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LACUSTRINE SUCCESSIONS IN FAULT-BOUNDED BASINS: 1. UPPER ANTHRACOSIA SHALE (LOWER PERMIAN) OF THE NORTH SUDETIC BASIN, SW POLAND

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Abstract: The Upper Anthracosia Shale is a 40-m thick succession of lacustrine deposits, terminating the Świerzawa Formation (lower Autunian) in the North Sudetic Basin. This succession contains a number of distinct lithofacies which represent the result of sedimentation in different lacustrine subenvironments. These lithofacies include: onshore flat, nearshore, offshore, deltaic, swamp/moor, carbonate, and mass-gravity deposits. The Upper Anthracosia Shale forms a transgressive-regressive succession which is subdivided into four segments connected with the four major phases of the Anthracosia Lake evolution. The onshore flat facies mark the initial phase of the lake development, when the basin floor originally occupied by fluvial channel belt evolved into the fluvially-influenced onshore zone of a lake. The phase of transgression was characterized by the development of widespread nearshore zone. The lake expansion was interrupted by several episodes of slope failures and subaqueous mass redeposition of sediments, which were generated along the tectonically active, NNE margin of the basin. Renewed nearshore conditions resulted in the formation of nearshore shoal bars. Organic-rich black shales representing the lacustrine offshore facies reflect a phase of the maximum lake extent. Lacustrine deltaic deposits forming coarsening-up sequence at the top of the lacustrine succession mark the regressive phase. The transgressive, thick portion of the lacustrine succession resulted from long-lasting transgression, while the thin regressive portion is related to rapid regression induced by rejuvenation of the southern basin margin. Water column in Anthracosia Lake was probably permanently stratified. Bottom conditions changed from oxic-to-suboxic in the nearshore zone to anoxic, sulphidic in the offshore one. The lake level fluctuated frequently. Stromatolitic buildups and swamps/moors appeared locally in the nearshore/offshore transitional zone and along the lake shore, respectively. Wave reworking played an important role in the nearshore zone. Synsedimentary tectonic activity and basin floor subsidence, climate, sediment supply, water feeding system, and the activity of living organisms were the most important factors controlling sedimentation in Anthracosia Lake.

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INTRODUCTION

Lakes which originated in tectonically active zones (e.g. continental rifts, strike-slip basins) are particularly interesting from sedimentological point of view. They come into existence when subsidence rate exceeds sedimentation rate in the basin (*cf.* Ryder *et al.*, 1976). Although such lakes are more diversified than other kinds of lacustrine basins (for comparison see Twenhofel, 1950; Hutchinson, 1957; Reeves, 1968), they have several features in common. Lakes in tectonic depressions are relatively large, deep, and elongated. They form rather long-lived sedimentary basins. These lakes usually display complicated control patterns upon sedimentation, with synsedimentary tectonics and basin floor subsidence as the most important factors. These factors influence facies arrangements and sediment dispersal patterns within the basin, the supply of water sediment input to the basin, and also basin geometry and lake depth. Sedimentary successions of such basins usually display a cyclic structure which is related to tectonic events. Lacustrine basins in tectonically active regions are characterized by permanent, high-rate subsidence and intense sediment supply, which result in the high preservation potential and large thicknesses of the lacustrine successions (e.g. Van Houten, 1964; Link & Osborne, 1976; Anadón *et al.*, 1988). Tectonic activity is frequently associated with volcanic and hydrothermal processes which have strong impact on sedimentation, water chemistry and organic life in lakes.

The Variscan orogeny resulted in the development of numerous sedimentary basins in central Europe. The processes of basin formation were induced by regional extension associated with the subduction of the European Carboniferous Ocean and the resulting crustal upwarping of the Bohemian Massif and its surroundings (Lorenz & Nicholls, 1976). These areas were dominated by the Basin and Range-style of topography during the Stephanian and Autunian. Elongated alluvial valleys acted as sedimentary basins, being separated by ranges which fed marginal alluvial fans. Periodically lakes spread over the vast areas of the basins. Climate conditions changed successively from warm and wet in the Carboniferous to warm and arid in the Saxonian (*cf.* Frakes, 1979; see also Scupin, 1922; Dziedzic, 1959; Holub & Tasler, 1978, 1982; Lützner, 1988).

The North Sudetic Basin originated in the Stephanian and lasted during the Autunian as a narrow intramontane graben (or graben system) with tectonically active margins (Milewicz, 1972; Ostromęcki, 1973). The Stephanian-Rotliegendes sedimentary infill of the North Sudetic Basin is characterized by the presence of large-scale (a few hundred of metres thick) fining-upwards cyclothems. A „modal" cyclothem starts with coarse-grained alluvial sediments, overlain by sandy fluvial ones, and the latter, in turn, pass upwards into fine-grained lacustrine deposits.

The purposes of this paper are: (1) to describe the characteristics of sedimentary facies of the Upper Anthracosia Shale — a thick horizon of lacustrine facies in the south-eastern part of the North Sudetic Basin, (2) to reconstruct the depositional conditions, environments, and the evolution of Anthracosia Lake, and (3) to discuss the role of the factors controlling the lacustrine sedimentation and basin evolution.

GEOLOGICAL SETTING

The North Sudetic Basin forms a relatively large synclinorial unit in the NW part of the Sudetes, south-west Poland (Fig. 1). This unit is bounded by prominent faults, some of which were active during filling of the basin. The basement and adjacent surroundings are built of epimetamorphic

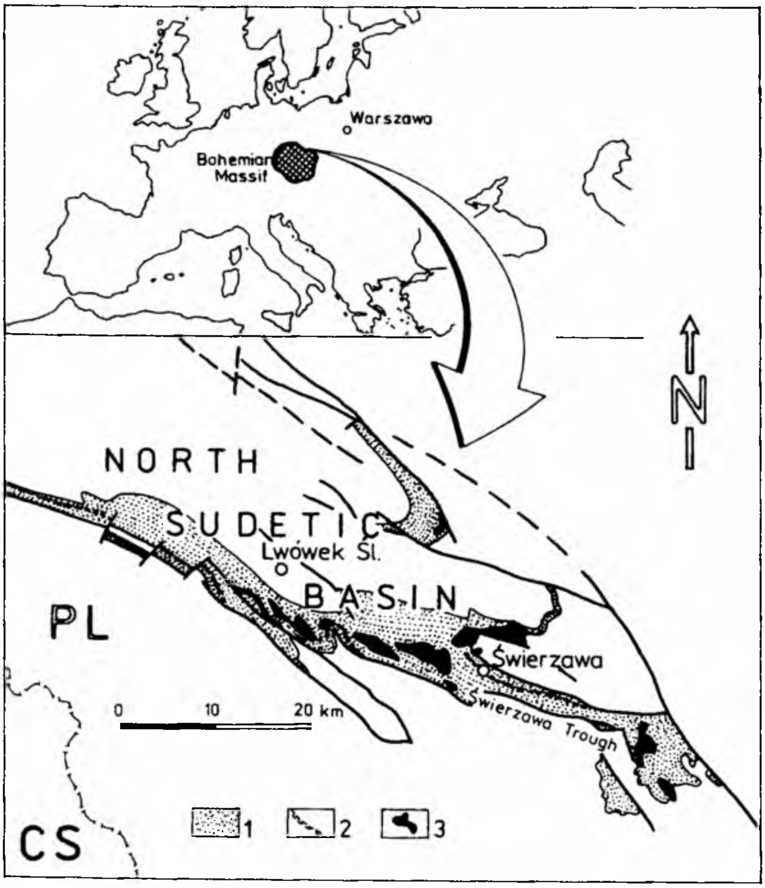

Fig. 1. Geological sketch-map of the North Sudetic Basin. *1* — Stephanian-Lower Permian sedimentary strata; *2* — Upper Anthracosia Shale; *3* — volcanogenic rocks

rocks of the Kaczawa complex, early Palaeozoic through early Carboniferous in age (Chorowska, 1978). The basin infill consists of sedimentary and volcanogenic rocks ranging from the Stephanian to late Cretaceous in age, but the stratigraphic column contains a few prominent hiatuses. The strata dip generally towards the basin centre. However, the basin is dismembered into several synclines and grabens in its eastern part. The original, initial depositional area was situated along the present-day southern basin margin (Krasoń, 1967; Milewicz, 1972) and extended into the Świerzawa Trough (Fig. 1).

The Permo-Carboniferous sedimentary strata of the North Sudetic Basin rest on the epimetamorphic basement with an erosional contact. The biostratigraphic record of these strata is poor. Several taxa of fossil plants and animals were reported from dark-grey shales of this succession (Becker, 1869; Scupin, 1922, 1931; Kühn & Zimmermann, 1918; Zimmermann & Haack, 1935; Zimmermann & Kühn, 1936), but they are of little stratigraphic value. The lowermost strata of the basin infill were determined palynologically as the Stephanian to the lowermost Permian (Górecka, 1970). The late Permian marine transgression ceased continental Rotliegendes sedimentation in the North Sudetic Basin.

There is no formal lithostratigraphy erected for the area, so far. The scheme presented in this paper takes into account the cyclic structure of the sedimentary succession and older stratigraphic subdivisions (Kühn & Zimmermann, 1918; Scupin, 1931; Dziedzic, 1959; Ostromęcki, 1972; Karnkowski, 1981). The Stephanian-Rotliegendes portion of the basin infill consists of three formations (Fig. 2):

The *Świerzawa Formation* (Stephanian — lower Autunian), 70 — 400 m thick, commences with conglomerates which rest disconformably on the metamorphic basement (Dziedzic, 1959). Reddish-brown conglomerates, sandstones and mudstones are the most common lithologies. Marly shales, black shales, and limestones occur locally in two horizons referred to informally as the *Lower* and *Upper Anthracosia Shales.* These horizons cap two fining-up megacyclothems which can be recognized in this formation (Fig. 2).

The *Wielisławka Formation* (upper Autunian), up to 900 m thick, commonly between 200 and 300 m, consists predominantly of reddish-brown conglomerates which are gradually replaced upwards by sandstones and mudstones. Thin calcareous intercalations, gypsum lenticles and vein infillings occur in the upper parts of the formation (Krasoń, 1967; Milewicz, 1965). The basal conglomerates rest erosively either on the Upper Anthracosia Shale in the southern part of the basin, or on metamorphic rocks in its northern part (Krasoń, 1967). Volcanogenic rocks form considerable portions of this formation.

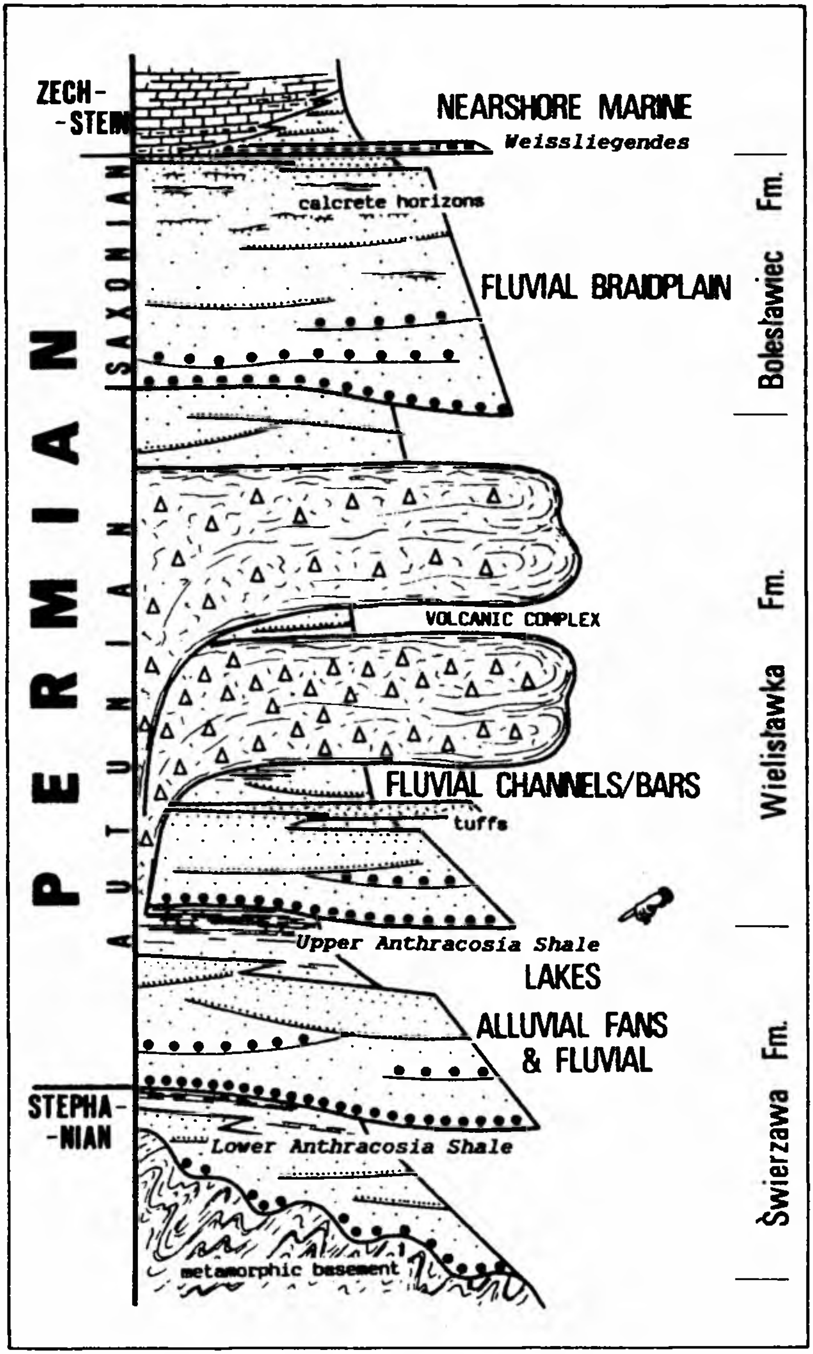

Fig. 2. Generalized lithostratigraphic column of the Stephanian-Lower Permian succession of the North Sudetic Basin

The *Bolesławiec Formation* (Saxonian), 200 — 400 m thick, comprises mainly conglomerates and arcosic sandstones. Granitoid pebbles are a characteristic component of the deposits (Milewicz, 1965; Krasoń, 1967). Abundant calcareous cements and caliche horizons occur in the upper part of the formation (Mroczkowski & Skowronek, 1980). The continental deposits of this formation are followed upwards by copper-bearing marls and dolomitic limestones with marine fauna, which mark the beginning of the late Permian marine transgression.

THE UPPER ANTHRACOSIA SHALE

The upper fining-up megacyclothem of the Świerzawa Formation attains about 200 m in thickness. The lower part of this cyclothem consists of coarse-grained, thick-bedded sediments which belong to alluvial fan and fluvial facies associations. These sediments are followed upwards by dark-grey, fine-grained, and often marly sediments with intercalations of conglomerates and limestones, and thin coal stringers. These deposits, up to 40 m thick near Świerzawa, are known under the informal lithostratigraphic name of the Upper Anthracosia Shale (Dziedzic, 1959; M. Mastalerz, 1983) (Fig. 2) and reflect one of the lacustrine phases in the development of the North Sudetic Basin. Several major lithofacies have been distinguished in the Upper Anthracosia Shale. These are: onshore flat, nearshore, offshore, deltaic, swamp/moor, carbonate, and mass-gravity facies.

The Upper Anthracosia Shale is exposed in several small outcrops located along the southern basin border (Dziedzic, 1959; Milewicz & Górecka, 1965; Milewicz, 1972; Ostromęcki, 1972, 1973; M. Mastalerz, 1983) (Fig. 1). The stratotype section is situated in the village Stara Kraśnica. The strata of this horizon were also identified in several drill holes (Milewicz, 1972).

ONSHORE FLAT FACIES

Description. This facies is composed predominantly of fine- to medium-grained, reddish-brown sandstones and mudstones. They are relatively poorly sorted, and considerable amounts of muddy matrix are present in the sandstones. The grain framework is composed predominantly of quartz, while feldspar, mica, and altered rock fragments are far less abundant. The cement is of clayey-ferruginous type with subordinate secondary calcite.

Ripple cross-lamination predominates in deposits of this facies, however, parallel lamination occurs also commonly. Solitary sets of trough cross-bedding are subordinate. Mudracks occur infrequently, while scattered mud chips and mud-chip lags are commonly found throughout the sequence (Pl. I: 1). Load and flame structures appear subordinately. Bioturbation in the form of subvertical burrows is rather scarce.

The deposits are organized into small-scale (a few tens of cm thick) coarsening-up cycles. Thin convex-up lenses of low-angle cross-laminated sandstones occur commonly at the tops of such cycles. The topmost parts of the cycles are usually bioturbated. Small-scale displacements along NW- to SW-dipping, listric surfaces are common in the deposits of this facies (Fig. 3). Just above these surfaces there often occur thicker, solitary trough-sets.

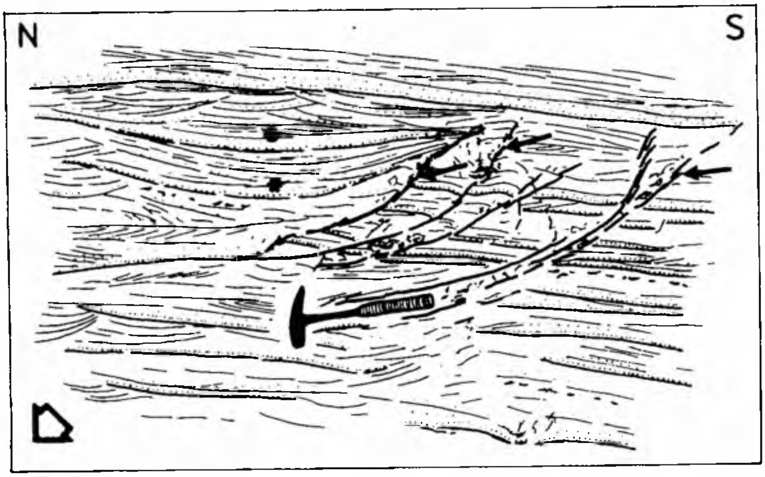

Fig. 3. Laminated sandstones and shales of the onshore facies, Stara Kraśnica. Note listric surfaces of synsedimentary faults (*arrows*) and sets of trough cross bedding (*asterisks*). Section oblique to palaeotransport direction (*large arrow*)

Interpretation. The deposits of the described facies reveal features typical of sedimentation from sheet flows over a relatively flat surface and, locally, in shallow channels. Stream and sheet-flood waters must have been heavily sediment-laden as inferred from the high matrix content and the effects of suspension sedimentation. The position of this facies in the succession suggests that the sedimentary area was originally occupied by a system of active fluvial channels. Such régime gradually evolved into a lake-related environment. It was a lacustrine, flat, onshore plain, often invaded by sediment-laden fluvial waters. Clastic material was deposited mostly under subaerial conditions from unidirectional flows and within isolated, shallow ponds from suspension. Abundant mud chips suggest frequent dessication of an exposed sedimentary surface.

Directional structures point to a gently westwards dipping palaeoslope (Fig. 4). The distinct mode of the northeasterly inclined ripple cross-lamination may have resulted from occasional wave reworking due to the temporary submergence by lake waters. The westerly dipping listric fault surfaces resulted from localized slope failures. The slight basinward displacements of coherent sediments could have been induced by slope weakening due to differential sedimentation and the formation of local steeper slopes (depositional lobes), changes in groundwater saturation, or seismic shocks. The resulting slump scars were readily filled with sandy sediment which now forms the solitary trough sets.

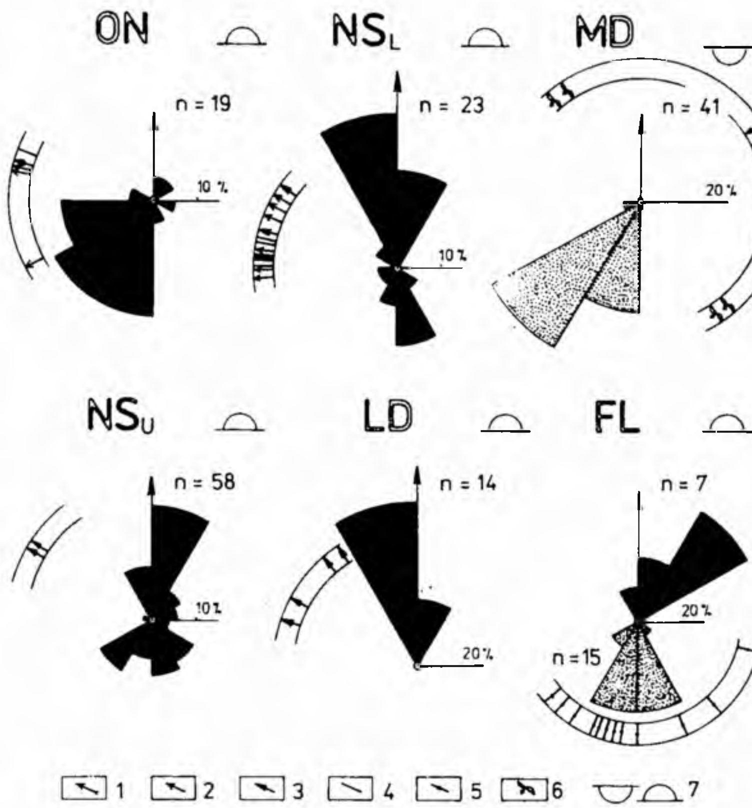

Fig. 4. Diagrams of directional sedimentary structures of the Upper Anthracosia Shale from the vicinity of Świerzawa. Rose diagrams: *black* — cross-lamination and bedding, *stippled* — pebble imbrication; facies: *ON* — onshore; *NS* — nearshore (*L* — lower part; *U* — upper part); *MD* — mass-gravity deposits; *LD* — deltaic; *FL* — fluvial of the basal part of the Wielisławka Formation. Other palaeocurrent indicators: *1* — channel axes; *2* — trough cross-set axes; *3* — sole marks, current crescents; *4* — parting lineation; *5* — *A*-axis pebble orientation; *6* — slump fold axes and sense of a motion; *7* — upper- and lower-hemisphaere projections

NEARSHORE FACIES

Description. Fine- to medium-grained sandstones with siltstones and subordinate mudstones are the main components of this facies. They are yellowish- to light-green in colour. Quartz, predominantly monocrystalline, constitutes 50 to 70% of the grain framework. The remaining constituents are feldspar, and varying quantities of mica and rock fragments. The matrix usually contains a considerable amount of micrite. The cement ranges from clayey-ferruginous with sparry calcite to prevailing calcareous. Clayey pellets and mud chips are found subordinately. Fine plant detritus and twig impressions occur locally in these deposits. In some zones the sediment becomes marly, with abundant calcareous nodules.

Ripple cross- and parallel laminations are typical sedimentary structures in the finer-grained parts of the nearshore sequences. Current ripples predominate in these deposits, while wave ripples become more abundant in the coarser-grained, upper parts of coarsening-up cycles. Small-scale, isolated trough cross-sets as well as low-angle and hummocky cross-strata occur less frequently. Some coarser-grained beds show loaded soles and even convoluted forms associated with flame structures. The thicker/coarser-grained cosets of ripple to hummocky lamination contain numerous root impressions at their tops. Raindrop imprints are found commonly, while mudcracks are less frequent (Pl. I: 2). Locally these structures are associated with mud ripples *sensu* J.R.L. Allen (1982) (= wrinkle marks *sensu* Reineck & Singh, 1973) (Pl. I: 3). Bioturbation is common but not abundant, with isolated, subvertical and subhorizontal burrow tubes prevailing (Pl. I: 4).

Ripple cross-lamination indicates a distinct bipolar inclination (Fig. 4), while other current indicators (trough sets, sole marks) indicate longitudinal transport directed towards the WNW.

Interpretation. The sediment features and stratigraphic position suggest that the above described facies reflects deposition in a lacustrine nearshore environment. This zone was influenced by WNW-flowing fluvial/deltaic waters but, in general, sedimentation took place under the control of weak wave activity on a shallow nearshore platform. The colonization of the bottom by animals was never intense. Frequently, due to temporary lake level drops, the nearshore zone was subaerially exposed.

Small-scale (tens of cm thick), coarsening-up sequences which frequently display evident signs of wave reworking at their tops suggest development of nearshore shoal bars. These bars were temporarily colonized by vascular plants and even subaerially exposed.

OFFSHORE FACIES

Description. In general, two types of sediments represent this facies: (1) finely laminated black shales, and (2) bioturbated, homogenized mudstones.

The black shales form a megascopically monotonous sequence of clayey to calcareous deposits with the considerable content (up to 20%) of organic matter. On the basis of organic components three varieties can be distinguished within the shales. The following associations: (1) alginite + sporinite,

(2) bituminite + sporinite, and (3) vitrinite + inertinite are characteristic of these varieties respectively (M. Mastalerz, 1988). Carbonate content ranges from a few to over 50%. Clay minerals and micrite are the dominant components of these shales. Framboidal pyrite is common and constitutes locally up to 5% of the rock.

The black shales contain a variety of well preserved fossils. *Walchia*, *Calamites*, some pteridosperm and large seed impressions are the most common plant remains (Pl. I: 5, 6). There is high concentration of *Anthracosia?* valve moulds (Pl. II: 1) in a thin horizon within the shales. *Acanthodes* and *Xenacanthus* remains (bones, fins and teeth) are scattered throughout the sequence (Pl. II: 2, 3). The fragments of euripterid? cuticles occur infrequently (Pl. II: 4). Large coprolites composed of collophane and enveloped by sideritic/sulphidic crusts (Pl. II: 5) are also typical of these deposits. The thin valves of ostracodes and/or gastropods are rather scarce.

Gray to greenish-gray mudstones and poorly sorted muddy sandstones are characterized by a considerable amount of micrite. The deposits contain abundant, finely macerated plant detritus, and locally there occur small calcareous and ferruginous nodules. Dense bioturbation is a characteristic feature. Subvertical and diagonal burrow tubes 3 — 10 mm wide, are the dominant bioturbation type, however, there occur also subhorizontal tubes as well as very thin, branching burrows. The signs of lamination are found only locally, where the bioturbation degree is lower.

Interpretation. The black shales are believed to represent slow deposition from suspension enhanced by micrite production. The deposition took place in an open lake zone, far off a densely vegetated, fluvially influenced deltaic/alongshore plain. Deltaic swamps and nearshore moors trapped nearly all clastic input and only clay-grade particles could reach the open lake zone.

In the upper part of the water column favourable conditions existed for algae development, enhancing micrite production. The abundance of tiny skeletons indicates planktonic blooms and suggests eutrophication of the lake waters. The abundance of food also promoted development of larger nectonic animals. However, strongly anoxic conditions in the bottom muds prevented the development of infauna. Such conditions facilitated the formation of dispersed framboidal pyrite, as well as the development of encrustations and concretionary forms during the early diagenesis.

The bioturbated mudstones represent sedimentation in relatively shallow parts of the offshore zone. The scarcity of traction structures suggests that this zone was situated close to, or slightly below, the mean wave-base depth. The intense bioturbation points to activity of infaunal inhabitants and suggests that the bottom muds were sufficiently oxidized and rich in nutrients.

LACUSTRINE DELTAIC FACIES

Description. This facies consists mainly of green, clayey to silty deposits which become sandier upwards in the sequence. They are moderately sorted and display variable matrix contents. The grain framework is composed of quartz (mainly polycrystalline), mica (up to 20%), feldspar, and epimetamorphic as well as volcanic rock fragments. The cement is calcareous to clayey-calcareous, with admixture of ferruginous components. Macerated plant detritus is found locally.

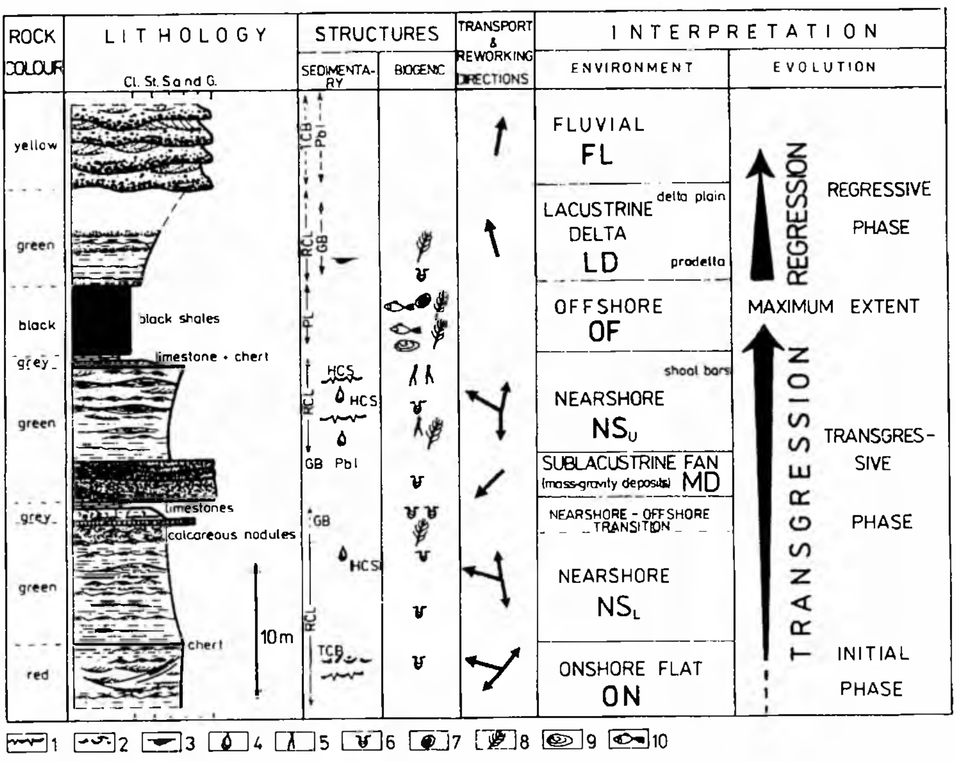

Fig. 5. Section of the lacustrine succession of the Upper Anthracosia Shale, Stara Kraśnica: *1* — mud cracks; *2* — mud chips; *3* — sole marks; *4* — raindrop imprints; *5* — root casts; *6* — bioturbation; *7* — coprolites; *8* — plant remains; *9* — pelecypods; *10* — fish

Parallel and ripple cross-lamination are dominant primary structures. Isolated starved ripples are found subordinately. Thin layers showing the Bouma *Tac* and *Tbc* divisions in sandy to silty material, occur freuqently. Some thicker (a few cm), normally graded sandy layers are scattered randomly in the sequence. Small-scale trough cross-sets occur subordinately. Ripple cross-lamination as well as tool and groove marks indicate a northward palaeotransport direction.

The ichnofacies assemblage of this facies is entirely different from that of the other parts of the lacustrine succession. Small crawling traces and isolated resting? moulds predominate in the finer-grained deposits of this facies (Pl. II: 6), while subhorizontal burrows are subordinate.

The deposits of this facies are organized into a distinct and relatively thick (5 m), coarsening-up sequence in the topmost part of the Upper Anthracosia Shale (Fig. 5). They pass gradually downward into the offshore facies forming a thin zone of grayish-black, mottled silty-clayey deposits. Small siderite nodules are relatively common in this zone, while the content of organic matter is considerably lower than in the underlying black shales.

Interpretation. The deposits of this facies document the final stage of the Anthracosia Lake development, signifying the phase of lake regression. This process is believed to have resulted from northwards progradation of a deltaic system, which brought about the overall coarsening and thickening in the sequence. Sedimentation from underflows (*cf.* Sturm & Matter, 1978) and clayey to silty hemipelagic suspension fallout in a prodeltaic zone were successively replaced by delta front and channelized delta plain deposits. Supply of oxygen-rich, fresh waters enabled some benthic biota to colonize this environment. The formation of early diagenetic nodules is related to the hydrochemical front between the fluvial inflow and lake waters at the toe of prograding delta.

SWAMP/MOOR FACIES

Description. This facies constitutes only subordinate elements of the Upper Anthracosia Shale. Two types of deposits can be distinguished within this facies. The first type is represented by homogenous, marly, fine-grained sandstones and mottled mudstones. They contain abundant plant detritus and display the zones of both iron-hydroxide concentrations and thin vitrinite stringers. They are also densely rooted.

The second variety of this facies is composed of impure coal layers which attain a few cm in thickness (Becker, 1869). Laminae of vitrinite, a few milimetres thick, with *Calamites* stem impressions can be found in the outcrops along the Kaczawa River in Stara Kraśnica (M. Mastalerz, 1983).

Interpretation. The homogenous, rooted mudstones and sandstones represent sedimentation of fine clastics and plant detritus in nearshore moor settings. These areas must have been densely inhabited by submersible plants living under a relatively permanent, shallow water cover. Sedimentation was enhanced by algal and bacterial production of micrite. Swampy conditions enabled locally more intense precipitation of iron hydroxides (*cf.* Postma, 1983). The coal layers represent accumulation of plant tissues and clay particles in delta plain/onshore swamps. The vitrinite laminae, in turn, were formed through redeposition of drifted, plant and/or peat substance derived from incipient peat-bogs of the onshore zones.

CARBONATE FACIES

Description. Limestones form thin (a few to several cm thick) layers and lenses, and they occur usually close to the nearshore/offshore facies transition (Fig. 5). Some layers show tiny, parallel or wispy lamination. However, various kinds of stromatolitic, often irregular buildups are the dominant structures. The deposits are mainly composed of micritic mud with a considerable amount of fine allochem grains. Intraclasts, peloids, and ostracod and/or gastropod valves are typical elements of these limestones. Cellular colonies of algal structures as well as scattered calcispheres are common. There are also endolithic micrite envelopes on some sparry elements. Quartz grains are the most common terrigenous allochem. Sparry calcite fills the irregular, often flattened vugs.

There are thin gypsum encrustations upon some intraclasts. However, thin gypsum laminae are also common element of some stromatolitic buildups. Large sparry pseudomorphs after gypsum occur occasionally. Some stromatolitic limestones contain diffuse cherty laminae and, locally, there occur chalcedony-filled pores in these rocks. Large cherty clasts and deformed lumps of calcareous material are present in some zones. Thin limestone layers and lenses occur in bundles interbedded with marly mudstone, or they form thicke- (up to 15 cm) single layers.

Interpretation. The limestones are connected with zones of relatively shallow and clear water in the lake. This environment must have been relatively well aerated, but with only weak water movements. The nearshore/offshore transition seems to display favourable conditions for the limestone development (*cf.* James, 1979). Such conditons favoured algae/bacteria development and the formation of the stromatolitic structures (*cf.* Schafer & Stapf, 1978; Dean, 1981; Casanova, 1986; Renaut *et al.*, 1986). However, the stromatolitic buildups were occasionally destructed during storm events, and the clastic material from the nearshore zone was incorporated into these structures (*cf.* James, 1979). Gypsum laminae and encrustations could have been formed either due to relative enrichment in sulphate of the lake water (lake level lowering, external supply by subsurface seepage) or by precipitation in subaerial conditions (*cf.* Bowler & Teller, 1986). Cherty interlamination are believed to reflect temporary activity of hot springs fed by hydrothermal solutions along tectonic discontinuities (*cf.* Hardie *et al.*, 1978; Casanova, 1986; Renaut *et al.*, 1986).

MASS-GRAVITY FACIES

Description. A packer of folded limestone/mudstone layers (Fig. 6) begins the sequence of redeposited sediments in the stratotype section. This folded packet passes laterally into a mud-supported conglomerate containing brecciated limestone fragments dispersed in an abundant muddy matrix. Two, thin graded beds cover this packet. The beds consist of poorly sorted muddy material with dispersed small limestone clasts. The topmost part of the upper bed reveals numerous, thin branching burrows.

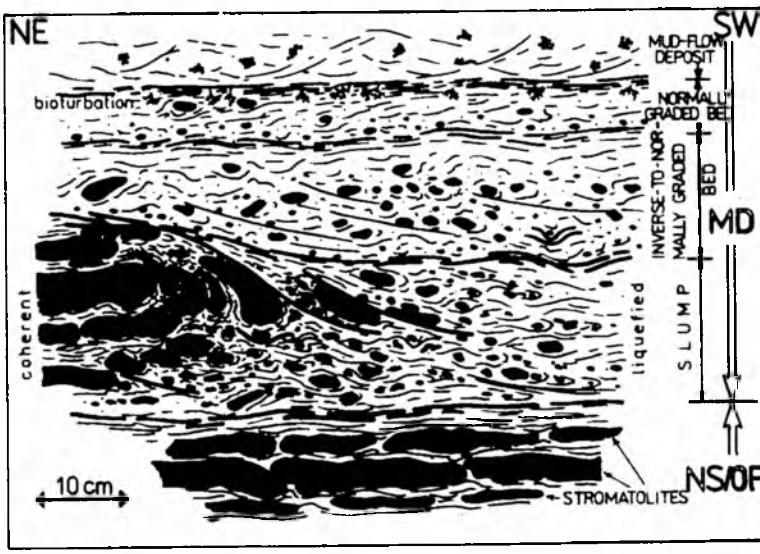

Fig. 6. Basal part of the sequence of mass-gravity deposits (*MD*) overlying stromatolitic limestones interbedded with mudstone of the nearshore-offshore transitional zone (*NS/OF*), Stara Kraśnica

The graded beds are followed by a thick (*c.* 180 cm) homogenous layer bearing scattered ferruginous and sulphidic nodules and concretions. These deposits are very poorly sorted, with grain size ranging from clay to granule grade. They show no megascopic signs of primary sedimentary structures, but thin sections display remnants of disturbed laminations. However, in the topmost part of this layer, the normal gradation of grain size and well-defined, thin lenses of sandstone are present. Large subvertical burrows also occur in this zone.

The homogenous layer is overlain by a set of amalgamated sandy conglomeratic beds. The beds are up to 50 — 60 cm in thickness and they show lenticular shapes in cross-section (Fig. 7). Their lateral margins are distinctly rounded, and only rarely they are tapered. The thin stripes of imbricated pebbles interlayered with sandstone are very typical feature of these beds (Fig. 8). However, pebbles are often randomly dispersed in an abundant sandy matrix. Thin layers of poorly sorted, sandy-muddy material separate these beds from each other. The axes of channelized beds dip gently towards WSW.

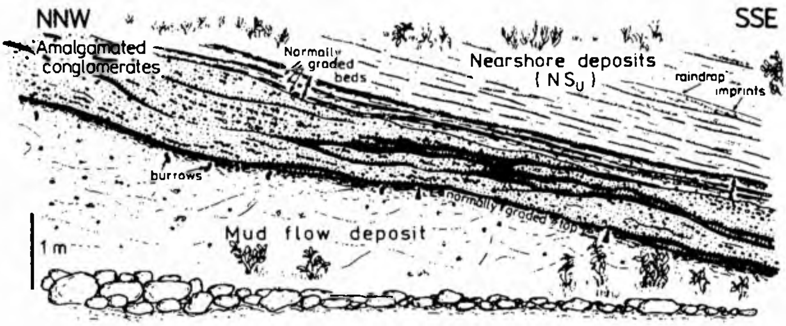

Fig. 7. Upper part of the sequence of mass-gravity deposits, Stara Kraśnica

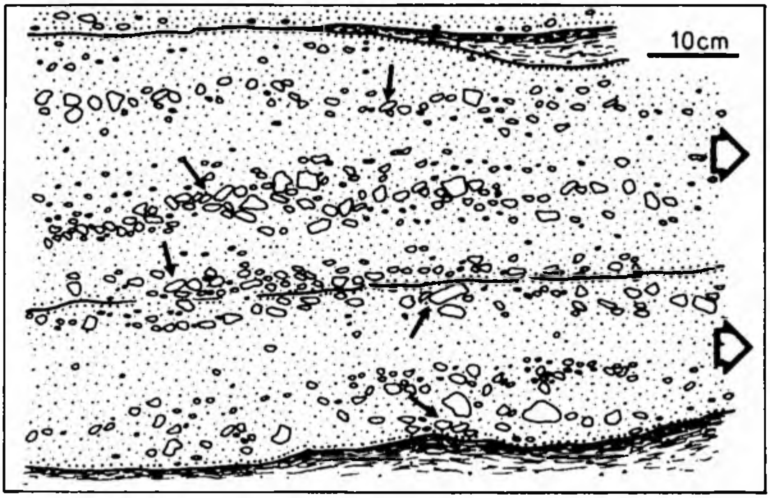

Fig. 8. Close-up view of the composite bed of amalgamated sandy conglomerate, mass-gravity facies. Note imbricate pebbles (*arrows*) and pebble segregation into stripes. Section oblique to palaeotransport direction (*large arrows*), Stara Kraśnica

The conglomeratic set is covered by a series of three diffuse beds with poor normal grading of granule- to clay-grade material. Some granules and even pebbles are scattered throughout these beds.

Interpretation. The above described deposits reflect a series of mass movements and redeposition which interrupted the development of the lacustrine facies. These movements were probably connected with a period of increased seismic activity and originated in the zone of relatively steep and unstable slope within the basin. Processes of mass transportation and deposition took place in subaqueous conditions. Palaeocurrent indicators suggest that the displacements were generated at the NNE basin margin (Fig. 4).

The basal, folded limestone/mudstone packet is a subaqueous slump deposit. The central part of the slump was coherent during the transportation, while slump head was liquefied due to its fragmentation and incorporation of water. The slump was followed immediately by dense flows of sediment-water mixture. The bioturbation at the top of the resulting set of beds suggests a successive period of quiescence.

The thick homogenized layer suggests deposition from a cohesive mud/debris flow. The emplacement of the debrite was followed by a fallout from dense suspension cloud, as is indicated by the normal grading at the layer top. Bioturbation suggests the successive period of more intense colonization of the bottom.

The arrival of gravelly material could have been connected with retrogradational slope failures, which reached the zone of an alluvial fan (fan delta?) or a fan-fed gravelly shore. The remobilized coarse clastic material was deposited mainly from surging, high-density turbidity currents. The flows were channelized, but this feature seems to be related to the sinking of the flowing mixture into fresh, muddy bottom sediments. Each set of these flows was followed by deposition from dense suspension clouds, probably stirred by sediment flows.

DEVELOPMENT OF UPPER ANTHRACOSIA LAKE

During the Stephanian and Autunian the North Sudetic Basin constituted a ESE — WNW trending depositional area which was filled with a complex of continental deposits. It was a trough, or system of troughs, over 70 km long and about 10 km wide in the vicinity of Świerzawa (see also Krasoń, 1967; Milewicz, 1972). The pulsatory character of subsidence rate and sediment supply resulted in repetition of cyclically arranged phases of the basin filling (Wojewoda & Mastalerz, 1989). Initial, diastrophic events caused rapid, short-term progradation of marginal alluvial fans and intense basin filling. During the fluvial phases the axial zone of the basin was dominated by river systems with a prevailing longitudinal transport towards the WNW. Nevertheless, much of clastic material was shed off laterally from high-relief margins and deposited in alluvial fan systems. The successive filling of the basin under relatively slow subsidence made the drainage conditions worse and, finally, induced the expansion of a lake from retented water (lacustrine phase). During the Autunian three distinct episodes of

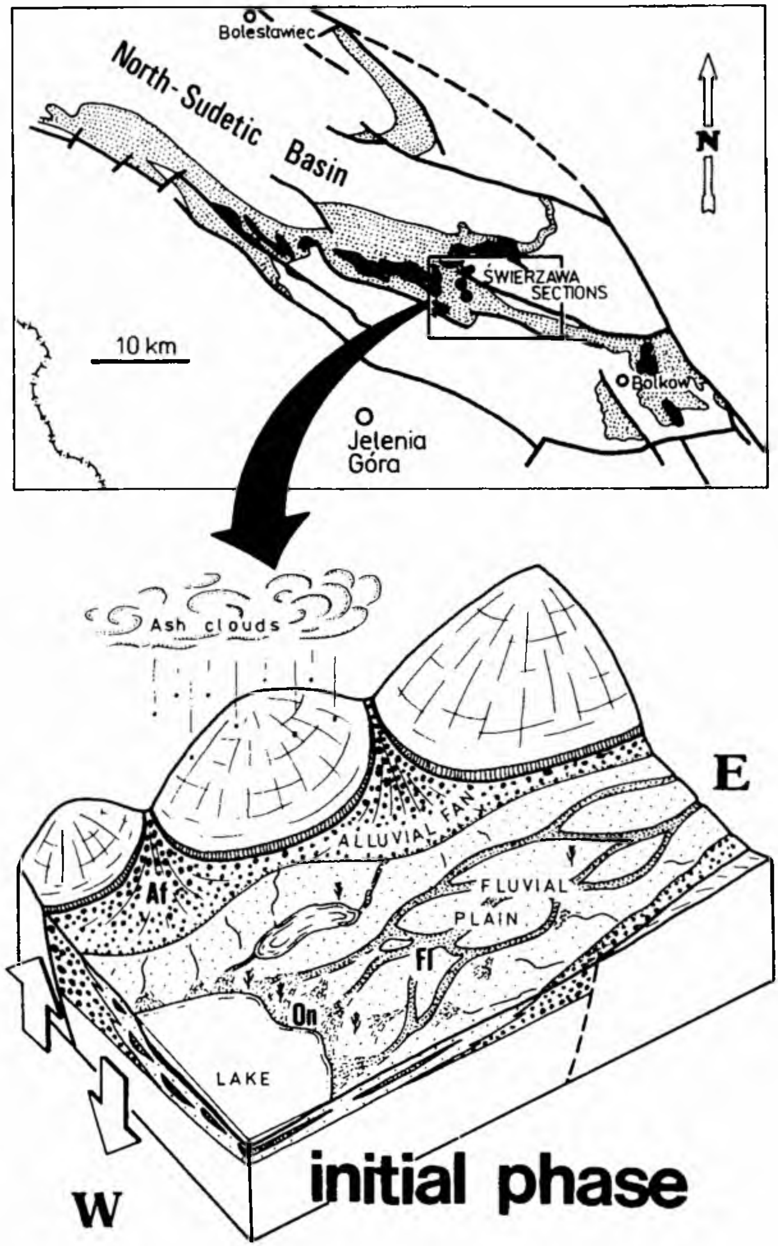

Fig. 9. Palaeogeographic reconstruction of the framed fragment of the North Sudetic Basin during the initial phase of the Upper Anthracosia Lake development. *Af* — alluvial fan; *Fl* — fluvial plain; *On* — onshore flat

basin submergence resulted in thick sequences of lacustrine deposits (Fig. 2).

The upper cyclothem of the Świerzawa Formation represents one large-scale cycle in the tectono-sedimentary development of the North Sudetic

Basin. This cyclothem consists of facies associations which are related to particular phases of the basin evolution. The first phases reflect intense activity of the fault-controlled basin margins, which resulted in thick series of conglomerates and sandstones. These sediments represent alluvial fan and fluvial facies associations which occupy the marginal and axial zones of the basin, respectively. The fluvial zone was dominated by in-channel processes. Overbank areas were restricted areally. The abundance of in-channel deposits and the relatively high dispersion of palaeotransport direction (Ostromęcki, 1973; K. Mastalerz, 1988) suggest a fluvial system with a wide, active channel belt composed of numerous, probably braiding, channels of considerable sinuosity. The abundance of volcaniclastic material suggests synsedimentary volcanic activity, as well as a high rate of accumulation and high preservation potential within the channel belt.

A gradual planation of the source areas led to diminished clastic input into the basin. During this period incipient Anthracosia Lake (or lakes?) started to spread over the basin floor (Fig. 9). At the termination of the present-day Świerzawa Trough, which formed the proximal part of the basinal fluvial belt, this process was recorded as a consequent lake transgression, the extent of which successively increased eastwards with time. The subsequent lake regression resulted in a pensymmetric character of the lacustrine stratotype section (Fig. 5). Thus, the whole Upper Anthracosia Shale can be generally subdivided into four segments reflecting the successive phases of the Anthracosia Lake development.

INITIAL PHASE

The interaction between clastic input and lacustrine processes brought about the development of a flat lacustrine onshore plain (Fig. 9). It was an area frequently invaded by flood waters and sedimentation was predominantly controlled by fluvial discharges. The relatively high sedimentation rate inhibited more intense colonization by plants and animals. The palaeotransport was directed generally towards the WNW, along the basin axis. The small-scale, coarsening-up cycles suggest the presence of low-relief depositional lobes in the terminal, mouth zone of the feeding fluvial system.

The lake level rised temporarily and the onshore zone was submerged, which led to sediment reworking by waves. Such episodes were, however, of very short duration, and they were probably connected with unusual rain storms, floods, or seismic events. Sedimentation and early cementation took place generally in subaerial, highly oxic conditions.

TRANSGRESSIVE PHASE

The following portion of the lacustrine succession, consisiting of nearshore, mass-gravity, and carbonate facies (Fig. 5), was deposited under subaqueous conditions, generally in a shallow nearshore zone of the lake. Sediment was generally transported from the ESE, however, the deposits were considerably reworked due to the wave activity, giving in result a bipolar system of ripple cross-lamination (Fig. 4). The lake bottom was occasionally colonized by some infaunal inhabitants, while the presence of fine plant detritus suggests the vegetation onto the onshore/deltaic plains. The lake level fluctuated on a small-scale, as suggested by the signs of subaerial exposure.

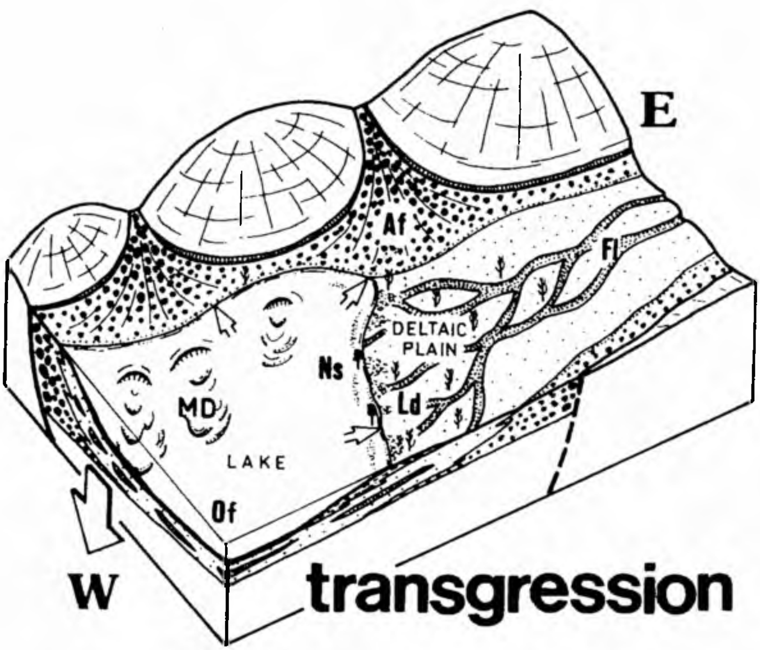

Fig. 10. Palaeogeographic reconstruction of the south-east part of the North Sudetic Basin during the transgressive phase of the Upper Anthracosia Lake development. *Af* — alluvial fan; *Ns* — nearshore; *Ld* — lacustrine delta; *Of* — offshore; *MD* — mass-displacement deposits

The lower part of the nearshore sequence displays a distinct tendency of successive deepening and further, slow lake expansion. This is marked by the gradual transition from the nearshore sediments into heavily bioturbated, homogenized mudstones and marls, with calcareous nodules and dispersed pyrite. The amount of finely macerated plant detritus increased due to the successive development of nearshore/onshore swamps. However, the supply of nutrients gradually diminished due to progressive lake expansion. This resulted in the ichnofaunal change from simple subvertical burrows (suspension feeders) to densely distributed branching channels (sediment feeders applying more systematic strategy of seeking food). The overlying stromatolitic limestones suggest prolonged periods of clear water conditions and algae/bacteria development. The supply of clastic material diminished considerably during this period.

The development of the transgressive lacustrine sequence (Fig. 10) was interrupted by several episodes of mass failures, which displaced large sediment volumes towards the basin centre. These episodes must have taken place when the lake shore impinged upon the alluvial fan system which bordered the basin from the NNE. The high sedimentation rate in the shore zone, rapid facies gradient, as well as the rise of groundwater level, all contributed to slope weakening, while seismic shocks could have caused slope failures and mass-gravity flows.

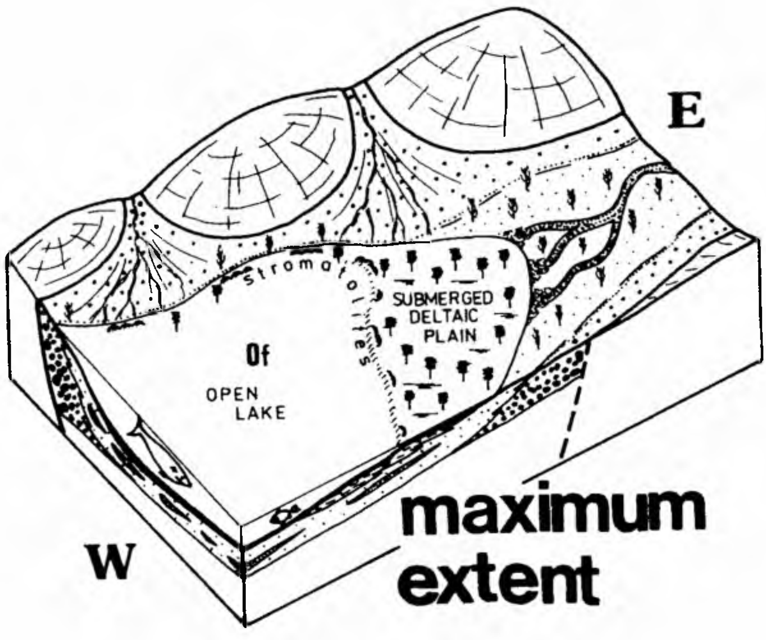

Fig. 11. Palaeogeographic reconstruction of the south-east part of the North Sudetic Basin during the phase of maximum extent of the Upper Anthracosia Lake. *Of* — offshore

The mass-redeposition of large volumes of sediment caused distinct, local shallowing of the lake. This, in turn, induced renewed development of the nearshore facies. The remaining part of the nearshore sequence displays a shallowing trend, with more frequent evidence of wave reworking and temporary subaerial exposure towards the top. Finally, the nearshore shoal bars started to develop and resulted in coarsening-up cycles. Some of the bars were vegetated by submersile plants. The stacked nature of the nearshore bar cycles suggests further lake development, but lake level fluctuations as well. This was probably connected with a period of increased basin floor subsidence, while the sediment supply must have kept pace with the subsidence. The thin layer of homogenous, marly sediments overlying the nearshore facies in the stratotype section (Fig. 5) resulted from development of densely vegetated nearshore reed moors. The intense plant colonization of these areas was favoured by gradual planation and/or widening of the shore/deltaic zone.

THE PHASE OF MAXIMUM EXTENT

The following rise of the lake level resulted in submergence of wide onshore areas. The intense plant colonization of the deltaic/shore plains prevented clastic input to the lake. In the open water, offshore zone of the lake, the slow sedimentation of organic-rich muds persisted for a long period. It was the stage of the maximum lake extent (Fig. 11). This period was preceded and accompanied by stromatolite development interrupted by silica precipitation from hot-spring solutions. The intense development of organic life and, particularly, planktonic blooms, caused autrophication of the lake. Changing environmental conditions resulted in the mass-mortality of freshwater bivalves at the beginning of the sedimentation of the black shale sequence. The water column was probably permanently stratified, with oxygenated epilimnion and anoxic or suboxic hypolimnion. Anoxic, sulphidic conditions in the bottom muds inhibited infauna development.

REGRESSIVE PHASE

The lake expansion was finally stopped due to the rejuvenation of the southern basin margin, which was induced by a prominent extrabasinal tectonic event. This resulted in the development of an alluvial system which rapidly prograded northwards over the lake (Fig. 12). The area of Anthracosia Lake became successively restricted by this system, and lacustrine deposits were buried due to intense supply of clastic material. This regressive phase of the lake development resulted in the coarsening-up, lacustrine deltaic sequence which form the topmost segment of the Upper Anthracosia Shale (Fig. 5). These deposits were successively covered, with erosive contacts, by conglomerates and sandstones of the fluvial channel facies marking the base of the Wielisławka Formation.

DISCUSSION AND CONCLUSIONS

The origin of the North Sudetic Basin and development of its lacustrine sediments were controlled by extra- and intrabasinal factors, including: (1)

synsedimentary tectonic activity and the character of the basin-floor subsidence, (2) climate conditions, (3) rate of sediment supply and gradation of source areas, (4) character of the water feeding system and the potential of water retention in the basin, and (5) activity of living organisms.

Fig. 12. Palaeogeographic reconstruction of the south-east part of the North Sudetic Basin during the regressive phase of the Upper Anthracosia Lake development. *Af* — alluvial fan; *Fl* — fluvial plain; *Ld* — lacustrine delta

The influence of episodic tectonics (and subsidence) on sedimentation resulted in the organization of the basinal sedimentary succession into asymmetric, fining-up megacyclothems (*cf.* Dziedzic, 1959). The episodes of intense, rapid tectonic movements (diastrophic events) were associated with the rejuvenation of source areas, increased rate of basin floor subsidence, and the sedimentation of coarse clastics. These initial diastrophic events were followed by long-term periods of relatively slow and steady subsidence associated with a gradual lowering rate of sedimentation and decreasing grain size of the sediment. During these periods the rate of sedimentation approached the equilibrium state with the rate of subsidence (Wojewoda & Mastalerz, 1989). The lacustrine deposits form the final segments of such externally controlled cyclothemic megasequences (Fig. 2).

The position of lacustrine deposits in the cyclothems may suggest that the development of lakes took place during the periods of „tectonic quiescence". However, such periods were frequently interrupted by seismic shocks of low magnitudes. Numerous signs of lake level fluctuations, effects of mass movements, the evidence of synsedimentary volcanic and hot-spring activity, and the presence of seismically-induced structures within the Upper Anthracosia Shale strongly support this suggestion.

The Upper Anthracosia Shale is typified by a pensymmetric character of vertical grain-size changes and arrangements of the depositional facies (Fig. 5). The thick transgressive portion of this lacustrine succession is believed to reflect a relatively slow and long-lasting transgression (K. Mastalerz, 1988). This is consistent with numerous effects of wave reworking and lake-level fluctuations preserved in the transgressive portion of the succession (Fig. 5). On the contrary, a relatively thin regressive portion of the Upper Anthracosia Shale is related to rapid regression. The lake regression could result either from an intrabasinal feedback of the subaerial depositional system in the basin on the maximum critical area of an expanding lake (Wojewoda & Mastalerz, 1989), or from an extrabasinal diastrophic event. The diastrophic cause seems to be more probable for the Upper Anthracosia Shale.

The frequent lake level fluctuations recorded in the Upper Anthracosia Shale could be related not only to seismic events which induces temporary changes in subsidence rate, base level, and groundwater circulation, but also to short-term climatic fluctuations. Variable precipitation distribution (seasonal rains, rain storms, dry periods) seems to be particularly relevant for lake-level fluctuations.

The climate was warm and wet during the sedimentation of the Świerzawa Formation (*cf.* Scupin, 1922; Dziedzic, 1959). Such conditions promoted the development of variety of plants, with localized dense vegetation of meso- to hydrophilic communities, and frequent algal blooms in Anthracosia Lake. This is compatible with the local development of swamp/moor facies and stromatolites in the Upper Anthracosia Shale. However, peat-bogs were restricted areally and short-lived (*cf.* Becker, 1869). The stromatolitic buildups, gypsum encrustations, together with the abundace and diversity of fauna, all point to high mean annual temperatures.

Anthracosia Lake probably was of a perennial type, but with a frequently fluctuating level. This may be connected with the abundance of water supply and perennial rather than ephemeral character of the feeding fluvial system. However, precipitation and fluvial discharges were strongly variable. The lake level dropped temporarily, probably in a response to prolonged drier periods.

The longitudinal palaeotransport system is well recorded in the fluvial facies of the Świerzawa Formation. This indicated an importance of the axial, feeding fluvial system and points to considerable elongation of the basin. The tendency for a permanent WNW-directed palaeotransport existed also during the development of Anthracosia Lake. Such a palaeotransport system in the lake was induced by the continuous axial, fluvial inflow throughout the active deltaic zone (Figs. 9 — 12). This suggests that Anthracosia

Lake formed a transitional basin with relatively short residence time, i.e., the inflow and outflow were significant, compared to the volume of water in the basin (see also Stoffers & Hecky, 1978). However, sediment transport and redistribution within the nearshore zone were strongly influenced by wave agitation. On the contrary, mass-gravity sedimentation occurred transversely to the basin axis: i.e. slump and sediment-gravity flows were generated at the steep and active northern slope of the basin.

Anthracosia Lake probably had stratified waters, with oxygenated epilimnion and oxygen-poor hypolimnion. The water stratification might have been permanent, due to the high mean annual temperature and salinity contrast. However, the position of the thermocline and halocline varied with lake level fluctuations. The inferred strong contrast between epi- and hypolimnion prevented overturns (*cf.* Dickinson, 1988).

The physico-chemical conditions in the bottom sediments ranged from oxic-to-suboxic in the nearshore zone, to anoxic, sulphidic (*cf.* Maynard, 1982) in the offshore zone. Salinity changes were caused by temporal variations in the temperature and humidity, and hot-spring (silica) as well as algae and bacteria (stromatolites) activity. The supply of juvenile solutions from hot springs (subaqueous?) contributed to the permanent density stratification.

The origin of cherty laminae within the stromatolitic structures is unclear. These laminae do not display any evidence of organogenic origin, and they are believed to be a chemogenic precipitate. However, silica requires different conditions to precipitation than calcium carbonate (Krumbein & Garrels, 1952; Eugster, 1967, 1986). Thus, it is likely that the cherty laminae resulted from local and temporal supersaturation in silica (*cf.* Renaut *et al.*, 1986), but not from a basin-wide changes in the content and composition of dissolved compounds or in pH. A hot spring activity, commonly reported from lakes in tectonically and volcanically active areas (Hardie *et al.*, 1978; Casanova, 1986; Eugster, 1986; Renaut *et al.*, 1986), seems to be a reasonable explanation in the present case.

Plant and animal inhabitants also played an important role in the Anthracosia Lake development. Vascular plants which colonized lacustrine onshore and nearshore zones prevented the lake from an intense supply of clastic sediments. They also stabilized the nearshore areas and prevented the vegetated shoals from wave reworking. These plants contributed a considerable amount of macerated detritus to the lake and locally played even a peat-forming role. Algae and bacteria activity aided in carbonate precipitation and local formation of stromatolitic buildups. Planktonic blooms induced the eutrophication of the lake. The intense decay of organic matter caused de-oxygenation of bottom sediments in offshore areas and prevented their colonization. Burrowing organisms destroyed original sedimentary structures and participated in changing of the sediment composition in some lake zones.

Lakes in tectonically active areas tend to be deep (Holmes, 1978; Freidman & Sanders, 1978). The minimum depth of Anthracosia Lake can be estimated only roughly. The evidence of frequent both wave reworking and subaerial exposure suggests shallow (a few metres) water in the wide nearshore zone. Stromatolitic structures must have been also formed in shallow (probably not deeper than several metres) and clear water (Schafer & Stapf, 1978; Casanova, 1986). However, locally the lake might have been considerably deeper, as inferred from the stratigraphic position and large thickness of the mass-gravity deposits (Fig. 5). During the final, regressive phase of Anthracosia Lake, the water depth at the western termination of the Świerzawa Trough must have been, at least, in the order of 15 to 20 metres, as inferred from the thickness of the deltaic coarsening-up sequence (Fig. 5).

The occurrence of hummocky cross-stratification and the development of nearshore bars also indicate shallow water in the nearshore zone. In modern environments, hummocks were reported from the depth of 4 m (Reineck, 1976) to 1.4 — 1.8 m (Greenwood & Sherman, 1986). The reconstruction of the Devonian lacustrine HCS from south-east Shetland (P.A. Allen, 1981) gives a similar result. Moreover, the small wavelength of HCS in the Upper Anthracosia Shale suggests rather narrow (several to a few tens of km) fetch zone (see for comp. Greenwood & Sherman, 1984).

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Streszczenie

OSADY JEZIORNE W BASENACH SEDYMENATACYJNYCH OGRANICZONYCH USKOKAMI: 1. GÓRNE ŁUPKI ANTRAKOZJOWE (DOLNY PERM) NIECKI PÓŁNOCNOSUDECKIEJ

Krzysztof Mastalerz

Górne łupki antrakozjowe (40 m miąższości) zbudowane są z utworów jeziornych stanowiących najwyższą część formacji ze Świerzawy (dolny autun) w basenie północnosudeckim (Fig. 1 i 2). Utwory te składają się z pięciu odrębnych litofacji obejmujących osady równiny nadbrzeżnej, osady przybrzeżne, otwartego jeziora, deltowe, bagienne, węglanowe oraz grawitacyjnych procesów masowych (Fig. 3 — 8, Pl. I i II). Górne łupki antrakozjowe stanowią sekwencję transgresywno-regresywną, która dzieli się na cztery segmenty odpowiadające czterem głównym fazom ewolucji „jeziora antrakozjowego".

Facja równiny nadbrzeżnej odpowiada inicjalnej fazie jeziornej, gdy centralna część basenu sedymentacyjnego, zajęta przez system koryt rzecznych, stopniowo przekształacała się w jeziorną strefę przybrzeżną poddawaną silnym wpływom środowiska rzecznego (fig. 9). Faza transgresji cechowała się znacznym rozwojem przybrzeżnych środowisk jeziornych (Fig. 10). Ekspansja jeziora przerywana była epizodami sedymentacji z grawitacyjnych procesów masowych, które rozwijały się wzdłuż północno-wschodniej granicy basenu, założonej na aktywnych skarpach uskokowych (Fig. 7 i 8). Czarne łupki, bogate w materię organiczną, reprezentują fację otwartego jeziora odpowiadającą fazie maksymalnego rozwoju jeziora (Fig. 11). Miąższa, transgresywna część sekwencji jest efektem długotrwałej transgresji, natomiast cienka, regresywna część reprezentuje efekt szybkiej regresji wskutek tektonicznego odmłodzenia południowej granicy basenu. Toń wodna „jeziora antrakozjowego" była najprawdopodobniej permanentnie warstwowana, a warunki przydenne zmieniały się od tlenowo-subtlenowych w strefie przybrzeżnej do beztlenowych, siarczkowych w centrum jeziora. Stromatolitowe budowle rozprzestrzeniały się lokalnie w strefie przejściowej przybrzeżno-odbrzeżnej, bagna natomiast rozwinięte były wzdłuż brzegów jeziora. Sedymentacja w „jeziorze antrakozjowym" kontrolowana była głównie przez synsedymentacyjne procesy tektoniczne, klimat, dostawę materiału klastycznego do basenu oraz działalność organizmów żywych.

EXPLANATIONS OF PLATES

Plate I

1 — Mud chips in laminated sandstone, onshore facies, Upper Anthracosia Shale, North Sudetic Basin

2 — Raindrop imprints on the rippled and cracked (*arrow*) sandstone surface, nearshore facies, Upper Anthracosia Shale

3 — Mud ripples, (wrinkle marks) on the top surface of muddy laminated sandstone, nearshore facies, Upper Anthracosia Shale

4 — Sections of subvertical burrow tubes (*arrows*) on the lamination surface of silty sandstone, nearshore facies, Upper Anthracosia Shale

5 — *Walchia piniformis* Sternb.?, impression of a twig fragment, black shales of the offshore facies, Upper Anthracosia Shale, Stara Kraśnica

6 — Seed impression, black shales, Stara Kraśnica locallity

Plate II

1 — Fresh-water pelecypod, left valve, external mould (*Anthracosia?* reported by Dziedzic, 1959 and *Anthracosia prolifera* Waterlot? reported by Milewicz, 1972; no descriptions and figures), black shales, Upper Anthracosia Shale, Stara Kraśnica locallity

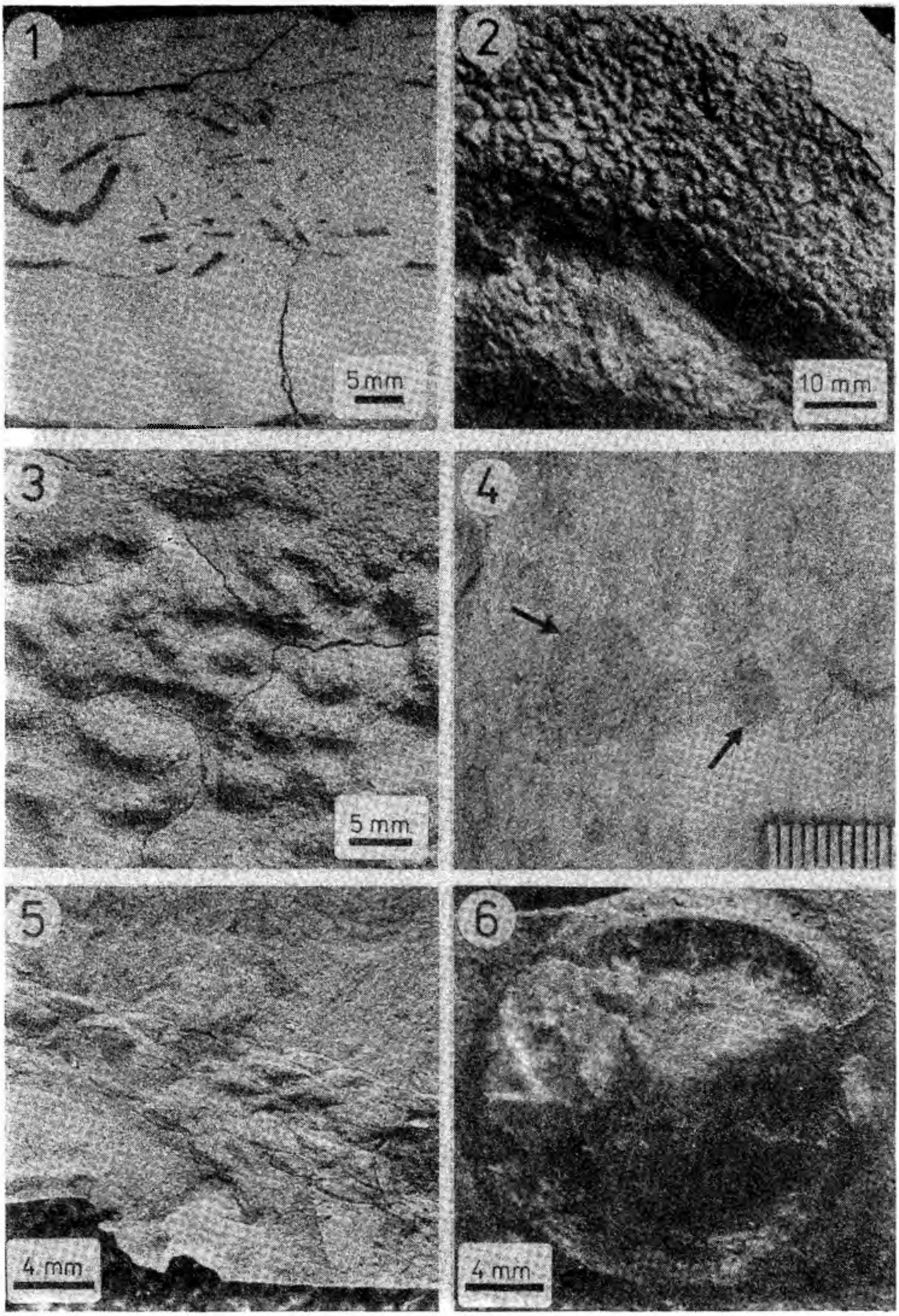
2 — Fish (Acanthodes?), fin impression, black shales, Stara Kraśnica

3 — *Xenacanthus cf.* Type O-m Schneider, 1985, tooth mould, lingual view, black shales, Stara Kraśnica

4 — Arthropod? (eurypterid?), segment of swimming leg?, composite mould, black shales, Stara Kraśnica

5 — Large coprolite composed of collophane and enveloped by thin sulphidic crust, black shales, Stara Kraśnica

6 — Trace fossil (resting track of segmented worm-like animal?), top of bed in concave relief, laminated siltstone, prodeltaic facies, Upper Anthracosia Shale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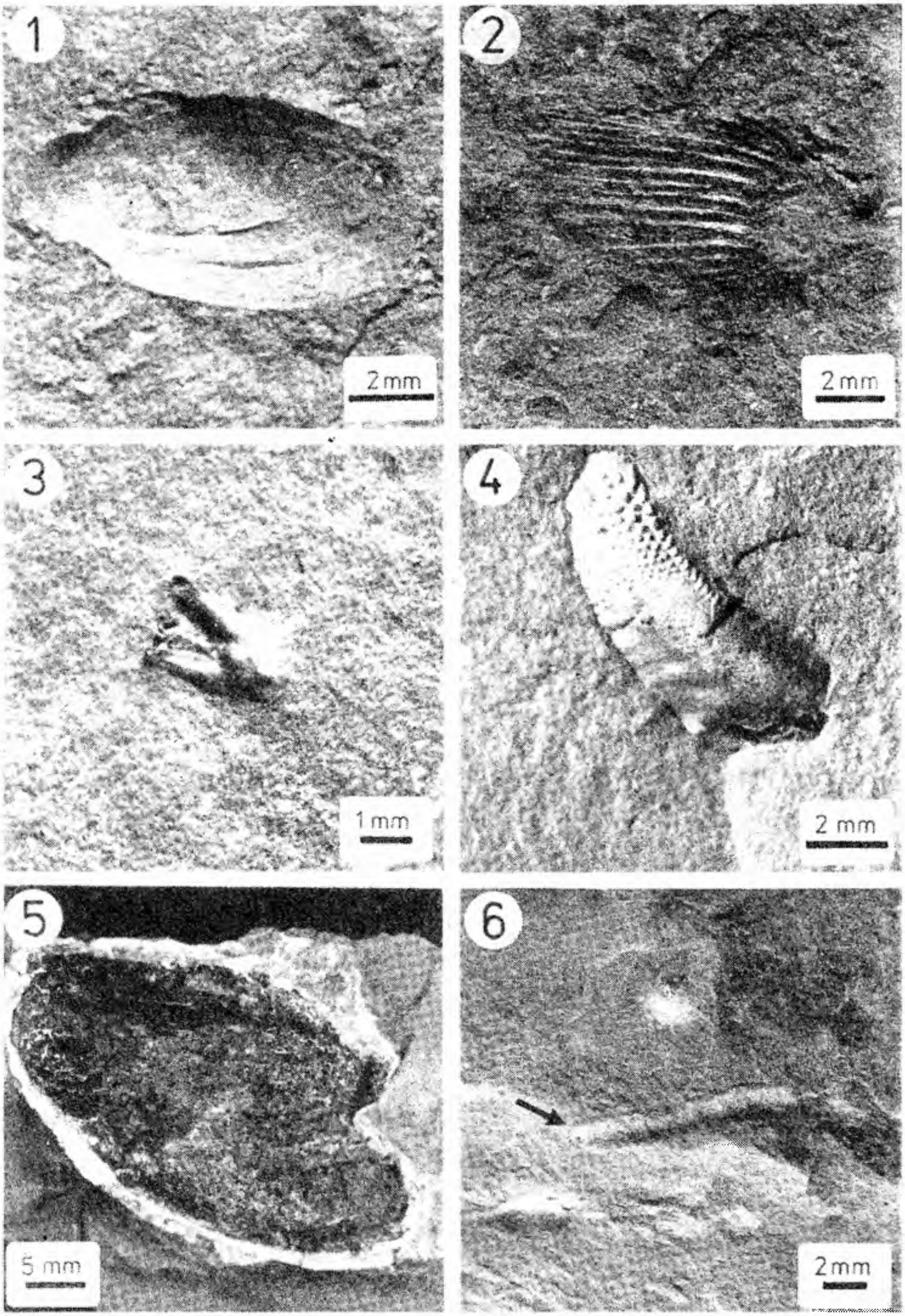
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