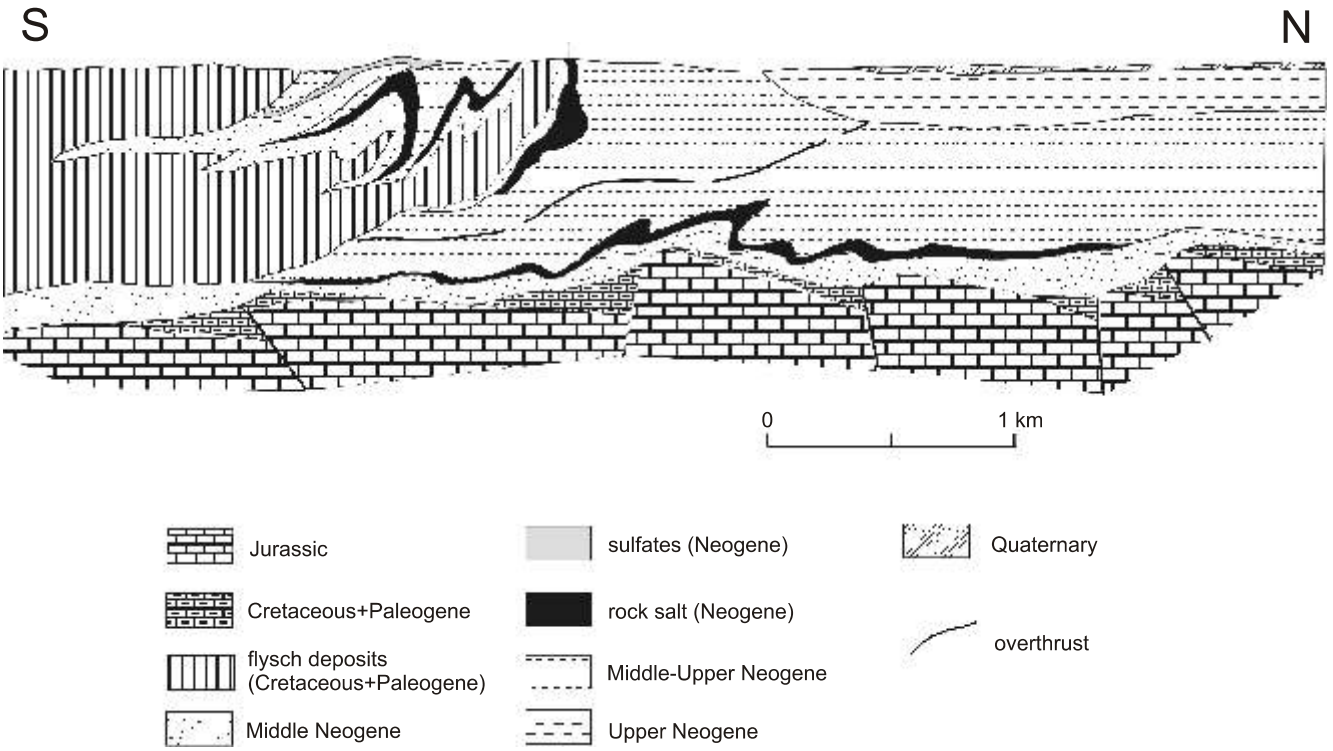

Fig. 6. Schematic geological section of the Bochnia rock salt deposit (Southern Poland)

These Badenian salt deposits have been exploited for over 750 years in underground mines. After 1996 exploitation of rock salt in this area has finished. Salt mines in Wieliczka and Bochnia become cultural heritage sites. In 1979 Wieliczka was included on the First International List of the World Cultural and Natural Heritage UNESCO. Today the mines are the famous tourist and recreation sites (Fig. 7), visited by tourists from around the world (*ca*. 1 million persons annually).

The anticipated economic resources of three unmanaged Badenian salt deposits (Rybnik–Żory–Orzesze, Siedlec and Wojnicz) are *ca*. 4.37×10^9 Mg (Table 2) being the equivalent of 5.1% of Polish salt resources. Because of the significantly greater resources and the higher quality of many Zechstein deposits, and because of complicated geological-mining conditions in the Badenian deposits, these deposits will probably not be exploited either for salt or as the sites for underground storage/depositories in the near future.

Potential (prognostic and theoretical) rock salt reserves, located in the Badenian strata in Southern Poland, were calculated (to a depth of 2.0 km) as 2.89×10^9 Mg.

POTASH SALTS

Potash salts in Poland are connected with the Zechstein evaporite succession and occur as individual lithostratigraphic units (K2 and K3; recognized in several salt diapirs e.g., Inowrocław, Góra, Mogilno, Kłodawa – Fig. 3), in SW Poland, and early diagenetic replacement of sulfate bodies in Northern Poland (Fig. 8).

The single potash deposit was documented in the Kłodawa diapir within the K3 salt unit (Fig. 5). This potash layer is 15–30 m thick, composed of halite and carnallitic kieserite with an average K_2O content at 8.5 and 8.1% of MgO. The anticipated economic resources are over 72×10^6 Mg (Table 3), but due to the complicated geological structure of the deposit it has only sporadically been exploited (1.4×10^3 Mg in 2000).

The most important documented potash deposits of early diagenetic character (Peryt *et al.*, 1998) are located in Northern Poland at Puck Bay, accompanying the giant salt stratiform deposits. In 1964–1971 four deposits of K-Mg salts (dominant polyhalite) were contoured with anticipated economic resources of 596×10^6 Mg (Table 3), being 89% of national potash resources.

Syn- and early diagenetic polyhalite was dispersed within: (a) the anhydrite interbeds in the rock salt (Na1) layer, (b) as dispersed aggregates in the rock salt and (c) in the upper part of the anhydrite unit (A1d), underlying the salt. The first two forms of polyhalite dominate in the Chłapowo deposit and the last one composes the resources of the Swarzewo and Zdrada deposits (Czapowski *et al*., 2008*b*).

The parameters of these potash deposits are listed in Table 4. The depth of potash salt layers varies from 737.8 to 858 m, their thickness achieves 73 m (average – 6–26 m) and

Fig. 7. Michałowice chamber, Wieliczka Salt Mine

Photo by J. Przybyło

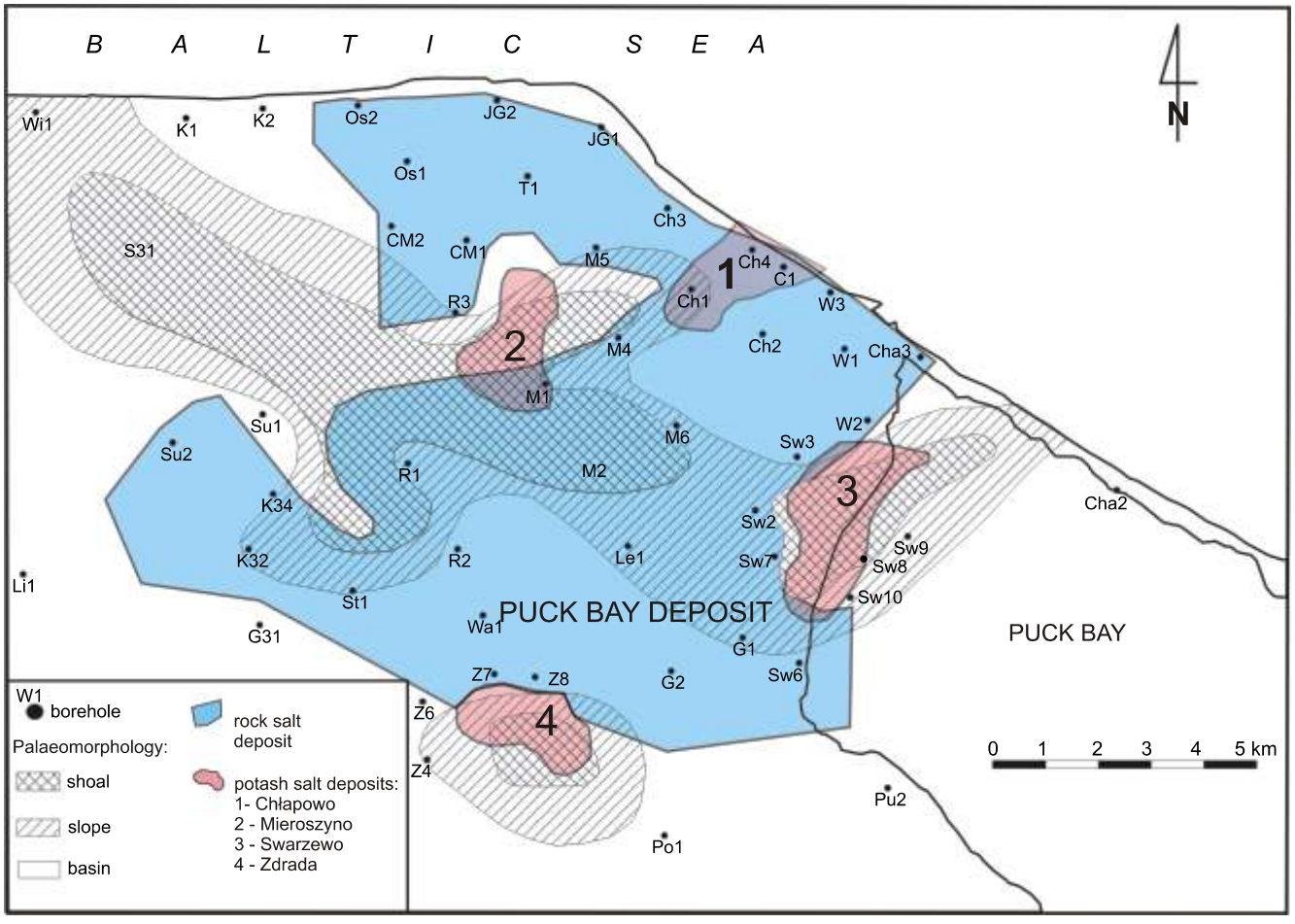

Fig. 8. Relation between the rock salt and the potash deposits in Northern Poland against a context of Zechstein salt basin palaeomorphology (after Czapowski *et al.*, 2008*b*)

Table 3

Actual resources and management status of potash salt deposits in Poland (some data after Wołkowicz *et al.*, 2009)

Deposit name and age	Deposit management	Geological resources [10^6 Mg]	
		Total	669.1
Kłodawa Center	S	72.1	
Chłapowo	P	32.1	
Mieroszyno	P	341.7	
Swarzewo	P	144.0	
Zdrada	P	79.2	

P – deposit with preliminary recognized resources, S – deposit with documented resources seasonally exploited

K_20 content is up to 15.97% (average value varies between 7.74 to 13.78%). Because of the irregular distribution of polyhalite concentrations the proper estimation of the resources is difficult and until now these deposits have not been exploited.

All these potash deposits are found at elevations of the Zechstein evaporite basin (sulfate shoals; Fig. 8). The basin depressions were then a place of intense chloride accumulation, finalizing with the giant Puck Bay rock salt deposit.

The potash salts in the K2 and K3 salt units have been found in many boreholes in SW Poland (Fore-Sudetic Monocline) area. The K2 potash layer up to 30 m-thick was detected at depths of 917–1880 m and consists of decimetre to metre-scale interbeds of halite+sylvine and halite+anhydrite+polyhalite with K_2O contents of 1–9% (max. 25%). The younger, K3 potash unit occurs at depths of 838–1068 m and consists of two potash layers separated by a rock salt body: (a) a lower one up to 6 m-thick (halite+anhydrite+polyhalite with K_2O contents of 1–4.5%) and (b) an upper one up to 12 m-thick (sylvine+kieserite+polyhalite with K_2O contents of 1–16%). These potash salt occurrences have never been documented as potash deposits.

Potential (prognostic and theoretical) potash reserves, located in the Zechstein strata in Poland, were calculated (in depth interval 0.5–2.0 km) at 1.02×10^9 Mg, including reserves of stratiform deposits (0.92×10^9 Mg) and of salt diapirs (0.1×10^9 Mg).

CONCLUSIONS

Of two salt-bearing evaporite formations in Poland only the Zechstein one is now exploited for rock salt (not for potash salts). Its resources and geological structure indicates future management both for salt production and for construction of safe oil and gas stores and waste depositories. The Badenian salt formation with several rock salt deposits (some having been exploited for centuries) are not now perspective for future mining because of their complicated geological structure and varied salt parameters, and so the existing mines have been adapted as historical-recreation centres.

Four managed rock salt deposits (one of stratiform type: Sieroszowice/Kazimierzów and three in the salt diapirs: Kłodawa, Góra and Mogilno) are exploited for salt as underground mines (Sieroszowice/Kazimierzów and Kłodawa) and solution mines accompanied by gas-oil storage in leached caverns (Góra and Mogilno). The rock salt production from these deposits provides the national demand for salt in chemistry, agriculture and winter road protection.

Three large stratiform rock salt deposits, contoured in the Northern Poland at Puck Bay (Puck Bay, Łeba and Mechelinki) could be quite easily managed both for salt production and cavern storages using the leaching method (leaching of gas caverns was started in the Mechelinki salt deposit in September, 2010). Their simple geological structure, homogeneity of salt quality and rare potash-sulfate interbeds create optimal conditions for such exploitation.

Several as yet unmanaged salt diapirs offer favorable conditions for construction of underground stores and depositories but because of their complex internal structure they require detailed geological study.

The potash salt concentrations belong to the Zechstein formation and only five potash deposits have been hitherto documented. They accompany the rock salt deposits and one is located in the Kłodawa diapir (sporadically mined for small amounts of potash salt) and the other four are adjacent to the large rock salt deposit at Puck Bay in Northern Poland. All these deposits are not now exploited mainly because of the low price of imported potash salts from giant potash salt deposits in Belarus, Ukraine and Russia.

In conclusion, the resource potential and production of Polish rock salt deposits is enough to meet national demands but the future direction of their management ought to be construction of safe hydrocarbons cavern stores as well as waste deposi-

Table 4

Main geological and geochemical parameters of potash salt deposits in the Puck Bay (Northern Poland)

Deposit name and area [km^2]	Depth of the potash salt seam (depth interval) [m]	Potash seam thickness (thickness interval/average) [m]	Content of main salt component (content interval/average) [%]
Chłapowo (3.55)	752.3–787.9	5.6–6.5/6.03	–/13.78 (K_20)
Mieroszyno (7.39)	737.8–802.0	1.9–73.0/26.02	7.74–15.97/8.75 (K_20)
Swarzewo (4.56)	799.4–823.0	15.0–36.3/13.5	7.19–8.48/7.74 (K_20)
Zdrada (2.25)	824.1–858.0	1.9–37.0/18.5	3.5–12.2/8.42 (K_20)

tories (with the prospect of atomic power plants being located in Poland to prevent an energy crisis).

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