Resedimented salt in the Northern Carpathians Foredeep (Wieliczka, Poland)

ANDRZEJ ŚLĄCZKA[1] and KRYSTYNA KOLASA[2]

[1]Institute of Geological Sciences, Jagellonian University, 30-063 Kraków, Oleandry 2a, Poland
[2]Salt-Work Museum, 30-020 Wieliczka, Poland

Abstract: Examination of sedimentary structures of the Middle Miocene salt (halite) deposits of the Wieliczka Salt Mine (Carpathian Foredeep) indicates that a part of the salt was deposited through the action of gravity currents and a resultant fan-like distribution of facies can be distinguished. The response to apparent continued tectonic movements was an increase in the rate of the redeposition processes. The development of the salt basin in this area ended with mass movements of marly-clay sediments containing halite olistoliths.

Key words: Miocene, salt, redeposition, foreland basin, Carpathians.

Introduction

In the Wieliczka mine, situated near Kraków (Poland), within the salt layers there are unique sedimentary structures that show that most of the halite layers have been formed from redeposition by gravity mass movements (Kolasa & Ślączka, 1985; Ślączka & Kolasa, 1987). While resedimented gypsum occurrences are well known (*e.g.* Kwiatkowski, 1972, Parea & Ricci-Lucchi, 1972; Schreiber et al., 1976; Meier, 1977; Catalano et al., 1978; Peryt & Kasprzyk, 1992) resedimented halite deposits are less common (*cf.* Schreiber, 1986) and therefore deserve particular attention.

To distinguish salt deposited by precipitation from resedimented salt, the term saltstone is proposed for salt layers that consist of redeposited salt grains: *cf.* sandstone or dolostone, and the term pebbly saltstone for layers that consist of fine grained redeposited salt that contains rock fragments: *cf.* pebbly mudstone.

Geological setting

Salt Rocks (mainly halite) occur in a narrow zone below and in front of the Carpathian flysch nappes (Tołwiński, 1956, Gaweł, 1962, Garlicki, 1979) (Fig. 1). They are strongly folded (with 3 principal folds) and are also thrust over the autochthonous Middle Miocene deposits of the European Platform.

The salt deposits of the Wieliczka Mine were formed during the salinity crisis that affected the region of the Carpathian Foreland (Fig. 2) in the Early Serravalian (± 15 My; Hamor, 1988). These evaporites accumulated within the Carpathian Foredeep and Foreland basins along the northern margin of the evolving Carpathian orogen (Alexandrowicz, 1965, 1971; Garlicki, 1979; Łuczkowska, 1978). The halite was deposited in a marine, euxinic (Garlicki, 1979) basin which was asymmetric in bathymetric profile (deeper to the south and shallow in the northern part). In the south, the basin was bordered by the active Carpathian orogen and towards the east it was connected with the ancestral Mediterranean by a narrow strait (Fig. 2). Deposition of halite was dominant in the southern part of the basin, while further

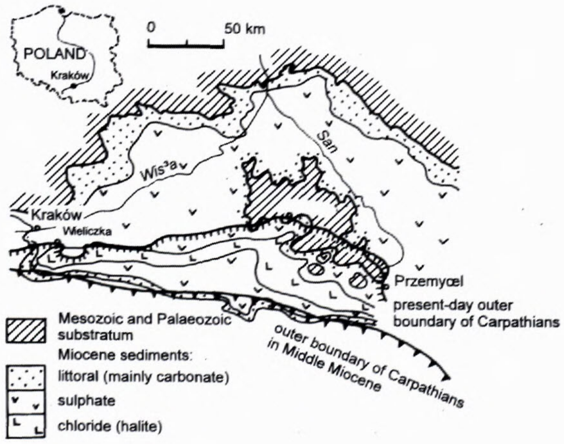


Fig. 1. Facies map of the Middle Miocene evaporites in the Northern Carpathian Foreland.

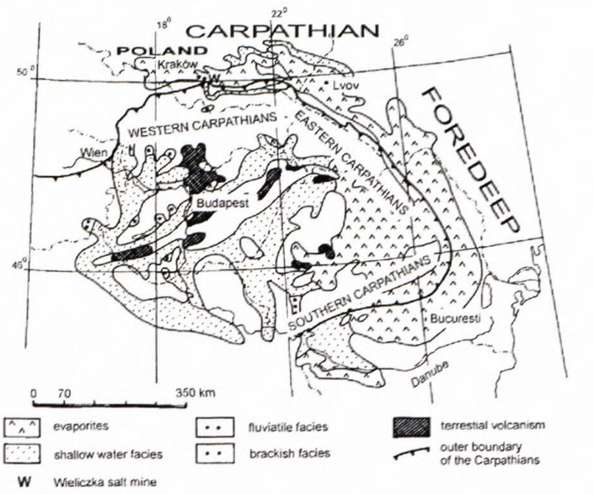


Fig. 2. Distribution of facies in the Carpathians during the Middle Miocene. Based on Hamor (1988).

north apparently only sulphate facies were deposited. The sulphate facies presumably also occurred along the southernmost margin of the basin, as indicated by the sulphate fragments redeposited in the adjacent sequences. The near shore sequences formed along the southern margin of the depositional basin are characterized by clays that contain bivalves, echinoderms, Lithothamnion, and individual corals (Caryophilia sp.) (Kowalewski, 1935; Morycowa & Roniewicz, 1988).

Plant fragments, abundant within the salt sequence, are typical of the continental, so-called younger mastixioid floras, known from the European Miocene (Mai, 1964). There are also some palaeotropical species (Łańcucka – Środoniowa, 1984). This association of plants derived from different climatic zones may be attributed to the morphology of the bordering land area and/or to long-distance transport.

During Late Miocene tectonism, the salt deposits, together with a part of the substratum, were detached, folded, and overthrust toward the north onto the autochthonous Miocene deposits of the European Platform. The lateral displacement of the overthrust Middle Miocene rocks exceeds 10 km but it is difficult to calculate this distance more precisely because postdepositional tectonic deformation has obliterated much of the evidence.

Wieliczka salt deposits

The main halite sequence of the study area is underlain by siltstones, anhydritic claystones and siltstones, together with sandstones containing anhydrite and/or halite cement (Pp on Fig. 4). There are sporadic intercalations of conglomerates and pebbly mudstones containing boulders derived from the Carpathian flysch rocks. The salt-bearing sequence comprises two members (Fig. 4): the Stratified Salt Member (SSM) and the overlying

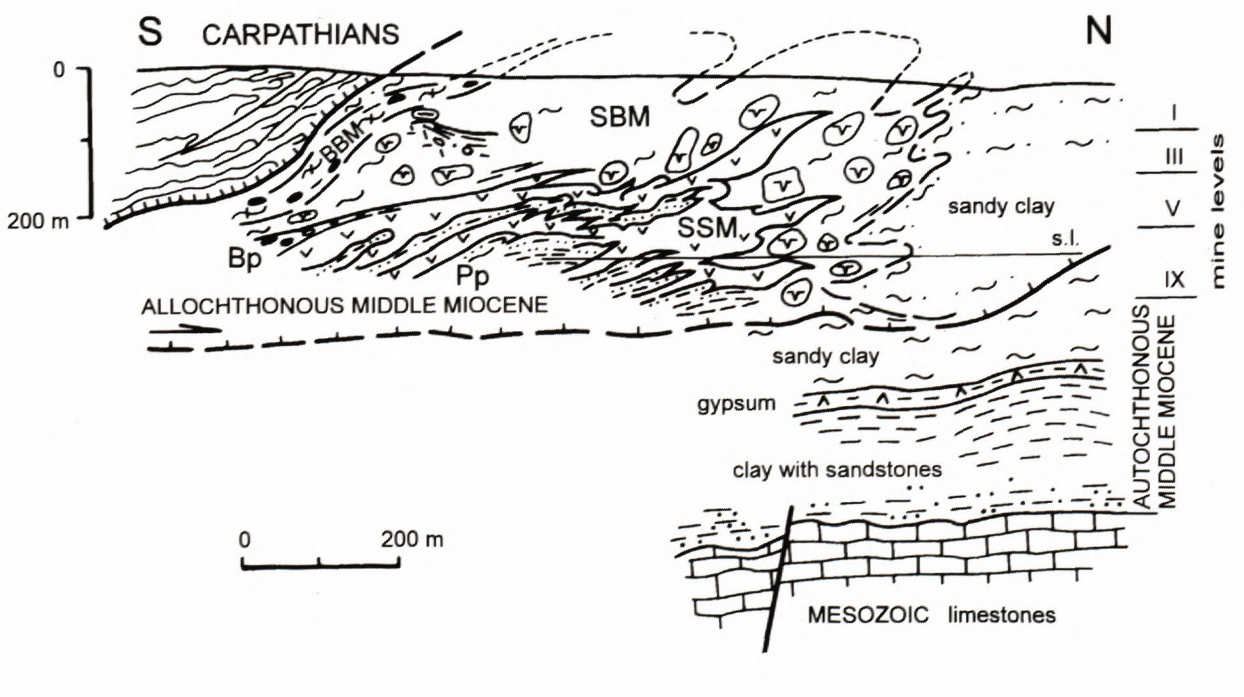


Fig. 3. Structural cross-section of the Wieliczka Salt Mine (after Gawel, 1959, modified). Explanation of letter symbols: P_p – clay and sandstones below the salt-bearing sequence; SSM – Stratified Salt Member; B_p – lens of halite conglomerates in upper Spiza; SBM – Salt Breccia Member; BBM – Barren Breccia Member.

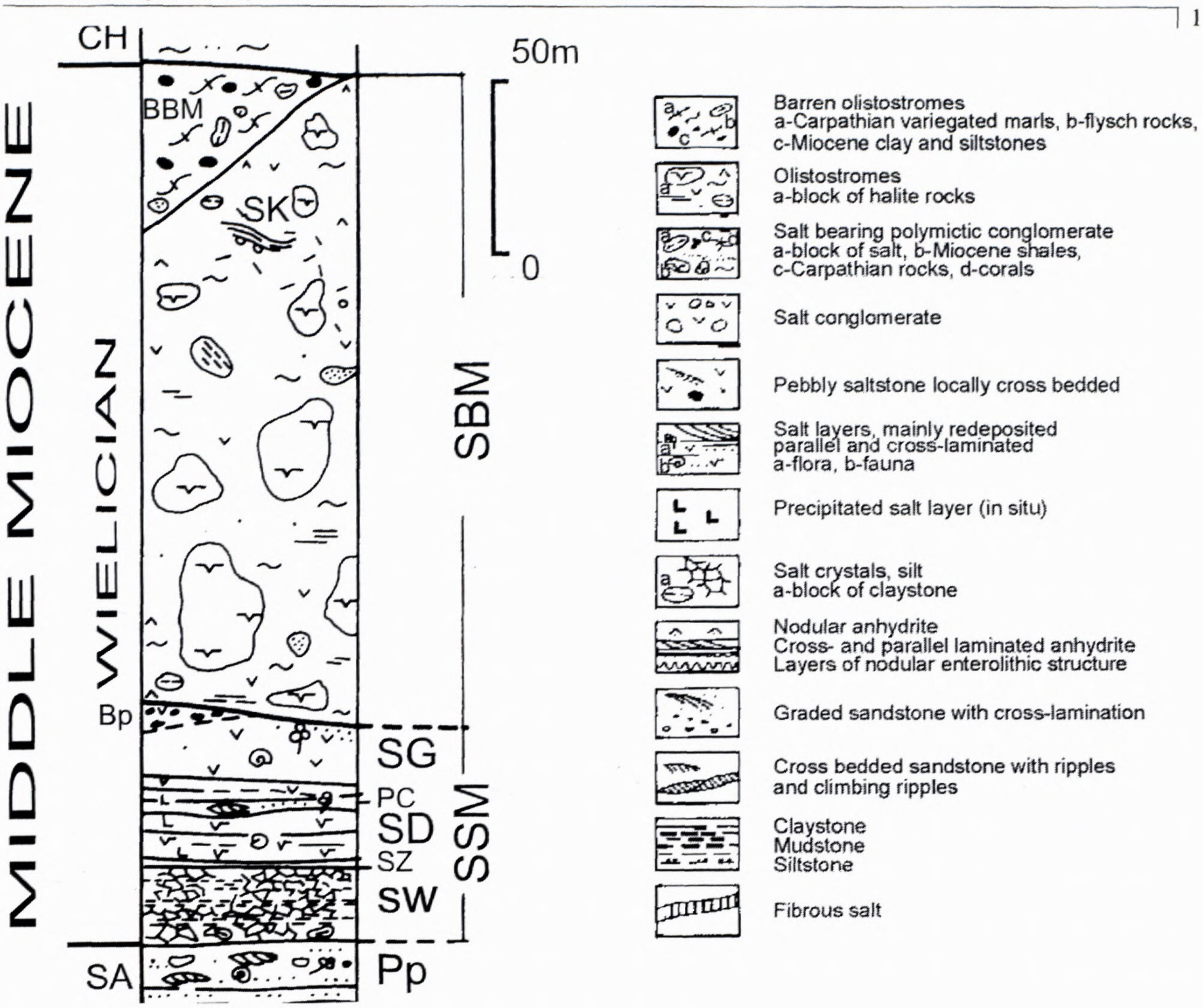


Fig. 4. Generalised litho-stratigraphic column of the Wieliczka salt deposits.
Explanation of letter symbols: Pp, SSM, SBM, BBM, - see Fig. 3; SA - marine clays and sandstones (Skawina Beds); SW - Green Salt; SZ - Shaft Salt; SD - Lower Spiza Salt; BP - pebbly saltstones and conglomerates; SK - intercalation of saltstones (Klęczki); CH - marine clays and sands (Chodenice Beds).

Salt Breccia Member (SBM) (Niedźwiecki, 1883, 1884; Gaweł, 1962). The lower member is made of stratified, partly redeposited salts (halite) together with "barren" rocks. The upper member is composed of olistostromes (Kolasa & Ślaczka, 1985) with huge halite blocks and grains chaotically distributed within a finer grained matrix of halite grains and clay. This type of deposit is known in mining nomenclature as the Zuber. The evaporitic sequence is overlain by tectonically deformed marine claystone and sandstone (CH on Fig. 4).

1. Stratified Member

The Stratified Member consists of three units: A) Green Salt, B) Shaft Salt, C) Spiza Salt.

A) Green Salt Unit (SW on Fig. 4).

The Stratified Member begins (Figs 4 and 5) with several layers composed of primary coarse halite crystals that originated from direct precipitation (Garlicki, 1979). These crystals are enclosed in clay material (Fig. 6), the Green Salt of mining nomenclature. Within some of the salt layers there are sporadic single pebbles and cobbles of Miocene marl and anhydrite and the layers resemble pebbly mudstones. These features suggest that resedimentation processes occurred during sedimentation of the Green Salt Unit. The salt layers are intercalated with thin rock layers devoid of salt crystals. These intercalations generally thin towards the north. They are composed of sandstones, cemented by salt and anhydrite, and mudstones. There are also anhydrite-rich layers that commonly occur in thin cyclic sequences. Such cycles consist of massive and laminated sandstones overlain by mudstone and then by anhydrite (Figs 6 and 7A). Commonly, the lower portion of the cycles is absent. The sandstones contain numerous anhydrite grains and nodules and a smaller quantity of biogenic debris. Part of the anhydrite layers are characterized by very thin laminations, probably indicating a quiet depositional environment.

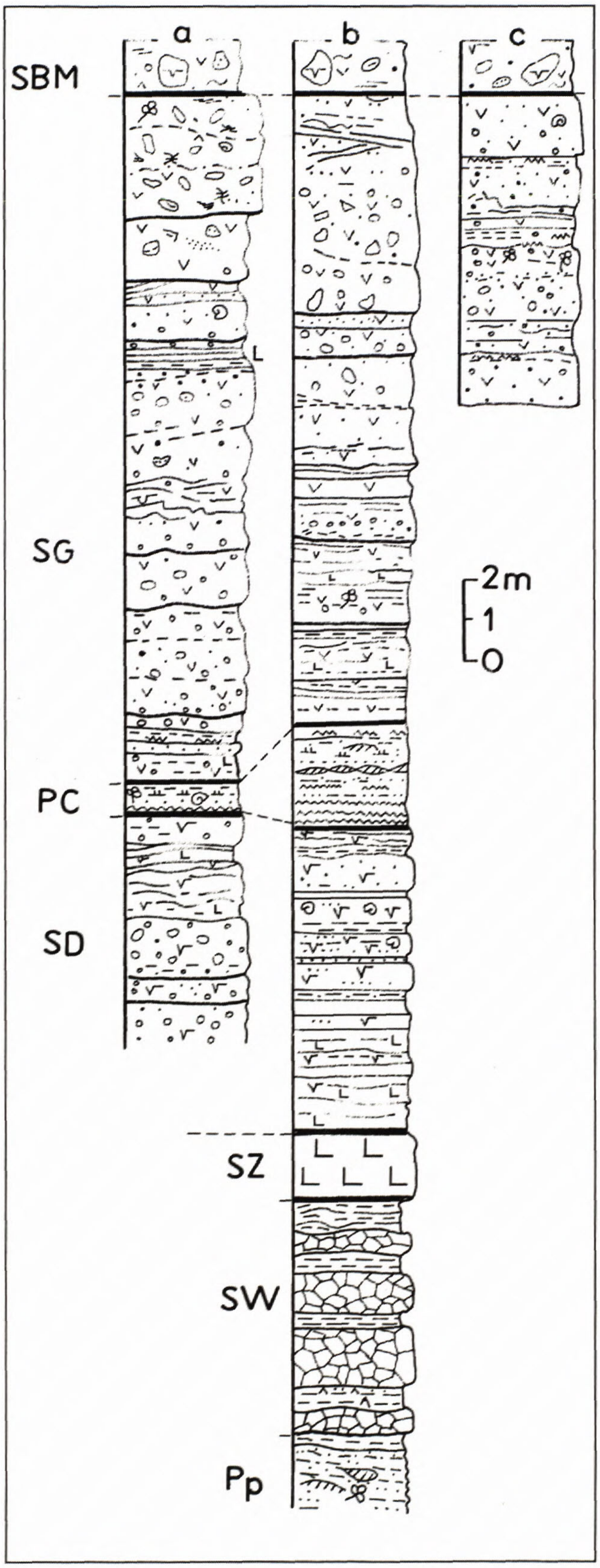


Fig. 5. Lithostratigraphic columns of the Layered Salt Member in the southern (a), central (b) and northern (c) part of the Wieliczka Salt Mine. (Explanation of lithological symbols as in legend to Fig. 4).

B) Shaft Salt Unit (SZ on Fig. 4)

The Green Salt Unit is overlain by about 2 metres of pure halite (Figs 4 and 5) which includes abundant primary cubic crystals. This salt represents a period of quiet deposition by precipitation. There is no evidence of redepositon within the salt layers.

C) Spiza Salt Unit

The Shaft Salt is overlain by salt layers formed partly by precipitation and partly by redeposition. The Unit can be divided into two parts: Lower Spiza (SD in Fig. 4) and Upper Spiza (SG on Fig. 4), separated by the Central Barren Intercalation (Figs 4 and 5).

The Lower Spiza sub-unit consists of layers of pure halite intercalated with thin laminae composed of quartz arenite material and anhydritic grains and nodules, banded white and grey pure halite, and layers of halite with fragments of Miocene marl and sandstone. There are also thin intercalations of mudstone and very fine sandstone.

The Lower Spiza salt is overlain by a few metres of the barren unit (Central Barren Intercalation - PC, Figs 4 and 5). In the central part of the Wieliczka salt succession the barren unit attains its maximum thickness (Fig. 7B) and becomes thinner both towards the south and north (Kolasa, 1990). Generally the barren unit is composed of sandstones (siliciclastic) but locally in the southern area it is dominated by homogeneous mudstones. In the area where the barren unit is clastic, the lower part is composed of several lithologies similar to those described from the stratified member. Commonly the individual cycles start with sandstone and pass upwards into marly mudstone, clayey shale, and terminate in anhydrite and sporadic salt layers (upper part of column PC A on Fig. 7B). In the upper part of the section, the number of evaporitic intercalations decreases. The lower parts of the sandstones are occasionally graded and often the sandstones and mudstones display current ripples (Fig. 8) and convolute laminations. The azimuth of the ripple-foreset planes is generally stable and directed towards the east and northeast.

Above the Central Barren Intercalation lies the main unit of redeposited salt (Upper Spiza salt - SG on Fig. 4, Fig. 5). In the lower part of this unit there are layers of transparent halite, sometimes with dark and white bands, made up of medium sized salt crystals mixed with quartz grains and fragments of reworked fossils from different environments and of different ages. In the middle portion of the sequence, layers of precipitated salt are intercalated with layers of redeposited salt. Thin intercalations of marls containing scarce, autochthonous foraminiferal assemblages occur sporadically. In the higher part of the section, most of the halite is reworked and forms layers composed of halite clasts, together with sandstones and conglomerates. The lateral and vertical distribution of the lithofacies is shown on Fig. 5. The pebbly saltstones and conglomerates (Figs 4 and 5) occur in the uppermost part of the salt sequences in the southern part of the basin (Fig. 9B). Salt-clast rudites (Figs 9A and 11A) prevail in the central area; saltstones prevail in the northern area.

Some of the layers are strongly folded (Figs 10 and 12). These structures may represent synsedimentary slumps although some of them may have a tectonic origin.

Petrographic composition of redeposited material in the Upper Spiza Subunit

Redeposited layers consist mainly of grains and fragmented crystals of halite. Large halite grains, up to a few centimetres across, are coated sporadically by thin layers of clay and gypsum. Besides the halite grains, there are anhydrite and gypsum grains or crystals, quartz grains, clay minerals (illite, kaolinite and less common montmorillonite, Pawlikowski, 1978), organic detritus (Spiculae, foraminifera, fragments of shells) and lithic fragments (micritic limestone, shale, sandstone). Minor accessories include feldspar, calcite, glauconite, micas, Fe-minerals, zircon, and titanite. The content of none-vaporitic material varies from less than one percent to more than 60 percent.

Locally there are zones enriched in fragments of carbonized flora (fruits, seeds, leaves and wood), preserved in the form of lignite (Unger, 1850; Zabłocki, 1928, 1930; Łańcucka-Środoniowa, 1984).

The grain size of the halite varies from fine to very coarse. The grain shapes are generally angular; cubic and ellipsoidal halite shapes are less common. Some of the cubic crystals evidently grew by displacement after sedimentation. The pebbles, mainly angular, range in size from 3 to 8 cm, and sporadically reach 1 m (boulders). They are composed of laminated salt, quartzitic sandstone, graywacke of Carpathian origin, Miocene clayey marls and smaller amounts of individual coral fragments, Bryozoa, Lithothamnion, molluscs and snails (Reuss, 1867; Niedźwiecki, 1883, 1884; Kowalewski, 1935; Kulka, 1980; Morycowa & Roniewicz, 1987). The laminated halite blocks generally differ from the laminated salt found *in situ* in the lower part of the salt sequence in the Wieliczka mine. The laminae in the blocks are wavy and often are similare to stromatolitic structures.

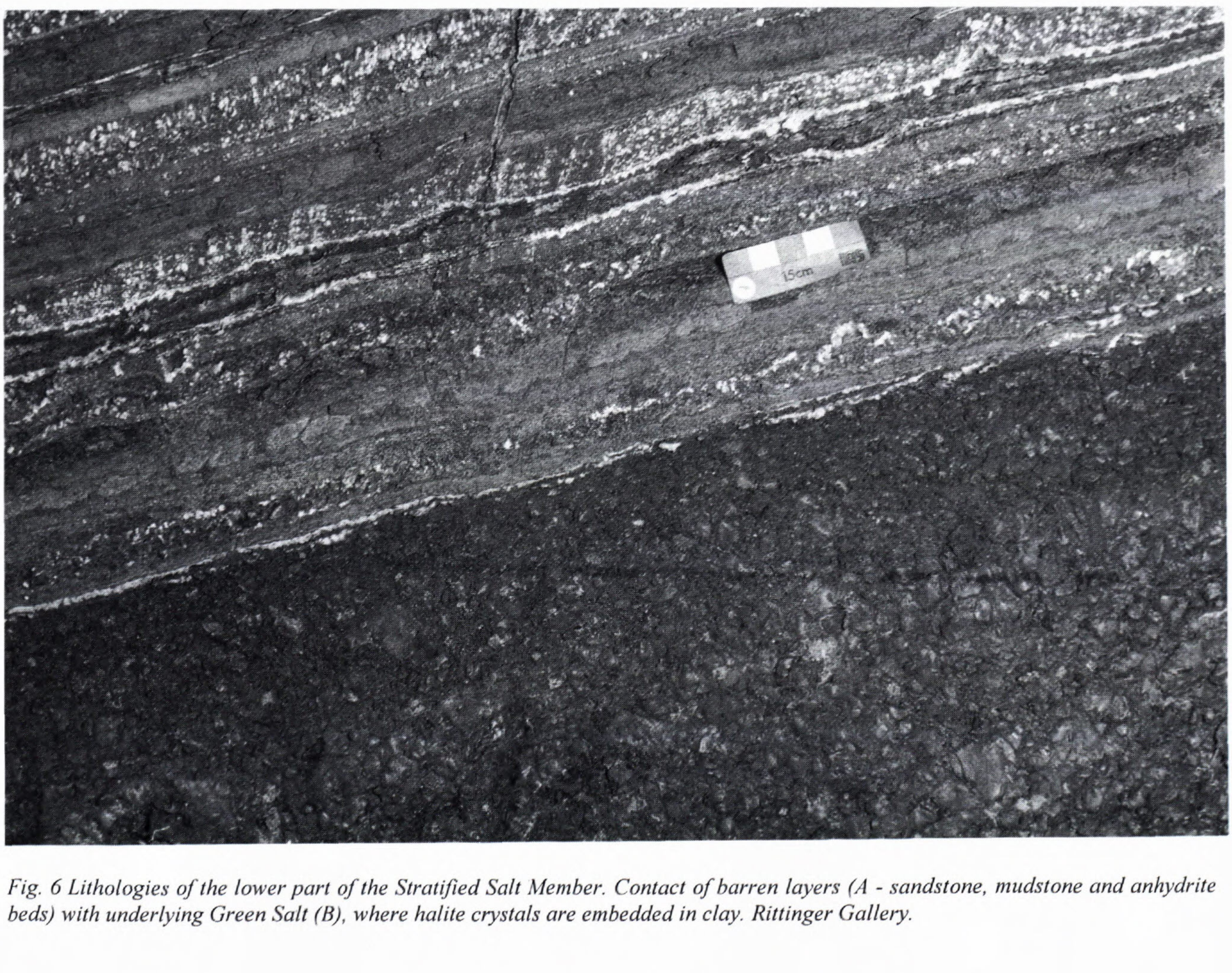


Fig. 6 Lithologies of the lower part of the Stratified Salt Member. Contact of barren layers (A - sandstone, mudstone and anhydrite beds) with underlying Green Salt (B), where halite crystals are embedded in clay. Rittinger Gallery.

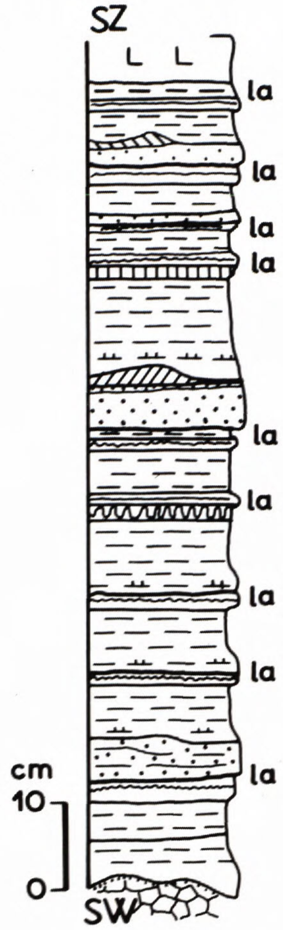


Fig. 7A. Sedimentary sequence of barren intercalation between Stained-glass type Salt (SW - see explanation in text) and Green Salt (SZ) with laminated anhydrite (la) in Prokopowicz Gallery.

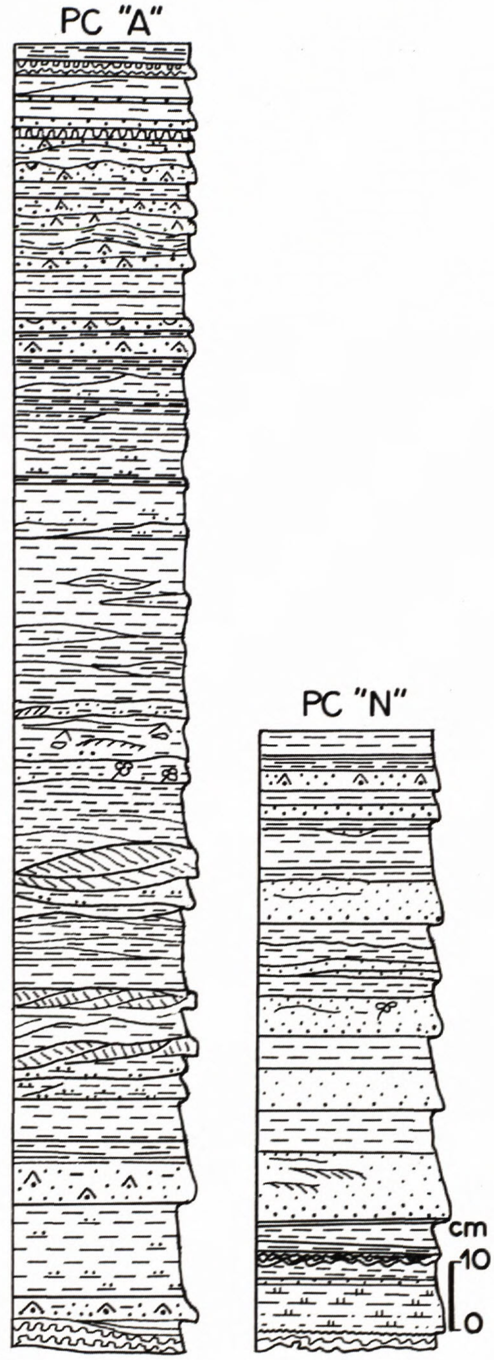


Fig. 7B. Comparison of sequences of the Central Barren Intercalation (PC) from the central ("A" - Albrecht Gallery) and northern part ("N" - Prokopowicz Gallery) of the Wieliczka Mine. (Symbol explanations as in Fig. 4).

Characteristic of resedimented salt

Laminated and graded saltstones

This lithofacies is represented by medium to very coarse grained, partly conglomeratic strata which commonly show parallel laminations (Figs 10 and 11B) or gradation and consist mainly made of salt particles.

Laminated saltstones occur either as individual beds or they form the upper part of graded beds. They consist of alternating grey and white laminae. Grey laminae are composed of a mixture of halite grains, clayey material and anhydritic sand. White laminae are composed mainly of halite. Sporadically there are siliciclastic laminae composed of quartz grains and clay. The thickness of individual beds varies from 0.5 to 1.5 m.

Parts of the saltstones infrequently display cross-lamination. Some layers are markedly structureless, almost homogeneous in grain size, and lensiform (Fig. 10B). The bases of these beds are sharp and flat.

Interpretation. The graded and laminated saltstones show many features characteristic of sediments deposited by debris flows, turbidity currents. The structureless beds might have been formed by grain flow or fluidised flow mechanisms. Most of the structures observed correspond to those in the A, B, and C divisions of the Bouma turbidite sequence; the structureless beds resemble the fluxoturbiditic sequences (F division according to Ślączka and Thompson, 1981). Some salt layers with crudely parallel lamination do not provide evidence of redeposition and might have been deposited by precipitation.

Conglomerates

These are composed of pebbly to bouldery salt clasts (Fig. 11A) scattered within a matrix of coarse- to medium grained salt (matrix-supported conglomerates). They contain occasional shaly clasts. Conglomerates form sheet-like and lens-like bodies that range in thickness from a few decimetres to 6 meters (Fig. 10a). The base of the conglomeratic beds is sharp, usually flat, but occasionally displays flame and load structures (Fig. 13) or scour marks. Wavy basal contacts, visible in some beds, are probably an effect of the sliding movement of already deposited beds, caused by depositional and post-depositional deformation. The majority of these conglomerate beds fine upwards and pass into horizontal- and cross-laminated saltstones. They can also show crude inverse grading.

In the southern part of the salt mine there are polymictic conglomerates. These are characterized by the occurrence of numerous unsorted or poorly sorted clasts, mainly poorly rounded blocks of different salt rocks as much as 1 m in length, broken halite crystals and grains, together with blocks of Carpathian flysch sandstones (as much as 50 cm in diameter) and Miocene marls (Figs 14, 15 and 16). Locally there are many fragments of corals. These polymictic conglomerates display cross bedding (Fig. 16A). The thickness of the layers is as much as 80 cm and contacts between them are usually indistinct (Fig. 14A). In sections perpendicular to the direction of sediment transport, the conglomerates are lenslike (Fig. 16B). In the central part of the lens, clast- supported conglomerates are common; towards the margins, they pass into matrix-supported conglomerates.

Interpretation. The features described indicates that the conglomeratic rocks were transported by high-density debris flows. However, those conglomeratic layers containing angular clasts might be storm deposits.

Pebbly saltstones

These rocks consist of thick (as much as 2 m) beds of medium to very coarse, poorly sorted salt grains together with irregularly scattered, subangular to rounded, sometimes imbricated, pebbles and boulders (< 1m) of Carpathian sandstones and Miocene marls (Figs 17B and 17A). In some beds the matrix contains clay. Locally, layers rich in anhydrite fragments can be found. The

Fig. 8. Central Barren Intercalation. Rippled and cross-laminated siliciclastic sandstones, siltstones and layers of nodular anhydrite, some having enterolithic structures. Albrecht Gallery.

pebbly saltstone beds are sheet-like and extend over distances of tens of metres. They are generally structureless, although some units display crude cross-laminae which dip up-current. In some cases the layers of the pebbly saltstones are terminated by a parallel-laminated section.

Interpretation. The observed structure suggests that pebbly saltstones similar to normal pebbly mudstones, represent sediments deposited by subaqueous debris flows or incoherent slump which passes into high density turbidity currents. That process best explains the sedimentation of layers containing chaotic mixture of multisized clasts (comp. *e.g.* Friedman & Sanders, 1978).

2. Salt Breccia Member

The Salt Breccia Member (SBM in Fig. 4) is an unsorted mixture of pebble-, boulder- and block-size clasts scattered in a finer grained matrix and is about 150 m thick (Fig. 4). The occurrence of sporadic intercalations of saltstone suggests that this complex was not formed in

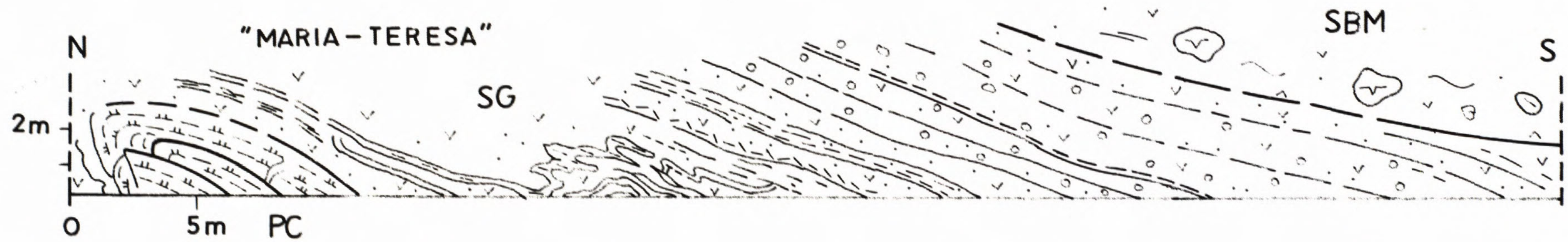


Fig. 9 (A) Cross-section through the folded Upper Spiza (SG) unit with salt conglomerates and contact with the overlying unit - Salt Breccia Member (SBM). Thrust-faulted Central Barren Intercalation rocks (PC) occur in the core of an anticline to the north. Maria Teresa Gallery.

Fig. 9 (B) Cross-section through the uppermost part of the Upper Spiza (SG) unit in the southern part of the Wieliczka Mine with pebbly saltstones and polymictic conglomerates. Salt Breccia Member (SBM) at the top. Gruszczyn Gallery. Symbol explanations as in Fig. 4

A

B

Fig. 10 Lithologies in the Upper Spiza unit (Gallery west of Kościuszko shaft): (A) laminated saltstones, strongly deformed in the lower part of the photograph; polymictic breccia in the upper part with halite and flysch blocks intercalated between laminated salt deposits. Scale is 1 meter long; (B) Laminated, bar-form saltstones overlain by pebbly saltstones.

one depositional episode. The known extent of this member is about 15 km in length and 4 km in breadth.

The contact with the underlying Stratified Member is sedimentary in character (Kolasa & Ślączka, 1985), although the Salt Breccia Member is regarded by some authors as an overthrusted tectonic breccia (Gaweł, 1962; Poborski & Skoczylas-Ciszewska, 1963; Garlicki, 1979). However, the contact has local irregularities caused by erosional processes (Fig. 18). Tectonic effects along that contact are only local and are mainly related to fold crests. On the fold limbs there is generally a lack of slickensided surfaces or other tectonic features.

Halite blocks are the chief component of the Salt Breccia Member (Fig. 19), forming more than 90 per cent of the clasts. The salt clasts are angular, subangular, and rounded. The sizes of the blocks range from a few cubic meters to 12,000 cubic meters, but several blocks have very large volumes, as much as 100,000 cubic meters. They consist of different salt lithologies, such as wavy laminated salt, layered salt, structureless salt, dolomitic salt, or the "stained glass" type of salt (a local name for a rock composed of irregular salt crystals separated by thin layers of clay). The structure of the salt in the clasts is usually different than the structures in the Stratified Member. Some of the salt blocks are enveloped by a thin layer of anhydrite, gypsum or salt of secondary origin which is usually connected with radial secondary veins. Large blocks are commonly imbricated, with their c-axes parallel to the trend of the Carpathian border. In the lower part of the complex the blocks commonly rest in horizontal attitude.

Less common within Breccia M. are much smaller fragments (as much as a few metres across) of Miocene rocks (marls, claystones and sandstones that are contemporaneous with or slightly older than the enveloping salt sediments). Other constituents include variegated Late Cretaceous marls, black Albian shales, and various Cretaceous sandstones of Carpathian provenance. Usually these clasts are angular or subangular and their lengths range from a few to about a dozen centimeters. They are insignificant in volume and commonly are concentrated near the base of the Breccia Member. Occasionally there are also large (as much as 30 cm in length) single crystals of halite that are covered by a thin film of gypsum-bearing mud.

The matrix contains varying proportions of calcareous mudstone and claystone, together with halite crystals and grains (Fig. 19)., many of which display hopper structure. Less common are grains (fragments and crystals) of anhydrite and gypsum. Halite crystals and grains can form as much as 75 per cent of the Breccia matrix but in the uppermost part of the sequence they are scarce. The matrix also contains redeposited foraminifera from different stratigraphic units of the Middle Miocene, Palaeogene, and Cretaceous. Redeposited shallow water faunal elements are minor constituents. The breccia matrix is marly in the lower part of the sequence and more clayey in the upper part. Locally, the amount of matrix diminishes, and the rocks described above pass into clast supported conglomerates. At one locality between two layers of sedimentary breccia an intercalation (Fig. 20) of graded salt conglomerate was observed. In the upper part of the layer the conglomerate passes upward into coarse grained, cross-laminated (Fig. 21) and parallel-laminated saltstone.

Interpretation. From the foregoing descriptions, based mainly on studies of the breccia, including the blocks of different provenance imbedded in fine grained material and the sedimentary structures, it seems clear that the Breccia Member is essentially a product of submarine debris flows and might represent "mega-debrites", which could result from earthquakes caused by Mid-Miocene tectonic movements.

3. Barren Breccia Member

In the southern part of the Wieliczka mine, the Salt Breccia Member is overlain by a sequence of debrites (Reading, 1986) (60 m thick) that are devoid of salt particles and clasts. The sandy, marly and clayey matrix of these debrites hosts abundant dispersed clasts of various Carpathian rocks (variegated marls, black shales, sandstones), together with Miocene marls that are older than the salt deposits (Alexandrowicz, 1975). Clasts of anhydrite and Miocene sandstones are less common. The Carpathian clasts are angular to subrounded and can reach 1 metre in diameter. The size of the Miocene clasts is usually greater, attaining several metres. Part of the Barren Breccia Member has been strongly affected by tectonism associated with overthrusting of the Carpathians.

Interpretation. Similar to the Salt Breccia Member, the Barren Breccia Member is also essentially a product of submarine debris flow - it is thick bedded, poorly sorted, internaly structureless and is composed of fine grained, mudstone matrix that contains rock fragments which range in size from pebbles to boulders.

The Salt and Barren Breccia Members are overlain by marine claystone containing gypsum crystals and sands (CH on Fig. 4).

Depositional setting

The development of the Wieliczka salt basin was closely related to vertical tectonic movements and the northward advance of the Carpathian nappes. At the beginning of salt sedimentation (Fig. 22), when tectonic activity was slow, halite and sulphates were precipitated throughout the basin. However, in the southern part of

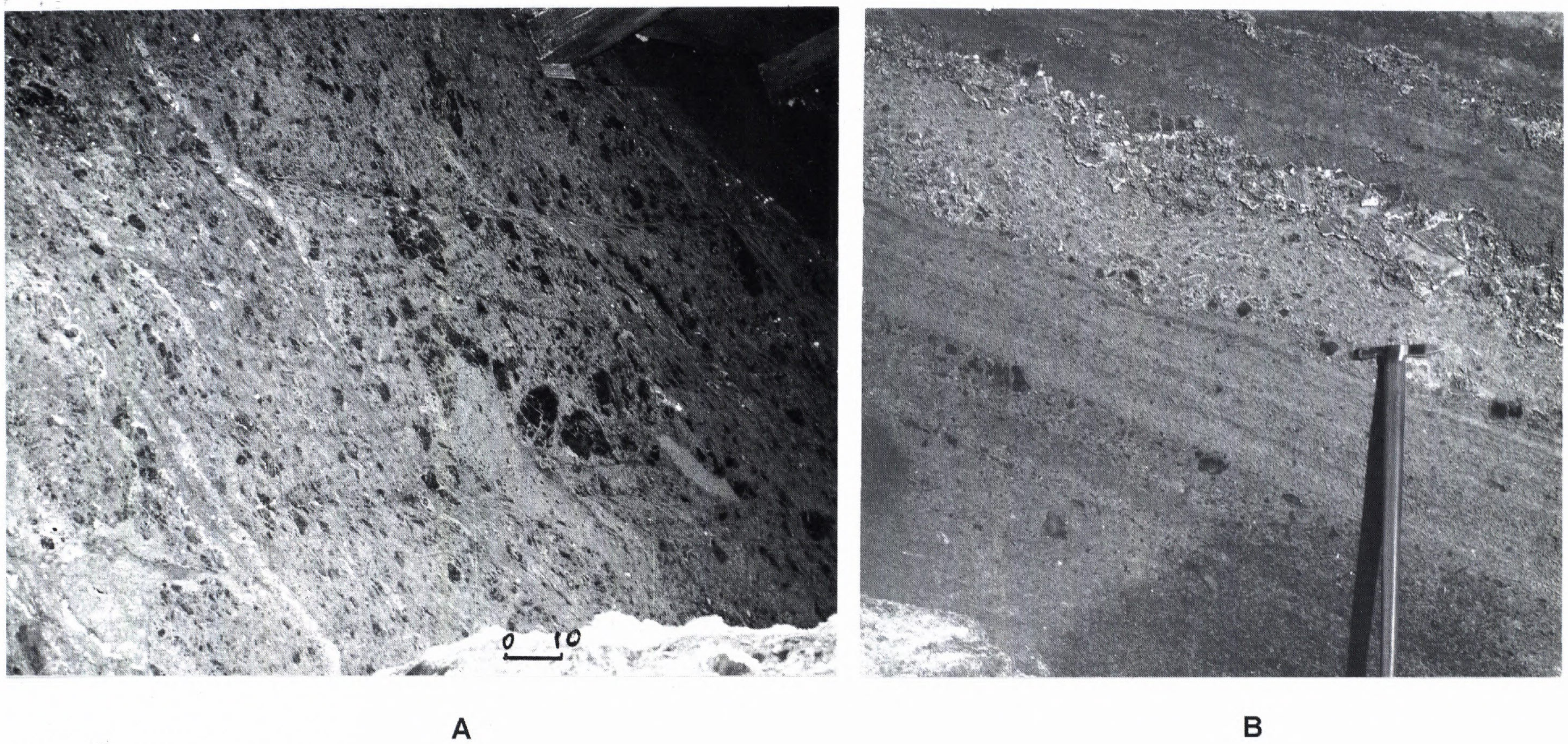


Fig. 11. Lithologies in the Upper Spiza unit:
(A) Conglomerate composed entirely of salt particles and pebbles. Warszawa Chamber.
B) Coarse-grained and conglomeratic saltstone, structurless in the lower part and laminated in the middle part of the photograph. Gallery west of Kościuszko shaft.

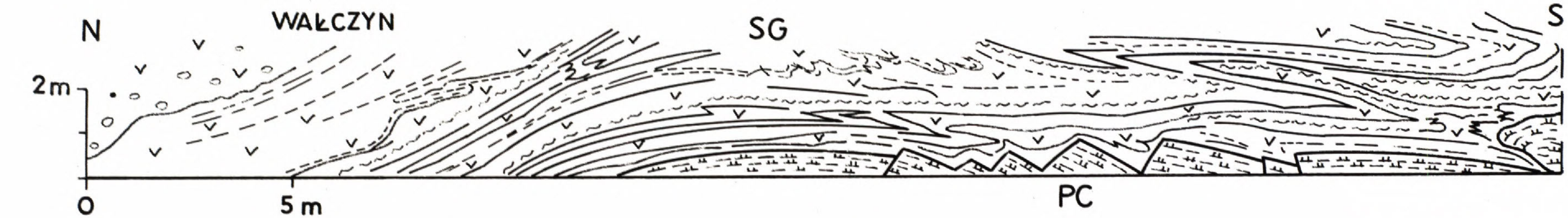


Fig. 12. Cross-section along the Wałczyn Gallery showing ductile folds in the Lower Spiza unit, probably of tectonic origin. In contrast, the Central Barren Intercalation (PC) displays more brittle deformation with faults. Symbol explanations as in Fig. 4.

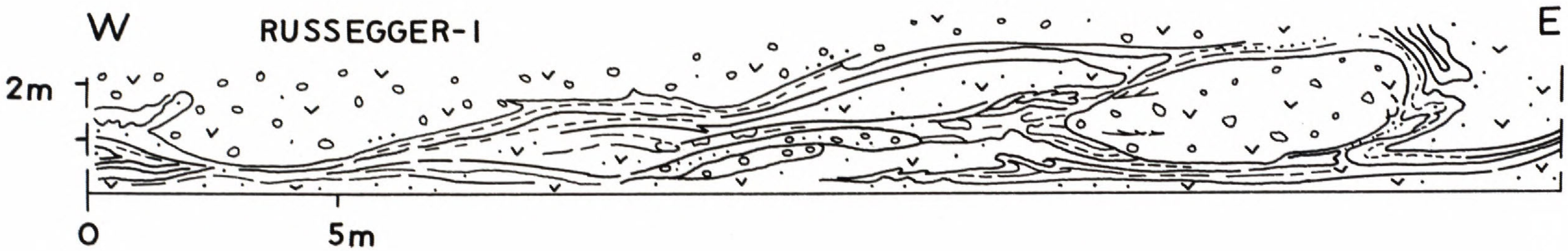
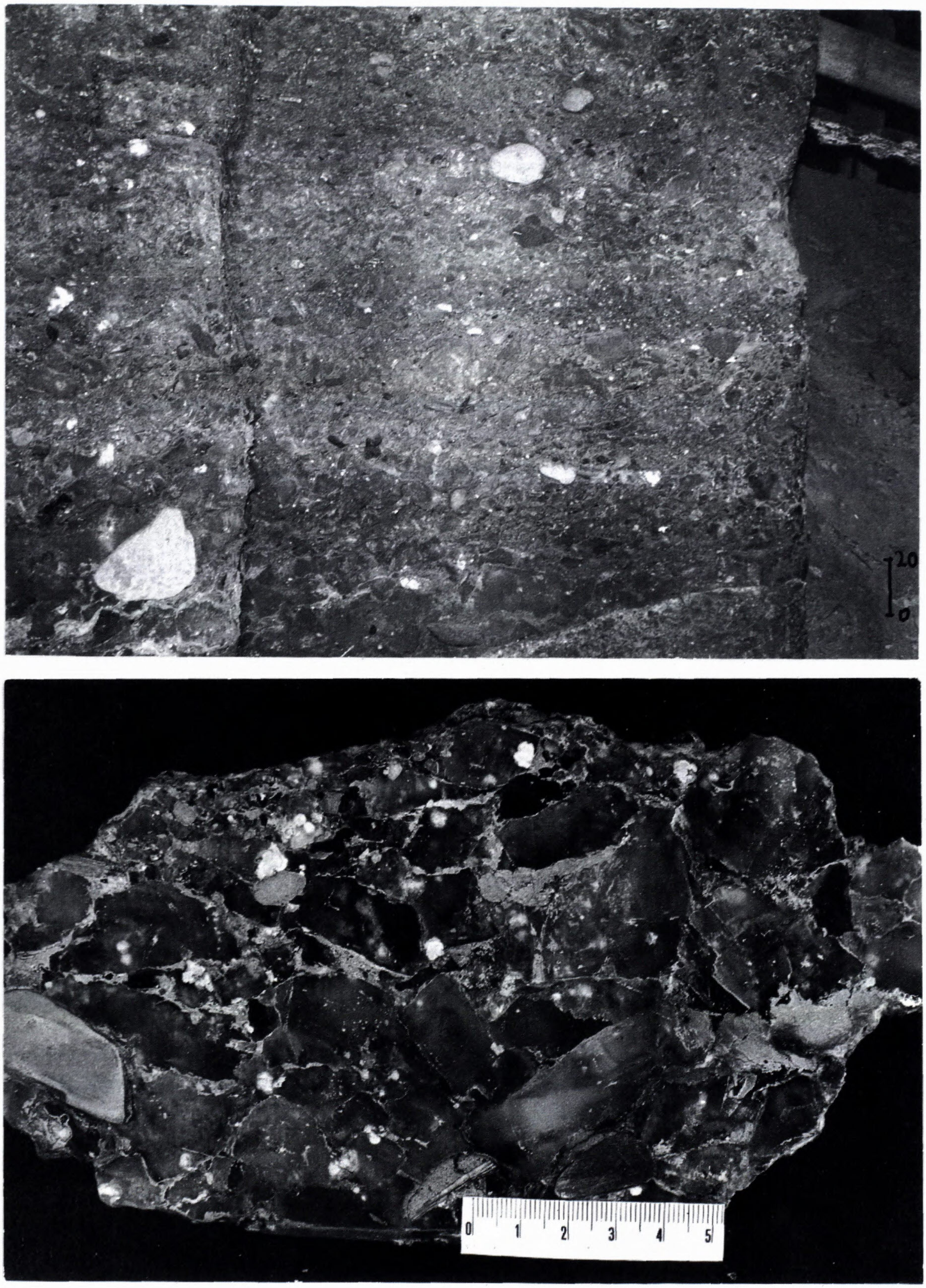


Fig. 13. Cross-section along the Russeger Gallery showing salt conglomerate beds in the Upper Spiza unit with giant load structures. Symbol explanations as in Fig. 4.

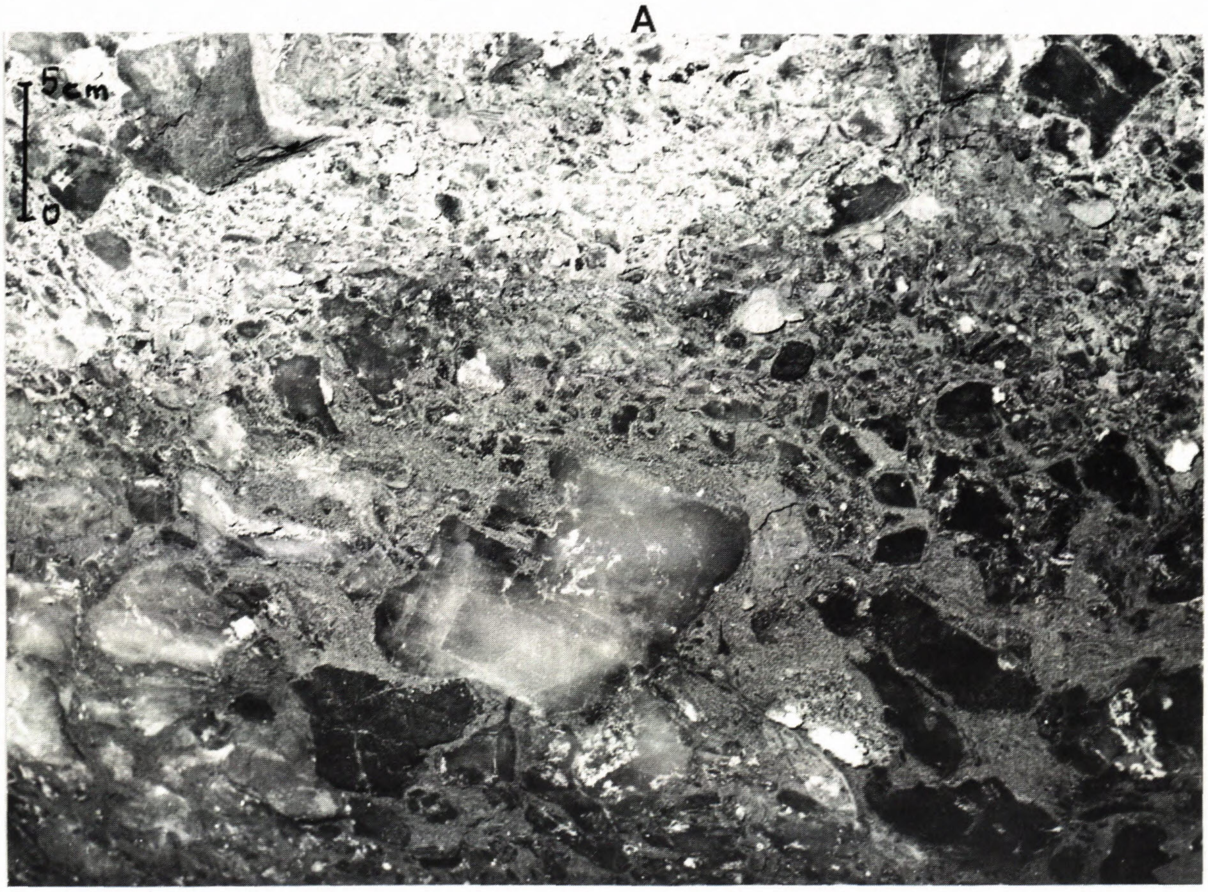


A

B

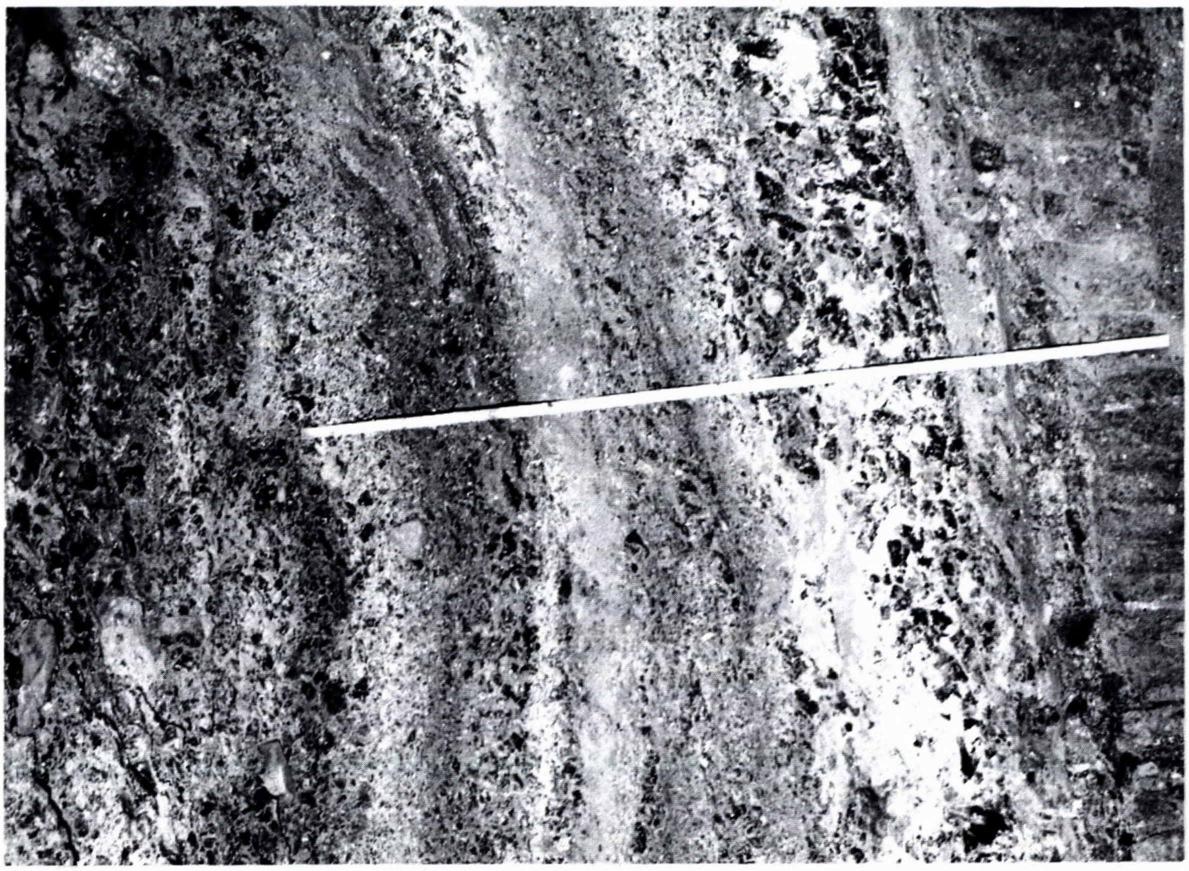
Fig. 14. Lithologies in the Upper Spiza unit from the Gruszczyn Gallery:
(A) Polymictic, clast-supported conglomerate with crude lamination. Scale bar is 20 cm;(B) Cut slab of unit shown in (A). Fragments of halite crystals, clast of marls (grey, rounded) and sandstones.

A



B

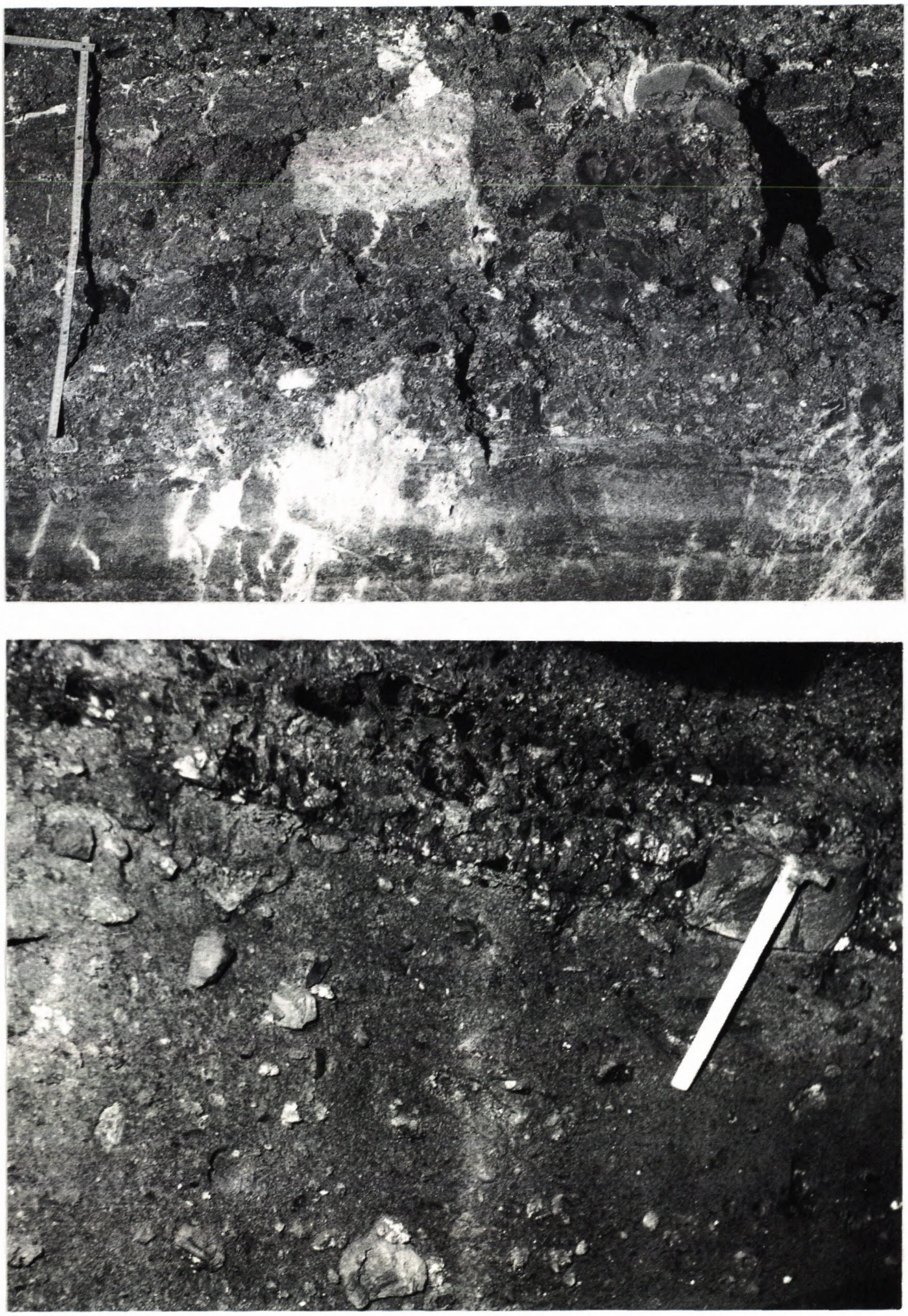
Fig. 15. Lithologies in the Upper Spiza unit: (A) Matrix supported, graded conglomerate with fragments of halite crystals and single clasts of angular to well rounded Carpathian and barren Miocene rocks. Secondary gallery of the Gruszczyn Gallery. Scale bar is 10 cm; (B) Close-up view of the unit shown in (A).



B

A

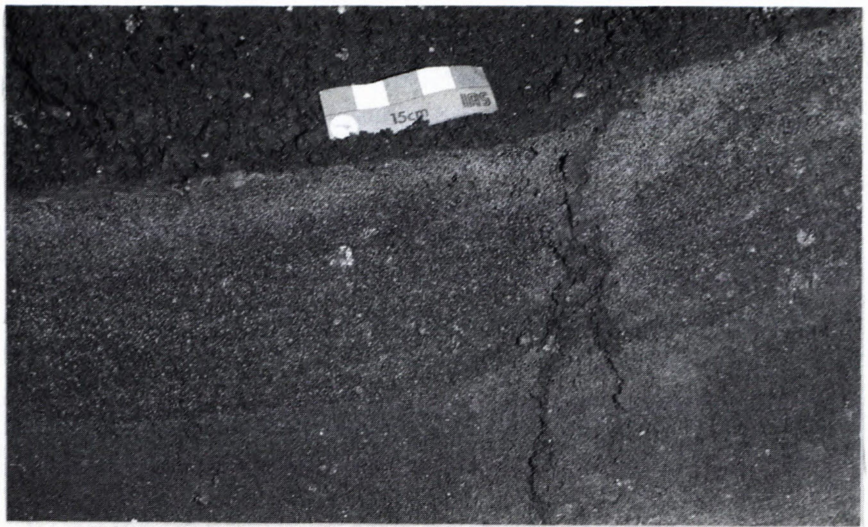
Fig. 16. Lithologies in the Upper Spiza unit: (A) Profile in terminal part of the Gruszczyn Gallery parallel to the direction of transport of detritic material, showing progradational, cross-bedded polymictic conglomerates; (B) Profile in the secondary gallery of the Gruszczyn Gallery showing polymictic conglomerates, perpendicular to the direction of transport. Note the pinch out of several layers and the contact with underlying pebbly saltstones (A). Length of measuring rod is 200m.



A

B

Fig. 17. Lithologies in the Upper Spiza unit:
(A) Polymictic conglomerate with a salt-rich matrix, transitional to pebbly saltstone. In addition to Carpathian and barren Miocene clasts fragments of large halite crystals are observed. Coral is visible at the lower end of the 80 cm. long scale. The conglomerate is underlain by laminated salt. Gallery west of the Kościuszko shaft.
(B) Thick-bedded pebbly saltstone. Pebbles and cobbles of Carpathian sandstones are scattered in salt matrix. The basal part of the polymictic salt conglomerate shown in (A) forms the top part of this photograph. Length of hammer is 40 cm. Thinfeld Gallery.

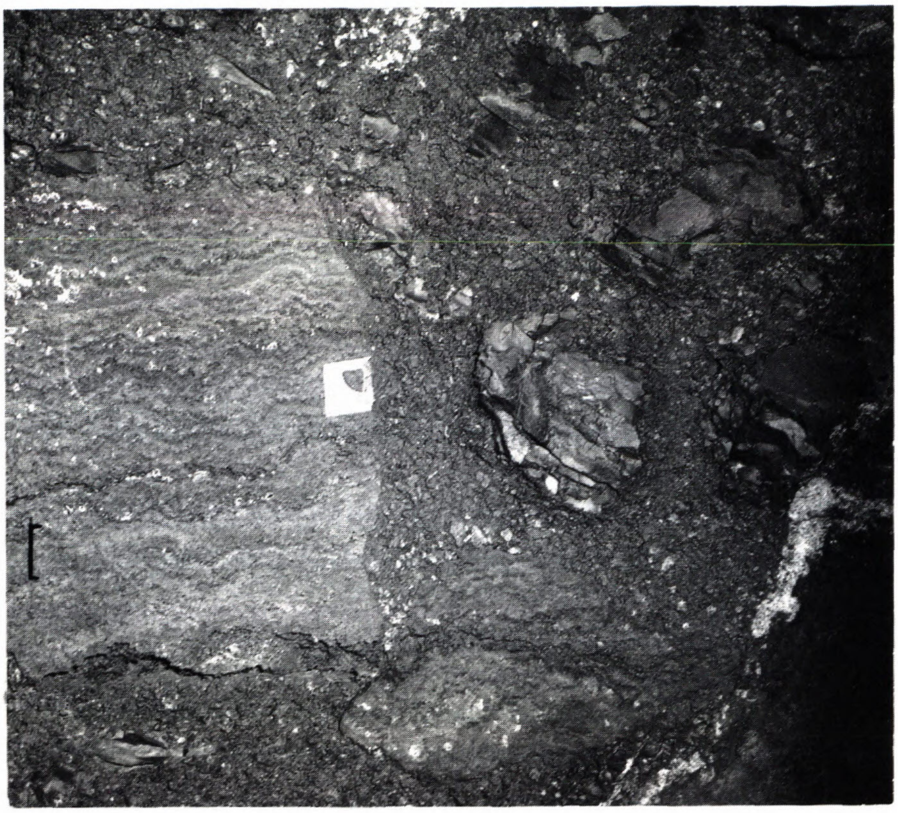


A

B

C

Fig. 18. Varied nature of the contact between the Stratified Salt Member and the overlying Salt Breccia Member.
(A) Upper contact of the Stratified Salt Member, as represented by coarse saltstones, and the Salt Breccia Member represented by clay rich matrix with halite crystals. Wessel Gallery.
(B) Similar contact as in (A) but here the Salt Breccia Member is rich in clasts. Lichtenfels Gallery.
(C) Uppermost part of the Stratified Member here shows parallel laminations and slump-like structures. Russeger Gallery. Length of hammer is 40 cm.



A

B

Fig. 19. Lithologies in the Salt Breccia Member:
(A) Clasts of laminated salt and Miocene marls imbedded in clay-rich matrix. Kunegunda Gallery. Scale bar is 10 cm. long.
(B) Salt clasts (dark) set in halite-rich matrix. Lichtenfels Gallery. Length of hammer is 40 cm.

Fig. 20. Cross-section in the Kłęczki chamber showing the nature of the unit intercalated between two mega-debrites in the Salt Breccia Member. The intercalation here comprises graded salt conglomerates terminated by cross-bedded saltstones.

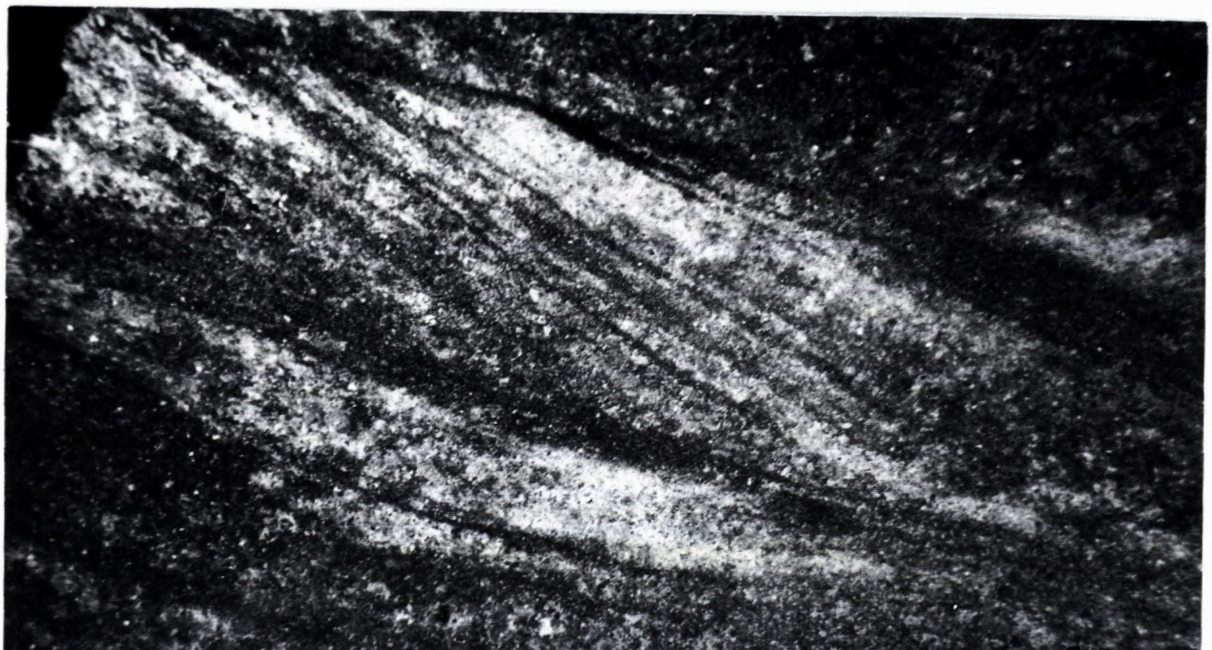


Fig. 21. Salt Breccia Member: cross-bedded, coarse grained saltstone in the intercalation between two mega-debrites. Kłęczki Chamber. Scale bar is 10 cm.

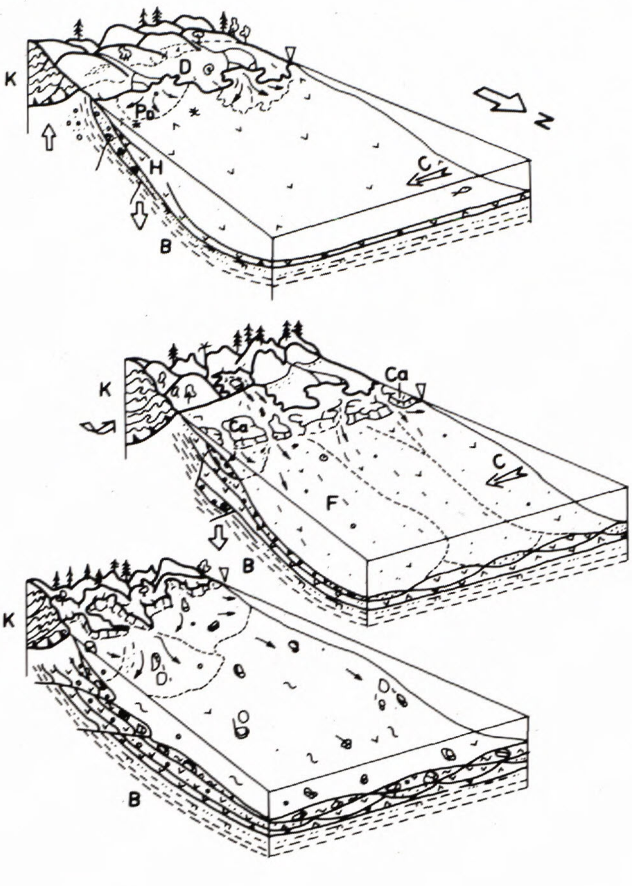


Fig. 22. Schematic diagrams illustrating the sedimentary evolution of the southern and central part of the Wieliczka salt basin. The transition towards the sulphate facies is omitted.
I. Initial stage: widespread precipitation of salt. FD-local fan-deltas; D-shallow water siliciclastic and carbonate deposits with fauna; H-evaporitic, mainly halite deposits; C-main current direction; K-Carpathian Thrust sheet; B-lower Badenian deposits.
II. Beginning of resedimentation of salt in response to tectonic movements in marginal area. Ca-?partially karstified older salt deposits; F-submarine fans P-polymictic conglomerates.
III. Final stage of salt basin development, with widespread mass movements. O-olistoliths.

the basin, the accumulation of halite was more rapid than in the central part, and resulted in the formation of thick layers, which can be inferred from the size of the salt blocks within the Salt Breccia Member. In the more northern, central, and probably deeper part of the basin, the precipitated salt layers were thinner (Green and Shaft Salt, Fig. 22-I). There was also sporadic deposition from density currents.

An increase in tectonic activity led to the accumulation of layers of redeposited salt (Spiza Salt). The siliciclastic sediments observed within the central barren complex can be ascribed most plausibly to a temporary lowering of sea level and an increasing supply of terrigenous material. However, even during this period the sea remained relatively deep, as can be inferred from the lack of desiccation marks, wave ripples, and a shallow water fossil fauna.

During deposition of the central barren complex, permanent longshore currents prevailed and moved in an overall W-E direction. Deposition from traction currents was followed by redeposition from density currents and subordinate debris flows (Upper Spiza, Fig. 22-II). In the area described, there were several depocentres of coarse material. This suggests the development of a system of small submarine fans that spread from the southern border of the basin. These fans were fed mainly from the southern flank of the Carpathian Foredeep and later also from the Carpathian orogen, although some of the Carpathian rocks also might have been recycled. Simultanously the southern part of the salt basin was disrupted. The subsequent reworking of the salt clasts and blocks presumably was affected by several processes, such as the transport of loose crystals by wave action, and by marine erosion following uplift of the seafloor, with destruction of the earlier deposited salt beds. The latter process might have been facilitated partly by dissolution of the salt beds. The clastic products of such mechanisms accumulated near channel heads and eventually were displaced downslope by density currents and/or slumping. Additional sediment input might have been generated by erosion of the substrate by the density currents. The redeposited material formed lenslike bodies which can be interpreted as small submarine fans. This interpretation is based chiefly upon bedding characteristics, the vertical and lateral arrangements of sedimentary structures, and the petrographic composition of the blocks. However, the Middle Miocene and later tectonic deformations have obscured much of the evidence required for detailed reconstruction of facies and their relations to the source area. The available data does, however, allow the fans to be divided into several parts: 1. the southern, internal part, which is characterized by polimictic conglomerates, pebbly saltstones, and breccias containing abundant material from the Carpathians; 2. the middle part, composed of conglomerates and coarse-grained saltstones, which can be massive, graded, and laminated, and are almost exclusively composed of salts; 3. the distal part, characterized by a general decrease in the clast-size and in the thickness of beds. The outermost margins of the fans are not exposed.

During the next stage (Fig. 22-III), strong orogenic movements gave rise to huge slumps which, in turn, were transformed into debris flows and olistostromes (Salt Breccia Member, Fig. 22C). In the latter phases of this stage, that part of the salt deposits which previously provided the material for mass flows was removed. Thus the latter redepositional processes involved only barren material (Barren Breccia Member).

The gravity-induced mass movements discussed in this paper occurred also in the other region of the Polish Carpathian Foredeep, and are evident from sequences in the nearby Bochnia salt mine. In the East Carpathian Foredeep, deposits similar to the Breccia Member have been described by Sandulescu et al. (1980), from the Pyrenaen Foredeep by Ślączka (1994), and in the Upper Permian salt deposits of the Halstatte Salt Mine by Schauberger (1953).

Acknowledgments.

We thank Stanisław Dżułyński and Gilbert Kelling for helpful discussions and their improvement of the manuscript. We also thank B.C. Schreiber and M. Rebelle for their comments, which considerably improved the manuscript. This work was partly supported by State Committee for Scientific Research grant no 728/P 2 and by Peri-Tethys Programme, grant no 95-96/48.

References

Alexandrowicz, W., 1965: La molasse miocene aux environs de Gdów. Bull. Acad. Pol. Sci., 13, 49-57.

Alexandrowicz, W., 1971: Regional Stratigraphy of the Miocene in the Polish part of the Fore-Carpathian trough. Acta Geol. Acad. Sci. Hung.. 15, 49-61.

Alexandrowicz, W., 1975: Pozycja stratygraficzna utworów mioceńskich z poprzeczni Kunegunda. Spraw. Pos. Kom. Nauk. PAN, Oddz. Kraków, 18, 510-513.

Catalano, R., Renda P. & Ślączka, A., 1978: Redeposited gypsum in the evaporitic sequence of the Cimmina basin (Sicily). Mem. Soc. Geol. Italiana, 16, 83–93.

Friedman G.M. & Sanders J.E., 1978: Principles of sedimentology. John Wiley & Sons, 792p.

Garlicki, A., 1974: Miocene salt deposits in Poland. Fourth Symposium on Salt, Cleveland, Ohio, 1, 129-134.

Garlicki, A., 1979: Sedimentation of Miocene salts in Poland. Prace geol. PAN, 119, 1-67.

Gaweł, A., 1962: Geological structure of the Wieliczka Salt Mine. Prace Inst. Geol. 30, 305-331.

Hamor, G., (editor) 1988: Neogene Palaeogeographic Atlas of Central and Eastern Europe. Hung. Geol. Inst. Budapest.

Kolasa, K., 1990: Geology of the Wieliczka Salt Deposits in the Region of Museum. Studia mater. do dziejów żup solnych w Polsce XVI, 7-62.

Kolasa, K. & Ślączka, A., 1985: Sedimentary salt mega-breccias exposed in the Wieliczka mine, Fore-Carpathian Depression. Acta Geol. Polonica, Vol. 35, 221-230.

Kowalewski, K., 1935: Zur Frage des Alters und der Fauna der Salzformation von Wieliczka. Spraw. PIG, 8, 218-223.

Kulka, A., 1980: Miocene Bryozoans from Spissum from Wieliczka. Zesz. nauk. AGH, Geologia, ,6, 35-49.

Kwiatkowski, S. 1972: Sedimentation of gypsum in the Miocene of Southern Poland. Prace Muz. Ziemi, Warszawa, 19, 3–93.

Łańcucka-Środoniowa, M., 1984: The results obtained hitherto in studies on the Miocene macroflora from salt-mine at Wieliczka (S.Poland). Acta Palaeobotanica, Vol. 24, 3-26.

Łuczkowska, E., 1978: Wielicien Holostratotypus: Wieliczka Salzgrube, Faciostratotypus: Bohrung Kłaj-1, In: Chronostratigraphie und Neostratotypen, Miozän M4 Badenian, pp. 149-151 and 155-158. Veda. Bratislava.

Mai, D. H. 1964: Die Mastixioideen Flora in Tertiar der Oberlausitz, Paleontologische Abh. B, 2, 1–192.

Meier, R., 1977: Turbidite und Olisthostrome-Sedimentationsphänomene des Werra-Sulfats (Zechstein 1) am Osthang der Eichsfeld Schwelle im Gebiet des Südharzes. Akad. Wissensch. DDR, Veröffent. Zentralinst. Physik der Erde (Berlin), 50.

Morycowa, E. & Roniewicz, E., !987: Sleractinian corals from the Middle Miocene salt deposits in Carpathian Foredeep, Poland. Acta Paleont. Pol. (Warszawa), Vol. 32, 105-119.

Mutti, E. & Ricchi-Lucci, F. (1975) Turbidite facies and facies associations. Field Trip Guidebook A-11, 9th Int. Sediment. Congr., Niece, 21-36.

Niedźwiecki, J., 1883: Stosunki geologiczne formacyi solonośnej Wieliczki i Bochni. Kosmos (Lwów), 8, 137-159, 244-252, 334-347, 455-466.

Niedźwiecki, J., 1884: Stsunki geologiczne formacyi solonośnej Wieliczki i Bochni. Kosmos (Lwów), 9, 565-580, 717-743.

Parea, G.C. & Ricci-Lucci, F., 1972: Resedimented evaporites in the Preadriatic trough (upper Miocene, Italy). Israel Journ. Earth Sci., Spec. Issue Sedim., 21, 125-141.

Pawlikowski, M. 1978: Petrographic Studies of the Wieliczka Salt Deposits. Pr. Miner. Komis. Nauk. Miner. PAN Kraków, 58, 65-110.

Peryt, T.M. & Kasprzyk, A., 1992: Earthquake-induced resedimentation in the Badenian (middle Miocene) gypsum of southern Poland. Sedimentology, 39, 235-249.

Połtowicz, S., 1977: Tectonic evolution of the rock salt deposits in the Wieliczka and Barycz. Rocz. Pol. Tow. Geol. 47, 279-299.

Reuss, A.E. 1867: Die fossile Fauna der Steinsalzablagerung von Wieliczka in Galizien. S.-B. Akad. Wiss. (Wien), 55, 17-182.

Sandulescu, M., Micu, M. & Popescu, B. 1980: La structure et la paleogeographie des formations Miocenes des subcarpathes Moldaves. Proc. XI Congr. Carpath-Balkan Geol. Ass., Tectonics (Kiev), 184-197.

Schauberger, O., 1953: Zur Genese des alpinen Haselgebirges. Z. deutsch. Geol. Ges. (Hannover), 105, 736-751.

Schmalz, R.F., 1969: Deep-water evaporite deposition: a genetic model. Bull. Amer. Ass. Petr. Geol., 53, 798-823.

Schreibner, B. C. 1986: Arid Shorelines and Evaporites, in: Reading, H. G. (Ed.), Sedimentary Environments and Facies. Blackwell Sc. Publ., 189–228.

Schreibner, B. C., Friedman, G. H., Decima, A. & Schreibner, E. 1976: Depositional environments of Upper Miocene (messinian) evaporite deposits of the Sicilian Basin. Sedimentology, 23, 729–760.

Ślączka, A., 1994: Redeposited sediments in evaporatic basins. Przegl. Geolog. (Warszawa), 42, 4, 251-255.

Ślączka, A. & Thompson III, S., 1981: A revisionn of the fluxoturbidite concept based on type examples in the Polish Carpathian flysch. Ann. Soc. Geol. Pol., 51, 3-44.

Ślączka, A. & Kolasa K., 1987: Deposition environments of the Wieliczka salt deposits. Ann. Inst. Geol. Publ. Hung., 70, 617-623.

Tollmann, A., 1985: Geologie von Osterreich. Band II, Franz Deuticke, Wien, 710p.

Tołwiński, K. 1956: The chief elements of the Carpathian Mts. And the Salidy Range. Acta geol. pol. 6, 34–226.

Unger, F., 1850: Die pflanzenreste im Salzstocke von Wieliczka. Denkschr. Akad. Wiss., 1, 311-322.

Zabłocki, J., 1928: Tertiare Flora des Salslagers von Wieliczka. Erster Teil. Acta Soc. Botan. Polon. , 5, 174-208.

Zabłocki, J., 1930: Tertiare Flora des Salzlagers von Wieliczka. Zweiter Teil. Acta Soc. Botan. Polon., 7, 139-156.