PAWEŁ HENRYK KARNKOWSKI

ORIGIN AND EVOLUTION OF THE POLISH ROTLIEGEND BASIN

POLISH GEOLOGICAL INSTITUTE *Special Papers* 3

WARSZAWA 1999

CONTENTS

Polish Geological Institute Special Papers, 3 (1999)

KARNKOWSKI P. H., 1999 — **Origin and evolution of the Polish Rotliegend Basin.** *Polish Geological Institute Special Papers* 3: 1–93.

Institute of Geology, University of Warsaw, Al. Żwirki i Wigury 93, 02-089 Warszawa, Poland. E-mail: phkarnk@geo.uw.edu.pl
Polish Oil and Gas Company, Geological Bureau GEONAFTA, ul. Jagiellońska 76, 03-301 Warszawa, Poland. E-mail: phkarnk@pgnig.com.pl

Abstract. The Polish Rotliegend Basin is a part of the great Southern Permian Basin in Western and Central Europe. Its basin history started in the latest Carboniferous but its origin was rooted as early as Cambrian time. Pre-Permian history of the area of Poland explains the origin of main later frames of the Polish Rotliegend Basin (PRB). It is clearly visible that boundaries of the PRB were determined by eastern margins of the Rheno-Hercynian Basin. Development of the PRB was controlled mainly by climatic and tectonic factors in an intensive rifting regime but it was manifested within individual sedimentary sequences as thicker conglomerate formations or members or increased thickness in most subsiding zones. Detailed sedimentological studies enabled distinguishing in the Rotliegend succession, independently of lithostratigraphic units also allostratigraphic (sequences) ones.

The evolution of the Polish Rotliegend Basin-fill had continued within the Permo-Mesozoic Basin (Polish Basin) until the Late Cretaceous when, due to inversion of the central part of the basin, the Mid-Polish Anticlinorium was uplifted.

The burial history of the Polish Basin reveals that the Late Permian and Early Triassic periods represent the main rifting phase and its later development resulted from thermal relaxation. A Late Jurassic rifting episode manifested itself only in the central part of the Polish Basin. In the Late Cretaceous basin any external tectonic factors initiating subsidence were unnecessary and the mechanism responsible for subsidence was a simple loading subsidence caused by a great sea transgression.

Analysing thermal history of the Polish Basin-fill it was surely evidenced that at the beginning of the Rotliegend volcanic period the high geothermal anomalies occurred in the western part of the developing basin. Initially these anomalies were characterized by higher values (100–150 mWm^{-2}) during the Late Permian–Early Triassic interval. Such high values were related to syn-rift stages of sedimentary basin development. During Late Triassic and Jurassic time some cooling of rift heat field took place, but the turning point in thermal evolution of the Polish Basin was at the Jurassic/Cretaceous boundary when the southwestern part of the Polish Basin was uplifted and intensively eroded. Then a heat inflow into the southern part of the Polish Basin decreased and distinct features of the prevoius epoch were obliterated in the heat flow field image.

Results of burial and thermal analysis of the Polish Basin as well as configuration of Moho surface in Poland seem to suggest the asymmetrical style of the basin model. The uppermost position of Moho is additionally accompanied by a very high helium concentration and corresponds to the area of the highest heat flow during the Late Permian, Triassic and Jurassic in the whole Polish Basin. It may be settled that the described palaeothermal-geochemical-tectonic anomaly, located about 60 km northeast of Wrocław and continued to the northwest, represented the Late Permian–Early Mesozoic rifting process. It is unambiguously indicative of the asymmetric rift character of the Polish Basin, in which volcanism and deposition of Rotliegend series marked the first phase of its development.

Key words: Polish Basin, Rotliegend, basin analysis, stratigraphy, palaeogeography, petroleum play.

Abstrakt. Polski basen czerwonego spągowca (PBCS) jest częścią wielkiego basenu sedymentacyjnego zwanego południowym basenem permskim, leżącym w zachodniej i centralnej Europie. Historia rozwoju polskiego basenu czerwonego spągowca rozpoczęła się na przełomie karbonu i permu. Jednak w jego rozwoju można odnaleźć pewne elementy zakorzenione w już przedpermskim paleozoiku.

Rozwój sedymentacji w polskim basenie czerwonego spągowca był kontrolowany głównie przez tektonikę i klimat. Wyraźna zmiana klimatyczna, z warunków wilgotnych na suche, nastąpiła dopiero w górnym czerwonym spągowcu (i to nie w jego najniższej części). Ruchy tektoniczne zaznaczały się natomiast poprzez tworzenie miąższych kompleksów zlepieńców. Takie spojrzenie na opracowywaną sukcesję osadów czerwonego spągowca umożliwiło wyróżnienie kilku sekwencji.

Ewolucja polskiego basenu czerwonego spągowca nie skończyła się wraz z transgresją cechsztyńską. Wypełnienie PBCS podlegało dalszej ewolucji związanej z rozwojem polskiego basenu permsko-mezozoicznego. Aby móc śledzić ewolucję wypełnienia PBCS wykonano dla tego obszaru analizę historii pogrążania i analizę historii termicznej.

Historia subsydencji basenu polskiego na omawianym obszarze pokazuje, że okres późnego permu i triasu były główną fazą ryftowania, a późniejszy rozwój basenu wynika głównie z relaksacji termicznej.

Analizując historię termiczną basenu polskiego widać, że w czerwonym spągowcu występowały tam wielkie anomalie geotermiczne. Anomalie te charakteryzowały się wysoką wartością strumienia cieplnego (100–150 mWm^{-2}) w czasie późnego permu i triasu. Tak wysokie wartości odpowiadają przeważnie synryftowemu etapowi rozwoju basenu. W czasie późnego triasu i jury wystąpiło pewne schłodzenie pola cieplnego, ale punktem zwrotnym w historii termicznej basenu polskiego było pogranicze jury i kredy, kiedy południowo-zachodnia część omawianego basenu została znacznie wyniesiona i zerodowana. Wtedy to wartość powierzchniowego strumienia cieplnego w południowo-zachodniej Polsce istotnie zmalała, a wyraźne cechy termiczne poprzedniej epoki zostały zatarte.

Występowanie złóż gazu w osadach czerwonego spągowca ograniczone jest do najwyższej części sekwencji osadowej. Skład gazu ziemnego wykazuje niekiedy znaczne zaazotowanie oraz istotne wzbogacenie w hel. Najwyższe koncentracje helu w gazie ziemnym, tak pod względem objętościowym jak i ilościowym, są zlokalizowane w tym samym miejscu, co permsko-jurajska wysoka anomalia geotermiczna i jednocześnie tutaj najpłycej występuje powierzchnia Moho w Polsce.

Wyniki analizy historii pogrążenia i historii termicznej analizowanej części basenu polskiego, jak również konfiguracja powierzchni Moho i związane z nią anomalie paleogeotermiczne oraz wysokie koncentracje helu wskazują na asymetryczny model budowy basenu. Strefa wysokich anomalii paleogeotermicznych, rozciągająca się od obszaru między Wrocławiem i Poznaniem i dalej na zachód, była zapewne głównym obszarem ryftowania. Pierwszym etapem rozwoju polskiego basenu ryftowego był wulkanizm, a następnie sedymentacja w czasie czerwonego spągowca.

Słowa kluczowe: polski basen, czerwony spągowiec, analiza basenów sedymentacyjnych, stratygrafia, paleogeografia, system naftowy.

INTRODUCTION

The Polish Rotliegend Basin is a part of the great Permian sedimentary basin in Europe (about 1500 km long and 350 km wide), extending from England through the Netherlands, Germany and Denmark as far as Poland. This giant basin is called the Southern Permian Basin and its Polish part — the Polish Permian Basin (Fig. I). It started to develop in the latest Carboniferous. The Polish Permian Basin is located within both the Variscides and their foreland and is limited from the northeast by the East European Craton. It continued to develop during the whole Mesozoic until the Cretaceous/Tertiary boundary when the general basin inversion took place. Thus, the Polish Rotliegend Basin was also situated in the area of the Permo-Mesozoic sedimentation which is termed as "Polish Basin".

The idea of the Polish Rotliegend Basin is derived from the notion of the "Polish Permo-Mesozoic Basin" which is understood as a sedimentary area located in the zone between the East European Platform from one side, and the Sudetes and Upper Silesia Massif on the other. The recognition of the area mentioned is a crucial point in the geology of Poland and Europe, because it is the contact zone between the East European Craton and Phanerozoic Mobile Europe. It is also the precondition for understanding processes that created the geological framework of Poland as well as all Europe. Current reconstructions of the southwestern margin of the East European Craton explain it as a collision zone of microplates derived from the Gondwana Supercontinent: on the Polish territory the existence of the East Avalonia Microplate is assumed. This contact zone, 2000 km long, cuts the European continent from the northwest to southeast, from the North Sea to Black Sea and it is called the Trans European Suture Zone (TESZ). The Teisseyre–Tornquist Zone (TTZ) defined in Poland, coincides mostly with this zone. Transition from the Phanerozoic structures of Central and Western Europe to the Precambrian structures of East Europe throughout TESZ is characterized by a great change in petrophysical properties of the Earth's crust. Crust thickness in the area of the Central and Western European Palaeozoic Platform is of 25–35 km, whereas the East European Craton is typified by 45–55 km crust thickness. These dramatic changes were reflected in the development of the Polish Permo-Mesozoic Basin and Cenozoic uplift. The central part of this basin is called the Polish Trough, with a maximum thickness of Permo-Mesozoic deposits and with a maximum inversion during the early Cenozoic period. Recently, the term "Polish Rift Basin" was introduced by J. Kutek (1994) as a synonym of the Polish Basin.

The knowledge on the Rotliegend in Poland is mainly connected with petroleum exploration. The Zechstein deposits, overlying the Rotliegend, are also in the area of economic interest: hydrocarbons in carbonate deposits of the Werra and Stassfurt Cyclothems and polymetallic (mainly copper) ore-bearing deposits in the lowermost part of the Zechstein and uppermost part of the Rotliegend. Data obtained during 40 years of exploration allow to draw serious conclusions, but on the other hand it puts a new challenge.

The aim of this work is to systematize the ideas on the basic matter concerning the Polish Rotliegend Basin and, moreover, to reconstruct the evolution of the Polish Rift Basin, over the area where this basin was located. In order to better understand the relationships between different factors which controlled each stage of the basin development the author has analysed the history of this basin and related area from the Cambrian until recent time. The terms "origin and evolution" are used in the title of this study. In this case the notion "origin" expresses all phenomena related to the basin formation and its development until the Zechstein limestone unit deposition during the Werra Cyclothem. The

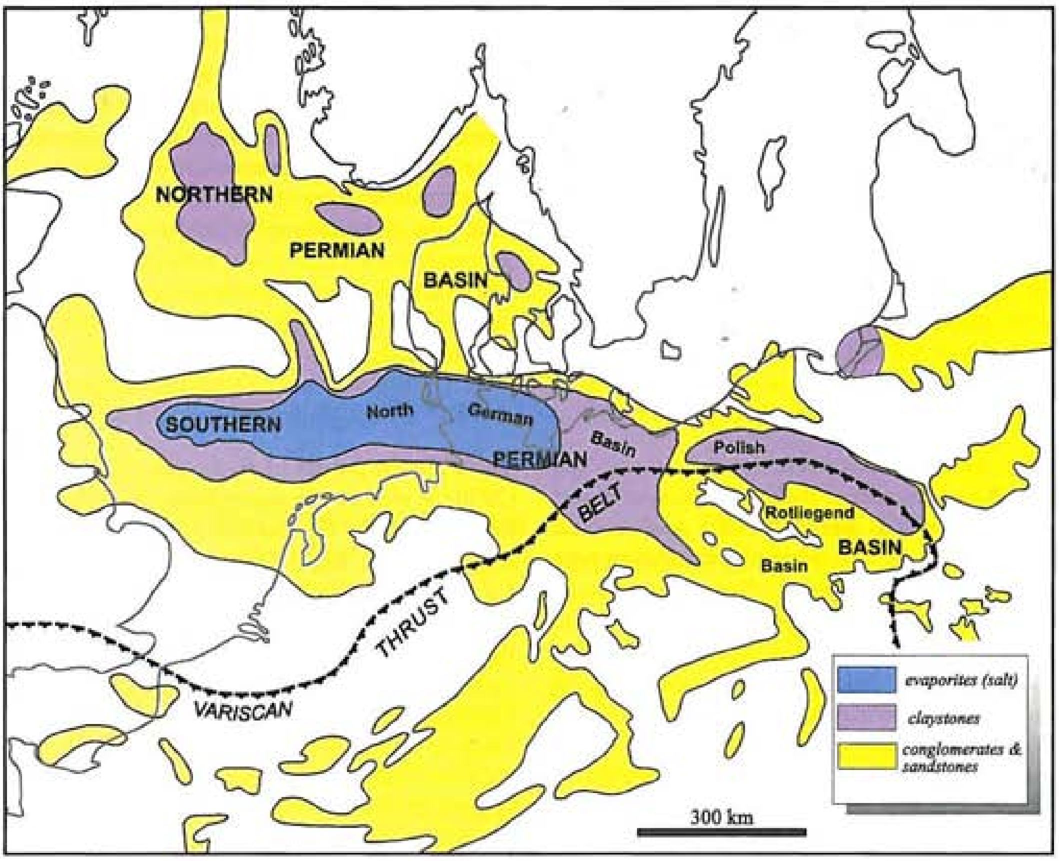

Fig. 1. Rotliegend basins in Central and Western Europe (main sources: S. Depowski, 1978; K. W. Glennie, 1984b; P. H. Karnkowski, 1987a, 1994; P. Gralla, 1988; J. Pokorski, 1988a, 1989; P. A. Ziegler, 1990; R. E Gast, 1991; N. Hoffmann *et al.*, 1997).

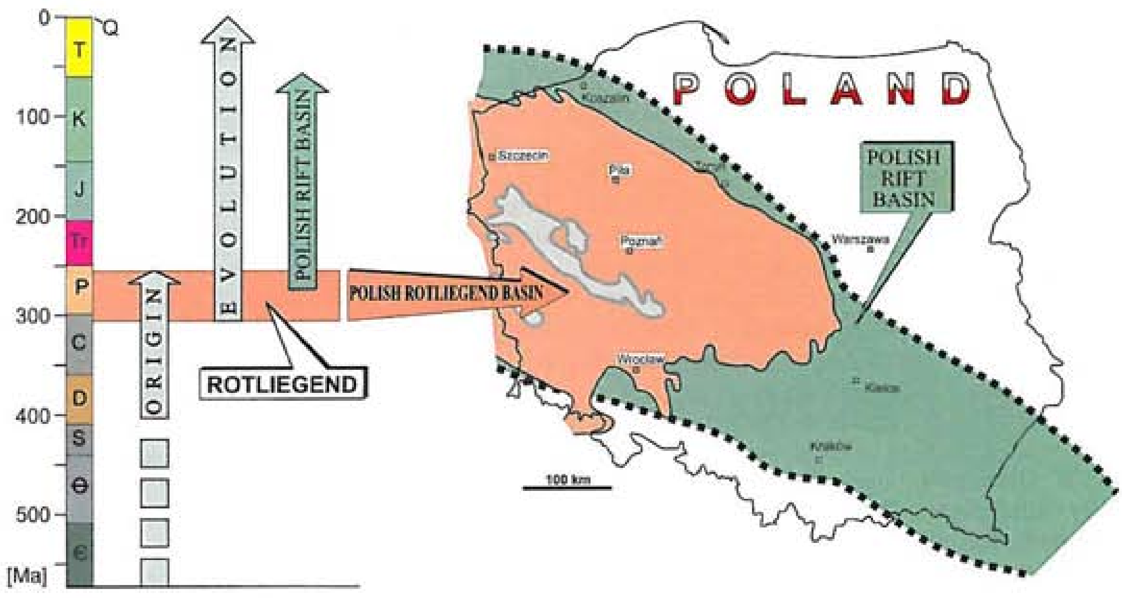

Fig. 2. Spatial and temporal relationships between principal notions used in the paper: origin and evolution of the Polish Rotliegend Basin, and Polish Rift Basin.

"evolution" of basin is related to the period from the earliest Lower Rotliegend (often latest Upper Carboniferous) until now. The Polish Permo-Mesozoic Basin existed as a rift basin just about from the Late Permian until Late Cretaceous when, due to inversion of the central part of this basin, the Mid-Polish Anticlinorium was uplifted. Relationships between these notions used in the study title and applied in this elaboration and their spatial and temporal relations concerning this basin are shown in **Figure 2**.

The analysis of the Rotliegend and Polish Basin is based on several thousands of boreholes and thousands of kilometres of seismic sections. The Rotliegend alone is documented by hundreds of boreholes from which the author has studied more than two hundred of the most important ones. To restore the thermal and burial history of the Polish Basin computer modelling was used. It has enabled a construction of a tectonic and tectonophysical model of this basin.

PREVIOUS RESEARCH

The knowledge on the Rotliegend in Poland is mainly the effect of hydrocarbon explorations. Before the Second World War investigations for oil and gas fields were concentrated in the Carpathians, one of the oldest petroleum industry area in the world. After the war, geological efforts were focused on the Carpathian Foredeep where in the Miocene deposits rich and numerous gas fields were discovered (e.g. Lubaczów, Jaksmanice, Przemyśl fields). The area situated north of the Carpathians and Carpathian Foredeep was also in the scope of interest. It was mentioned as early as in the 1930s, when a few papers emphasizing an interest of petroleum investigations in the Kujawy, Wielkopolska and Pomerania areas were published (S. Czarnocki, 1935; K. Bohdanowicz, 1930, 1936; A. Paszkiewicz, 1936). These authors noticed exploration possibility in the vicinity of salt diapirs, by analogy to the oil field pattern in Germany (Hannover region). As a result of the II War, the Polish state border was shifted to the Odra River and the Polish Lowlands was widened to the west. In consequence, the branch of Polish Oil and Gas Company, called "North", was seated in Kłodawa, nearby a huge salt diapir. It expresses well the mood of petroleum exploration expecting discoveries in the zones around the Zechstein salt diapirs. According to the technology of those times the geophysical prospecting was conducted by gravimetry and magnetometry which mapped a lot of salt diapirs and halotectonic/halokinetic structures. Drilling works, concentrated in the zones located close to salt diapirs, did not give positive effects, so that until now, there are no oil fields of Hannover type in Poland, i.e. no oil plays within Mesozoic deposits and situated close to diapirs. In the 1950s, when the concept of large scale exploration in Poland was born the validity of basin analysis was appreciated. Z. R. Olewicz's (1959) paper entitled "Sedimentary and structural basins of Poland" was the summary of Polish subsurface geology of that time. In spite of poor geological and geophysical data the correctness of isopach maps and regional cross-sections is striking. Z. R. Olewicz distinguished the Wielkopolska Basin (recently called the Epi-Variscan Basin in the Polish Lowlands), the Baltic Basin, i.e. the Old Palaeozoic Basin of the Polish part of the East European Craton as well as the Carpathian Basin together with its foredeep.

Before the World War II, the knowledge on Permian rocks, except in the North- and Intra-Sudetic Basin and southern part of the Fore-Sudetic Monocline, was very poor. There are the papers of H. Scupin (1931) and O. Eisentraut (1939) as well as core descriptions from the vicinity of Wrocław and Opole (P. Assman, 1925; F. Berger, 1933, *vide* J. Sokołowski, 1967). On the basis of synthesis prepared by J. Zwierzycki (1947, 1951) and J. Czarnocki (1951), and the project of petroleum drillings prepared by A. Tokarski, the Polish Oil and Gas Company began exploration of the Fore-Sudetic Monocline area. In the late 1950s, J. Wyżykowski (1958) published a notice on the Kupferschiefer in the vicinity of Sieroszowice and then, basing on drilling results in the Fore-Sudetic Block, he defined main features of the Rotliegend in this region (J. Wyżykowski, 1961, 1963). The results of works conducted in the 1950s were published in the paper of J. Milewicz and K. Pawłowska (1961) where stratigraphy and facies of Permian rocks on the whole territory of Poland were presented. The first oil field was discovered in 1961 on the Polish Lowlands (Rybaki near Krosno Odrzańskie), located within the Zechstein Main Dolomite deposits and the first gas field — in 1964 in the Rotliegend reservoirs (P. Karnkowski *et al.*, 1966) (Bogdaj–Uciechów near Ostrów Wielkopolski). Petroleum exploration in the Fore-Sudetic Monocline contributed to the discovery of rich copper-bearing deposits in the Lubin and Polkowice vicinities. Results of core studies from the Wschowa-1 petroleum drilling donated to J. Wyżykowski from the Polish Geological Institute, were the basis for drilling locations documenting the existence of huge polymetallic-bearing deposits in the uppermost part of the Rotliegend and the lowermost part of the Zechstein.

The results of hydrocarbon exploration conducted by the Polish Oil and Gas Company with co-operation of specialists from the Polish Geological Institute, geology and geophysics faculties of the universities in Cracow, Wrocław and Warsaw, and the Polish Academy of Science, enabled documentation of more than 80 gas fields (mainly in the Rotliegend deposits) and more than 30 oil fields in the Zechstein carbonate rocks.

At the beginning of the 1960s many geological and geophysical data collected from the exploration and documentation of hydrocarbons and copper-bearing deposits in the southern Fore-Sudetic Monocline were obtained; J. Wyżykowski (1964) described clastic sediments of the Lower Permian including their sedimentology, and J. Kłapciński (1967) characterized problems of stratigraphy and palaeogeography of the Rotliegend. In the monograph of the Fore-Sudetic area, devoted mainly to structural problems, J. Sokołowski (1967) included a lot of new and interesting evidences of Lower Permian rocks development. The extensive monograph of the Permian in the Fore-Sudetic Monocline prepared by J. Kłapciński (1971) emphasized main ideas on stratigraphy, facies and palaeogeography of the epoch. In the 1970s a further recognition of the Rotliegend was continued, especially in the Wielkopolska and Pomerania regions. It was expressed by numerous publications: J. Pokorski, R. Wagner (1972), J. Kuchciński (1973), J. Pokorski (1976a, b), P. H. Karnkowski (1977). This stage of geological investigations was summarized during the International Symposium on the Permian in Central Europe (Jabłonna, Poland, 1978). This meeting came to fruition in multitudinous papers (e.g. P. Karnkowski *et al.*, 1978; A. Maliszewska, J. Pokorski, 1978; J. Pokorski, 1978a, b, 1989; W. Ryka, 1978a, b; E. Siemaszko, 1978; P. Roniewicz *et al.*, 1981). During recognition of the Rotliegend in Poland a discussion on the formal lithostratigraphy was initiated (P. H. Karnkowski, 1981; J. Pokorski, 1981a). Later the formal lithostratigraphic subdivision of the Polish Rotliegend Basin was published (P. H. Karnkowski, 1987a, 1994).

The research state on the Rotliegend in the Polish Permian Basin in the last decade was summarized during the XIII International Congress on the Carboniferous and Permian (N. Hoffmann *et al.*, 1997; P. H. Karnkowski, 1997a; H. Kiersnowski, 1997a).

BASEMENT PROVINCES OF POLAND AND TECTONIC POSITION OF THE POLISH ROTLIEGEND BASIN

Tectonic position of the Polish Rotliegend Basin and its relation to the main tectonic units in Poland is shown in the basement provinces map (Fig. 3). The map was compiled by the author using various source materials and a lot of details will be explained not only in this chapter but also further in the text.

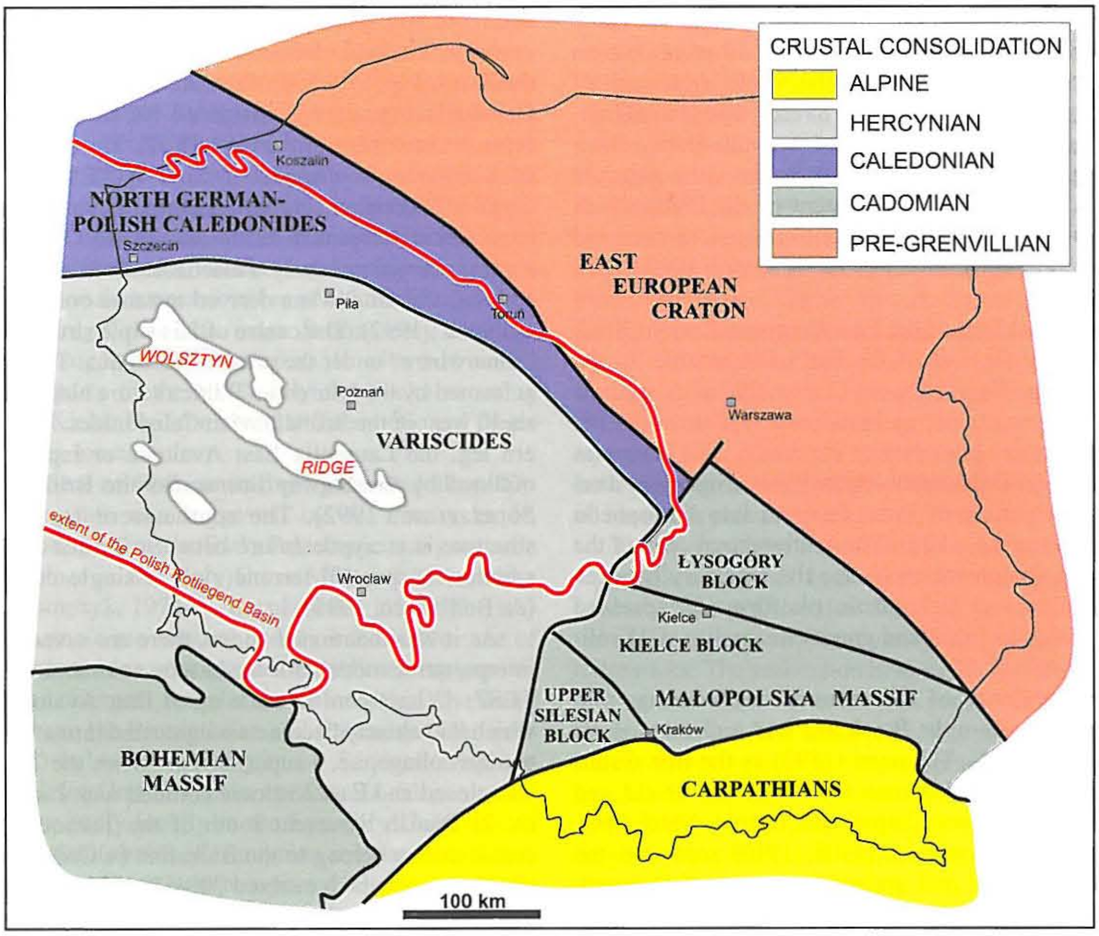

Fig. 3. Basement provinces of Poland and adjacent areas.

The main basement provinces of Poland are the Precambrian East European Craton, the Cadomian blocks of the Upper Silesia and Małopolska Massif, the areas of Caledonian, Variscan and Alpine fold belts. During a long and complex evolution of the crystalline basement of Poland the mosaic of crustal elements became stepwise consolidated. The basement provinces are assumed here by the youngest orogenic event that affected the corresponding crustal segment sufficiently to give rise to widespread dynamo-metamorphism (P. A. Ziegler, 1990).

The oldest basement province is formed by the East European Precambrian Craton. The age of its crustal consolidation was determined by radiometric measurements of magmatic intrusives and metamorphic rocks. The crystalline basement of the Polish part of the East European Craton was primarily shaped during the pre-Svecofennokarelian epoch (older than 2500 Ma), during formation of "ensialic" granitoid blocks and "ensimatic" fold zones. Rocks of the Svecofennokarelian cycle (2500–1600 Ma) were presumably widely distributed. However, deep pre-Vendian peneplanation resulted in a removal of the bulk of them so they are nowadays present in the area of 10% of the platform only. Granitization was intensively developed in the Gothian epoch (Rapakivi-like granitoides, 1470 Ma). Vein granitoides cutting charnockites, migmatites and metasomatic granites (Pre-Svecofennokarelian oval-shaped granitoid massifs) are of the isochrone age of 1340 Ma and until now have been described as a final repercussion of a Gothian transformation that occurred along the whole border part of the East European Platform. The Sveconorwegian (Grenville) Orogeny (1100 Ma), described in southwestern Sweden, may explain the age of some granitoides cutting the old pre-Karelian complexes. Development of the Precambrian basement finished with Vendian platform magmatism and volcanism (T. Depciuch *et al.*, 1975; W. Ryka, 1982, 1984, 1985).

The blocks that formed the East European Craton (EEC) were accreted by the end of the Early Proterozoic. In the western part of the East European Craton, the major tectonic elements of this basement trend southeast, and are cut by the present southwestern boundary of the craton. The latter was formed during the Dalslandian-Grenvillian orogeny as a result of the partitioning of Proto-Pangaea into lithospheric plates (R. G. Garetsky, 1993). The southwestern edge of the East European Craton which is also the boundary between the pre-Vendian and Palaeozoic platform is expressed mainly by strong magnetic and gravity anomalies (C. Królikowski, Z. Petecki, 1995).

A geological sense of this tectonic line running from southern Scandinavia to the Black Sea was acclaimed at the end of last century. W. Teisseyre (1893) as the first distinguished a fault system between the Ukrainian Shield and Podole Platform, and the Carpathians (Berdo–Narol line). Somewhat later A. Tornquist (1908, 1910) separated the magnetically disturbed and undisturbed areas of Denmark and northern and central Poland where the boundary between these areas runs from Koszalin to Bydgoszcz and the Toruń vicinity and farther to the northern edge of the Łysogóry Mts. (Holy Cross Mts.). W. Teisseyre (1921, p. 106) supported the opinion that "SW border of the Russian Platform consists of anastomosing lines among which three lines are the most important: Scania–Radom line, Berdo–Narol line and Prut River line". In honour of these two scientists the southwestern boundary of the East European Craton (EEC) was called the Teisseyre–Tornquist Line (TTL). For almost one hundred years a large amount of geological and geophysical data have been collected contributing to the recognition of the TTL role in geological history of Central Europe. Primary meaning of the TTL was defined as a set of deep-seated faults separating two crustal blocks. Later geological and geophysical investigations underlined the influence of this line in both sedimentation and tectonics of the area mentioned. Notion of the line was replaced by the zone (W. Pożaryski *et al.*, 1982a). Recently, the term T–T Zone is also applied to an elongated block of thickened crust paralel to the East European Craton, and placed partly within the EEC and partially outside of it. On the map of basement provinces (Fig. 3) the line limiting the EEC to the west is marked in its traditional meaning. The northwestern segment of the T–T Zone including Scania, southern Baltic Sea and northwestern Poland — Pomerania region corresponds roughly with the Trans-European Suture Zone (TESZ). It is a new term to describe the crustal domains of continental Europe that separates "Ancient Europe" (with intact >850 Ma old Precambrian basement) from the Variscan, Cimmerian, and Alpine foldbelts of Young Europe (A. Berthelsen, 1993). Scarced geological information indicate that pre-Cadomian and Cadomian (>900/650–550 Ma) basement rocks — as well as Caledonian-metamorphosed (530–400 Ma old) rocks locally form the basement of the NW-TESZ. The structure and age of the basement underlying the NW-TESZ, south of the cryptic Caledonian suture in northern Germany and Poland, have been interpreted as the enigmatic Caledonian triple suture, formed in Early Palaeozoic time when Laurentia, Baltica, and Gondwana-derived terranes collided (D. Blundell *et al.*, 1992). The centre of this triple structure is located "somewhere" under the present North Sea. The northern leg is formed by the Laurentia–Baltica suture hidden beneath the shelf, west of the Scandinavian Caledonides. The southwestern leg, the Laurentia–East Avalonia or Iapetus suture, is outlined by the Solway line across the British Isles (N. J. Soper *et al.*, 1992). The southeastern leg in the triple structure is a cryptic suture between Baltica and/or several smaller, suspect(?) terrane(s) or a single composite one (A. Berthelsen, 1993).

As it was mentioned above, there are several alternative interpretative models for the basement structure of the NW-TESZ: 1) basement is made up of East Avalonian terranes which had already become amalgamated into a "ready made" terrane collage, i.e. a super-terrane, when the Tornquist Sea was closed and East Avalonia collided with Laurentia-Baltica; 2) Danish basement south of the Tornquist Zone was considered to belong to the Baikalian (= Cadomian/Pan-African) orogen which evolved 700/650–550 Ma ago along the SW-margin of the Shield-Platform (K. B. Jubitz *et al.*, 1986); 3) W. Pożaryski (1990), W. Pożaryski *et al.* (1992) suggested successive, sidewise docking of individual, suspect terranes along a major Mid-Caledonian strike-slip fault drawn at the northern border of a marginal thrust belt; 4) R. Dadlez *et al.* (1994a) questioned the terrane hypothesis along the edge of the East European Craton in Poland. They consider this area rather to be parts of the EEC passive margin (miogeocline), deformed in late Caledonian times into a fold-and-thrust belt. The questions about the age and nature of the TESZ basement and its border relations to the Shield and the foundation of the platform is still open, but there are some geological data that allow to establish the following probable solution.

In the Pomerania region (northern margin of the EEC in Poland) the folded Early Palaeozoic rocks from Llandeilo to Pridoli (R. Dadlez, 1978) are known from several boreholes. Their thickness, metamorphism degree and tectonism, discriminate them clearly from the adjacent platform Palaeozoic rocks. The folding age here is considered to occur at the Ordovician–Silurian boundary (Taconian folding) by W. Pożaryski, A. Witkowski (1990) or at the end of the Silurian (R. Dadlez, 1982). The latter seems more probable. The Pomeranian strongly folded Early Palaeozoic rocks are correlated with very similar complexes from Rügen and are joined together as the North German–Polish Caledonides. The southeasternmost borehole documenting this phenomenon is Toruń-1. Farther to the east, along the EEC margin, the next points disclosing the Early Palaeozoic rocks outside the EEC are placed in the area of the Łysogóry Block. The name Łysogóry is derived from the name of the highest mountain belt of the Holy Cross Mountains (HCM), composed of Early Palaeozoic rocks (mainly Upper Cambrian). The Holy Cross Mts. are divided by the Holy Cross Fault separating the northern Łysogóry Unit and the southern Kielce Unit. It has existed at least since the Cambrian, as inferred from the different development of Palaeozoic sediments belonging to the Łysogóry and Kielce units. The Cambrian to Lower Carboniferous rocks of these units markedly differ with respect to facies, thickness and stratigraphic gaps. The Early Palaeozoic successions are of epicontinental character in both Holy Cross Mts. units. Sedimentary development in the Łysogóry Unit is comparable with that one of more internal parts of the EEC, only the thickness being greater. In the Kielce Unit the lateral differentiation of facies and thickness is more distinct.

Consolidation of both units during the Baikalian/ Cadomian movements was suggested by W. Pożaryski, H. Tomczyk (1968). During the Early Palaeozoic many tectonic phases took place in the Holy Cross Mts. and Małopolska Massif (H. Tomczyk, 1974; P. Karnkowski, 1983). The recognition of tectonic movements based on the occurrence of angular unconformities, stratigraphic or sedimentary gaps or even on facies changes. Angular unconformities have been found 1) between the Precambrian and Cambrian (Małopolska phase), 2) below the Arenigian — Sandomierz phase (only in the Kielce Unit), 3) below the Emsian–Siegenian — Ardenian phase (only locally in the Łysogóry Unit) and 4) below the Permian (phases of Hercynian movements). Other tectonic movements have been recognized between the Early and Middle Cambrian — the Holy Cross phase, within the Ordovician — Łysogóry phase, between the Ordovician and Silurian — Taconian phase, and the Cracovian phase within the Silurian. In the Łysogóry Unit sedimentation between the Silurian and Devonian was either continuous with a gradual passage from marine to fluvial environments (H. Łobanowski, T. Przybyłowicz, 1979; E. Turnau, L. Jakubowska, 1989) or with an insignificant gap with penecordant contacts (E. Mariańczyk, 1973). Multiple tectonic phases in the Holy Cross Mts. during the Palaeozoic and their different image depending on their locality (Kielce or Łysogóry units) have caused a controversy between the supporters of main Caledonian folding (J. Znosko, 1974, 1984; Z. Kowalczewski, 1981) and those of main Variscan folding (W. Mizerski, 1992, 1995; E. Stupnicka, 1992). The author's opinion is that the Łysogóry Unit was affected much more strongly by Variscan tectonics and the Kielce Unit was more intensely subjected to the Palaeozoic tectonic movements. In the case of both units the possibility of occurrence of any orogenic processes after the Cambrian was denied (M. Szulczewski, 1977). Thus, the conclusion can be drawn that there is no prolongation of the North German–Polish Caledonides into the area of the Łysogóry Unit or Kielce Unit. The boundary separating the North German–Polish Caledonides from the Łysogóry Block perpendicular to the margin of EEC can be correlated with the most distinct fracture — the Grójec–Opoczno Fault Zone, clearly visible in gravity maps (C. Królikowski, 1993; C. Królikowski, Z. Petecki, 1995). It was an active fault system during the Devonian and Carboniferous, causing the facies and thickness diversity on both sides of this fault system in the Lublin and Warsaw area (A. M. Żelichowski, 1983, 1987a).

The oldest rocks in the Małopolska Massif are represented by dark-grey-green or red meta-argillites which are strongly tectonized (60–80°). Their age was compared to the Dobrugea schists (E. Głowacki, P. Karnkowski, 1963) and assumed as Ryphean. The extent of meta-argillites is very large and embraces all the area of the Małopolska Massif as far as the Upper Silesia Massif. Cambrian rocks (15–20° inclined) occur on this folded basement. Thus, the Cadomian age of the basement formation may be accepted. As far as the age of the Małopolska Massif basement was established, there are no boreholes piercing the Cambrian rocks in the Łysogóry Unit. The same Cadomian age of consolidation for both the Kielce and Łysogóry units is assumed on the map of basement provinces (Fig. 3).

The Małopolska Massif is bordered to the west by the Upper Silesia Massif. In the latter area drilling cores provide evidence of the Devonian Old Red Sandstone succession, unconformably overlying a variety of Lower Palaeozoic and older rocks. The succession below the unconformity consists of several hundred meters of terrigenous rocks that form two structural units. The upper unit was reported to consist of almost flat-lying and unmetamorphosed rocks intruded by igneous rock bodies, whereas the lower unit was said to be composed of steeply dipping (40–80°) rocks that had undergone the greenschist facies metamorphism (Z. Kowalczewski, 1990). Basing on the occurrence of trilobites (S. Orłowski, 1975) and acritarchs (Z. Buła, M. Jachowicz, 1996), and on lithologic similarities, the upper unit was considered to be Cambrian in age. Rocks of the lower unit were therefore thought to be of Upper Proterozoic age (A. Kotas, 1973, 1982; A. Ślączka, 1985). Thus, the Cadomian age of basement consolidation may be accepted.

Both the Cambrian and Ordovician sediments within the Upper Silesia Block differ from the Lower Palaeozoic and Vendian rocks occurring within the western part of the Małopolska Block with respect to their tectono-stratigraphic development. A close position of both types of development suggests that a tectonic contact of both blocks exists along a narrow (approx. 0.5 km wide) tectonic zone (Z. Buła, M. Jachowicz, 1996). The above evidence suggests that the Małopolska Massif and Upper Silesia Massif are possible terranes (W. Pożaryski *et al.*, 1992; R. Dadlez *et al.*, 1994a).

The boundary between the above mentioned massifs is more or less known whereas their northwestern boundary is poorly known. The northeastern edge of this border zone is identified with the Grójec–Opoczno Fault, and the western border of the Upper Silesia Massif is recognized by the Variscan flysch extent (Fig. 3). Such two sections determined this way were linked together into a single line. The additional circumstance to recognize the Cadomian basement is the extent of the Variscides. Their existence is well known in the Upper Silesia but farther north it is documented only by few boreholes.

The area of Hercynian crustal consolidation is determined here (Fig. 3) by the extent of strongly folded and metamorphosed Late Palaeozoic flysch. During the study on the Rotliegend the author has examined all drilling cores from beneath the Permian deposits in the Polish Permian Basin and adjacent areas, and his opinion on the extent of the Variscan Thrust Belt is almost concordant with the idea expressed on the map of Poland during Variscan time (W. Pożaryski, P. Karnkowski, 1992). Main differences are referred to the area of the northern Holy Cross Mts. periphery, where thick and folded Lower Carboniferous deposits occur. In the author's opinion they can not be compared to those from the Fore-Sudetic Monocline. Generally, the Palaeozoic rocks of the Holy Cross Mts. are moderately folded and it gives the reason to consider the Hercynian tectonic movements as the important episode in geological history of this area (W. Mizerski, 1979; E. Stupnicka, 1992), although there are also the advocates of main Caledonian folding (e.g. J. Znosko, 1974, 1984; Z. Kowalczewski, 1981). Undoubtedly, the Hercynian tectonic movements manifest themselves outside of the Variscides. This zone where the basement is overprinted by Caledonian, Cadomian or older consolidation, and where the influence of Hercynian tectonics is clearly visible, is proposed to be named as "Peri-Variscicum" (Z. Kotański, 1997a). It well reflects the relationship between the Variscides *sensu stricto* and adjacent areas where the Late Palaeozoic rocks of platform facies are moderately folded and faulted.

In Poland, the Variscides are subdivided into two zones: the external and internal ones. The latter is represented by the Sudetes and the Fore-Sudetic Block, which to the north is bounded by the NW-trending fault system of the Middle Odra River, separating it from the Fore-Sudetic Monocline and considered to be an equivalent of the Saxo-Thuringian Zone. The Sudetic structure consists of numerous, relatively small, tectonostratigraphic domains, usually with tectonic boundaries, forming a mosaic pattern. The borders between these domains are usually characterized by sharp metamorphic contrasts, different internal sedimentary-stratigraphic development and also differences in a style of tectonic deformations. These differences suggest that the Lower Silesian region can be considered to form a foldbelt composed of several suspect terranes (Ph. Matte *et al.*, 1990; Z. Cymerman, 1991; G. J. H. Oliver *et al.*, 1993; Z. Cymerman, M. A. Piasecki, 1994; Z. Cymerman *et al.*, 1997). The external zone, located mainly beneath the Fore-Sudetic Monocline is regarded as an equivalent of the Rheno-Hercynian Zone (Wielkopolska Externides). The rocks of this zone are represented mainly by the Lower Carboniferous flysch.

CRUSTAL CONFIGURATION

The Earth's crust in Poland was recognized along deep seismic sounding profiles (DSS) LT-2, LT-3, LT-4, LT-5, LT-7, and VII. They penetrated the Moho boundary and determined boundary velocities within the crystalline complex of the Earth's crust. The blocks distinguished correspond to the Precambrian Platform, Palaeozoic Platform and Teisseyre–Tornquist Zone and they have distinctly different tectonophysical properties (A. Guterch *et al.*, 1983, 1986, 1991, 1994). In the Fore-Sudetic Monocline the top of the crystalline basement is also well defined by the shallow seismic-refraction data (S. Młynarski, 1982). Deep seismic recognition is confined only to profiles GB-1, GB-2 and GB-2A cutting the Sudetes and their western foreland. The quality of these profiles is moderate and only the GB-2A which may be considered as an overlapping continuation of the DEKORP MVE-90 (East) gave the basis for a construction of crust models in SW Poland (A. Żelaźniewicz *et al.*, 1997).

In the author's opinion, the configuration of the crust-mantle boundary (Moho Discontinuity) is the most important. It has been revealed in all the original DSS profiles from Poland and published data from the Southern Baltic (A. Guterch *et al.*, 1983, 1986, 1991, 1994; J. Makris, S. R. Wang, 1994), and it was summarized in the map (**Fig. 4**) where data around Poland were taken from the map by P. A. Ziegler (1990) published earlier. The maximum thickness of the Earth's crust under the Sudetes is about 35 km, while that in the Fore-Sudetic block does not exceed 28–30 km. In the region corresponding to the Fore-Sudetic Monocline the depth of Moho discontinuity varies from 32 to 35 km. This zone extends into NW Poland and farther towards eastern Germany. The crustal thickness of the Precambrian Platform in Poland is 42–47 km. In the marginal zone of the East European Craton in Poland a thickness of the crust ranges from 50 to 60 km. It is called the T–T Zone and its width

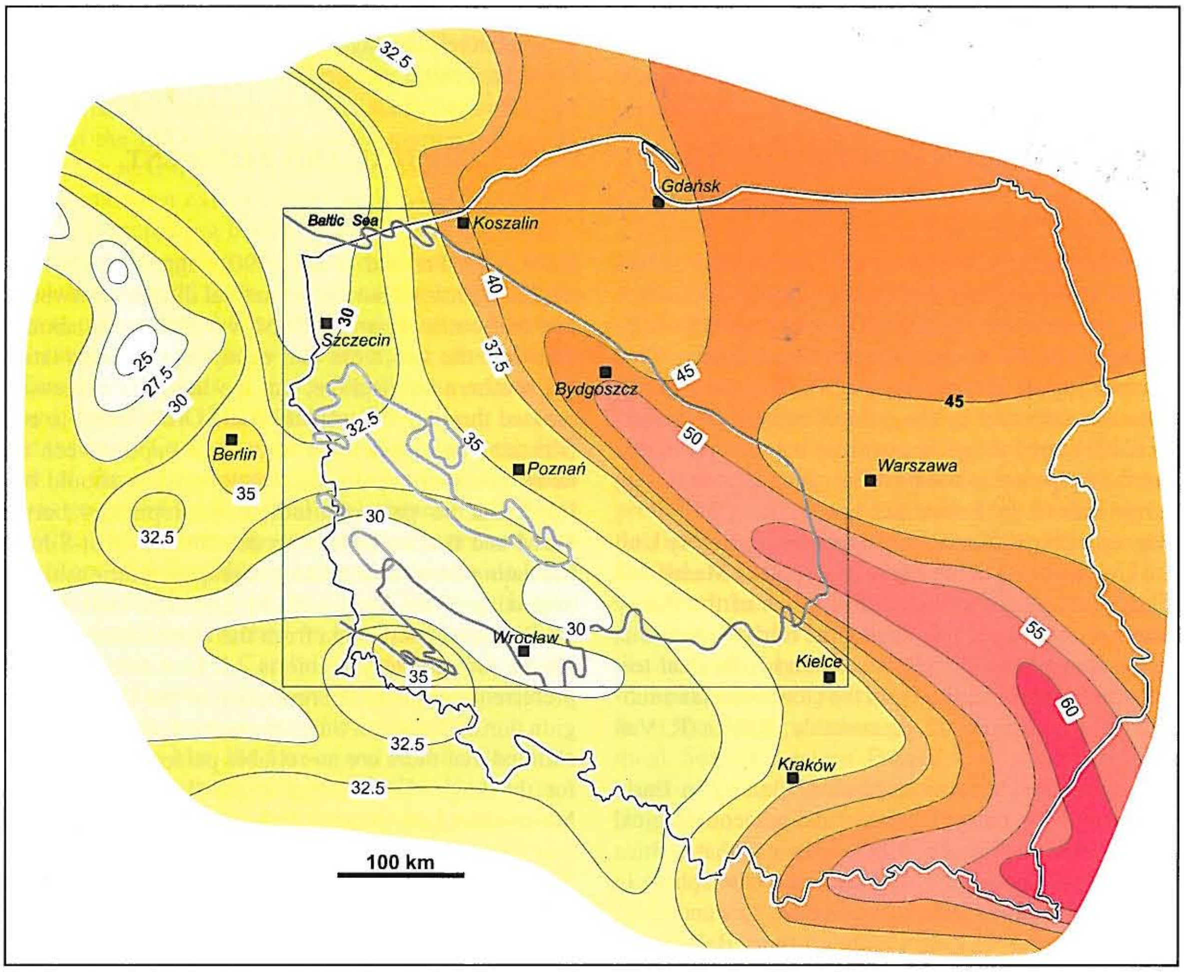

Fig. 4. Moho discontinuity depth map (in km) of Poland and adjacent areas (main sources: A. Guterch *et al.*, 1983, 1986, 1991, 1994; P. A. Ziegler, 1990; J. Makris, S. R. Wang, 1994); rectangle marks the author's study area; inside rectangle the present extent of the Polish Rotliegend Basin is shown.

varies from 50 km in Central Poland to about 90 km in southeastern Poland.

The internal crust structure in Poland is relatively poorly studied and only one of DSS profiles (LT-7) is of high quality with well recognized pattern of seismic velocities (Vp) within the crust (A. Guterch *et al.*, 1994; R. Dadlez, J. Pokorski, 1996). The Precambrian Platform is composed of three crystalline layers: upper (Vp = 6.2–6.3 kms^{-1}), middle (Vp = 6.5–6.6 kms^{-1}), and lower crust layer (Vp = 7.0–7.15 kms^{-1}). The crust between the Precambrian Craton and German territory is also three-layered but the thickness of the lower and middle layers (with almost identical Vp pattern like within the Precambrian one) is thinned by the half. The upper layer (Vp = 5.8–5.9 ms^{-1}, 12–14 km thick) is regarded as the presence of slightly metamorphosed rocks. In the German territory, just outside of the state boundary, two-layer crust is detected (upper, Vp = 6.2–6.3 kms^{-1}, and lower, Vp = 6.5 kms^{-1}). This crust is regarded as a typical Variscan crust (A. Guterch *et al.*, 1994).

In eastern Germany different crustal types are correlated by P. Bankwitz (1993) with the distribution of the Variscan zones of F. Kossmat (1927). In the Saxo-Thuringian zone the crustal velocity, directly above the Moho boundary, is generally very low (Vp = 6.2 kms^{-1}). In the Rheno-Hercynian zone the mean crustal velocity ranges from Vp = 6.4 to 6.6 kms^{-1} immediately above the Moho discontinuity. The third type of the crust forms the foreland north of the Variscides. It differs from the other two types by a significantly higher velocity of the lower crust (Vp = 7.2 kms^{-1}) (P. Bankwitz, 1993).

The crustal structure in southeastern Poland (Małopolska Massif) markedly differs from that observed in the northwestern and central parts of the country but a closer opinion of its nature and connections to sedimentary basins is premature due to scarce of geophysical data.

The above described structures of the crust are often related to past sedimentary basins and/or orogenic belts but the crust-mantle boundary reflects, as a rule, the present-day situation. P. A. Ziegler (1990) underlines that the relief of the Moho Discontinuity in Western and Central Europe hardly shows any relation to the age of crustal consolidation. This is particularly true for the Caledonian and Variscan basement provinces, which were subjected to a crustal extension during the Mesozoic and Cenozoic what is expressed by a close relation of the positive and negative anomalies of the crust–mantle boundary and zones of extension and compression. It indicates that the position of the present Moho Discontinuity is a relatively young feature (R. Meissner *et al.*, 1987; J. Dyment, 1989).

PALAEOMAGNETIC CONSTRAINTS ON THE CRUSTAL AND BASEMENT PROVINCES IN POLAND

The palaeogeographic considerations on the pre-Permian basins in the Polish territory are based mainly on subsurface data. Basinal deposits are largely burried and only the Holy Cross Mts. area and the margins of the Upper Silesia Coal Basin are outcropped. The presence of Palaeozoic rocks in the outcrops is evidenced by the palaeomagnetic investigations that enable establishing the positions between particular blocks and their relation to the East European Craton during individual periods of the Palaeozoic time.

Palaeogeographic differences between the Łysogóry Unit and Kielce Unit and also between the Małopolska Massif and Upper Silesia Massif are interpreted in terms of the theory of terranes. It is considered that during the Early Palaeozoic, Armorica became gradually fragmented and individual terranes successively drifted away from the Gondwanaland subsequently to join Laurentia and, presumably, Baltica (R. Van der Voo, 1988).

A palaeogeographic reconstruction of Baltica in Early Palaeozoic time using palaeomagnetic and palaeobiological data (J. Dzik, 1983; D. Franke, 1993) indicates that Baltica occupied temperate latitudes of the southern hemisphere in the Cambrian. Palaeomagnetic studies of M. Lewandowski (1987, 1991) show that in Late Cambrian time, Baltica and the southern province of Holy Cross Mts. (HCM) were separated at ca. 40° of latitude, while the northern province of HCM was an integral part of the East European Craton in the Early Palaeozoic (H. Tomczyk, 1988).

It should be noted, however, that the new palaeomagnetic data from the Lower and Upper Ordovician limestones of Baltica (H. Perroud *et al.*, 1990) suggest that at least from the Early Ordovician the latitudinal distance between Baltica and the southern part of HCM was reduced to about 10°. At that time the two areas had occupied moderate latitudes on the southern hemisphere, but the latitudes successively decreased through sub-tropical (Late Ordovician) to equatorial (Emsian) ones, when the latitudinal gap between the areas under comparison already disappeared. It should be underlined that no palaeolatitudinal discrepancies between the HCM and Baltica have been detected for post-Silurian time indicating their close palaeogeographic relationship since the beginning of the Devonian (M. Lewandowski, 1993).

Palaeomagnetic data from the Upper Silesia Massif gave rise to contradictory opinions. M. Lewandowski (1994) has preferred mobilistic interpretation of the Cracow–Silesia region during Variscan time; however, J. Nawrocki (1995) has claimed that there are no reliable palaeomagnetic arguments for the large-scale dextral strike-slip displacement of the Małopolska and Upper Silesia massifs during Late Palaeozoic time, and possible smaller-size tectonic rotations (up to 30°) in the syn-Asturian tectonic phase are less probable than a relative stationary model.

As it is visible from the opinions presented above, the accretionary model of the Cadomian blocks from southern Poland has a lot of uncertainty and must be continued to test. In the considerations on the palaeogeography of Poland during the Palaeozoic presented below, the stationary model of the Cadomian Southern Poland area is adopted with no palinspastic restoration made.

PRE-PERMIAN SEDIMENTARY BASINS OF POLAND

The history of the pre-Permian sedimentary basins in the Polish territory may be studied from Cambrian time because the basement of the Cambrian deposits is composed of the Proterozoic formations of different age and, in places, of the Archaean itself. Only in the western part of the Peri-Baltic Syneclise and in the Lublin slope of EEC a sedimentary continuity was maintained from the Vendian through Cambrian. (K. Lendzion, 1983). In other regions of the Polish part of EEC, the Cambrian series directly overlie the crystalline basement (K. Lendzion, 1970).

CAMBRIAN

At the beginning of the Cambrian an increase in the volume of world's mid-ocean ridges is thought to have caused a transgression (K. W. Glennie, 1984a), which is also recognized in Poland. Generally, the area of Poland was a part of the huge Iapetus Ocean bordered from the east by EEC and from the southeast by the pra-Carpathian Land. The sea covering the western part of EEC and the Cadomian massifs was within the shelf range depth, whereas western Poland was included into a deep-marine basin (Fig. 5). It is called the Tornquist Sea and extended to the north separating Scandinavia and England and currently corresponding to the suture marked by the North German–Polish Caledonides

(P. A. Ziegler, 1978), known in Poland within the Koszalin–Chojnice zone. In this zone, rocks older than Ordovician have not been encountered in any drillings up to now.

From the Middle Cambrian the basin started to shrink due to uplifting of the EEC. It caused a slow marine regression to the west. The next transgression was as late as the Ordovician. The maximum extent of the basin was in the Early Cambrian. The decreasing extent of the Middle–Late Cambrian basin and increasing of land area around the basin caused a clastic material to be eroded and transported to the basin. It was predominantly derived from older sedimentary rocks. A ratio of magmatic to metamorphic clasts in the Lower Cambrian deposits is much higher than within the Middle and Upper ones (K. Lendzion, 1970).

While the Early Cambrian sedimentation within the Polish sector of the northwestern part of the East European Craton was governed by terrestrial environments (K. Jaworowski, 1979, 1982), marine areas dominated over the southeastern territory of Poland. In the latter area the marine basin existed from the beginning of the Upper Vendian. It progressively expanded and reached its maximum extent in the Holmia Zone of the Lower Cambrian. Source areas for the Lower Cambrian deposits were located not only in southern Poland (pra-Carparhians area) but also in Belarus.

In the Holy Cross Mts. the Lower and Middle Cambrian deposits occur only in the Kielce region. The Upper Cambrian formations are encountered only in the Łysogóry region (S. Orłowski, 1988). They are mainly composed of shaly claystones, shaly siltstones, and sandstones. In the Łysogóry region the Upper Cambrian deposits transitionally pass into the Lower Tremadocian sediments.

To recognize the provenance of the Cambrian clastic material in southern Poland the K/Ar age determinations have been carried out on detrital muscovites (Z. Belka *et al.*, 1997). In the Łysogóry Unit which is located close to the EEC, muscovites from the Middle/Upper Cambrian series show Cadomian cooling ages but for the Kielce Unit the Svecofennian crust (Belorussian?) as a source rock is indicated. Towards the southwest, at the SW margin of the Maopolska Massif and in the Upper Silesia Massif, detrital muscovites in the Cambrian deposits also show Cadomian age. For these detrital micas Z. Belka *et al.* (1997) suggested the Brno Batholith as a possible source. All these above preliminary determinations indicate a dominant role of Cadomian source areas for the Cambrian clastics in southern Poland.

Over most of the Polish part of the platform area, the Cambrian–Ordovician boundary is of erosive nature, so it is distinct and sharp. On the contrary, in the northwestern areas of the Peri-Baltic Syneclise, there is a sedimentary continuity from the Cambrian through Ordovician. In the deep Tornquist Sea of western Poland the lack of interruption in Cambro-Ordovician sedimentation is generally accepted (Fig. 5).

ORDOVICIAN

The Ordovician sedimentary cycle that began in the Lower Arenigian continued till the Ashgillian. A marine transgression covered almost the whole area of eastern and southeastern Poland where a thickness of Ordovician platform deposits reach from 25 to about 100 m (H. Tomczyk, 1963). Abundant clay and carbonate sediments are accompanied by minor marls, siltstones, bentonites, glauconitites, and conglomerates (Z. Modliński, 1982).

All the platform area between the Belorussian High and the deep marine zone of western and central Poland (Fig. 5) represents different facies associations: 1) grey carbonates deposited in an epicontinental sea which occupied the slopes of slightly elevated highs, 2) alternations of red and grey carbonates and black clays deposited within an epicontinental sea but in a deeper zone than those previously mentioned, 3) terrigenous and carbonate deposits with glauconite at the bottom, deposited on a labile shelf of the Cadomian massifs of southern Poland, 4) black bituminous clays deposited probably in the area of a continental slope within an environment marked by a transition from deep-neritic to hemipelagic conditions, 5) shales and greywackes originated in deep water of a hemipelagic environment (graptolitic shales).

The palaeotectonic development from the Arenigian to Ashgillian took place between two phases of tectonic movements; the Sandomirian and Taconian ones, which were responsible for sedimentary gaps and erosion during the Ordovician (H. Tomczyk, 1963). Deep-water sedimentation in the Tornquist Sea was continued through the whole Ordovician and thick fine-clastic series were deposited at that time.

SILURIAN

The Silurian basinal pattern in Poland had been similar to the Ordovician one, particularly until the turn of the Early and Late Ludlovian when the Cracovian tectonic movements took place (K. Łydka *et al.*, 1963). They radically changed the facies distribution in southern Poland: shales with graptolites were replaced by graywacke and conglomerate deposits. The shelf zone pushed from the south towards the northern and southern Poland became a land area (Fig. 5).

Central and western Poland was occupied by the deep Tornquist Sea and the Silurian deposits were similar to the Ordovician ones, consisting mainly of a clay-mudstone association of a giant, still unestimated thickness. The Ordovician (Caradocian and Llandeilo) and Lower Silurian (Llandovery and Wenlockian) deposits are strongly folded in the Pomerania region where they are contoured by almost thirty wells. J. Znosko (1962) and R. Dadlez (1982) date here the Caledonian foldings at Late Silurian time.

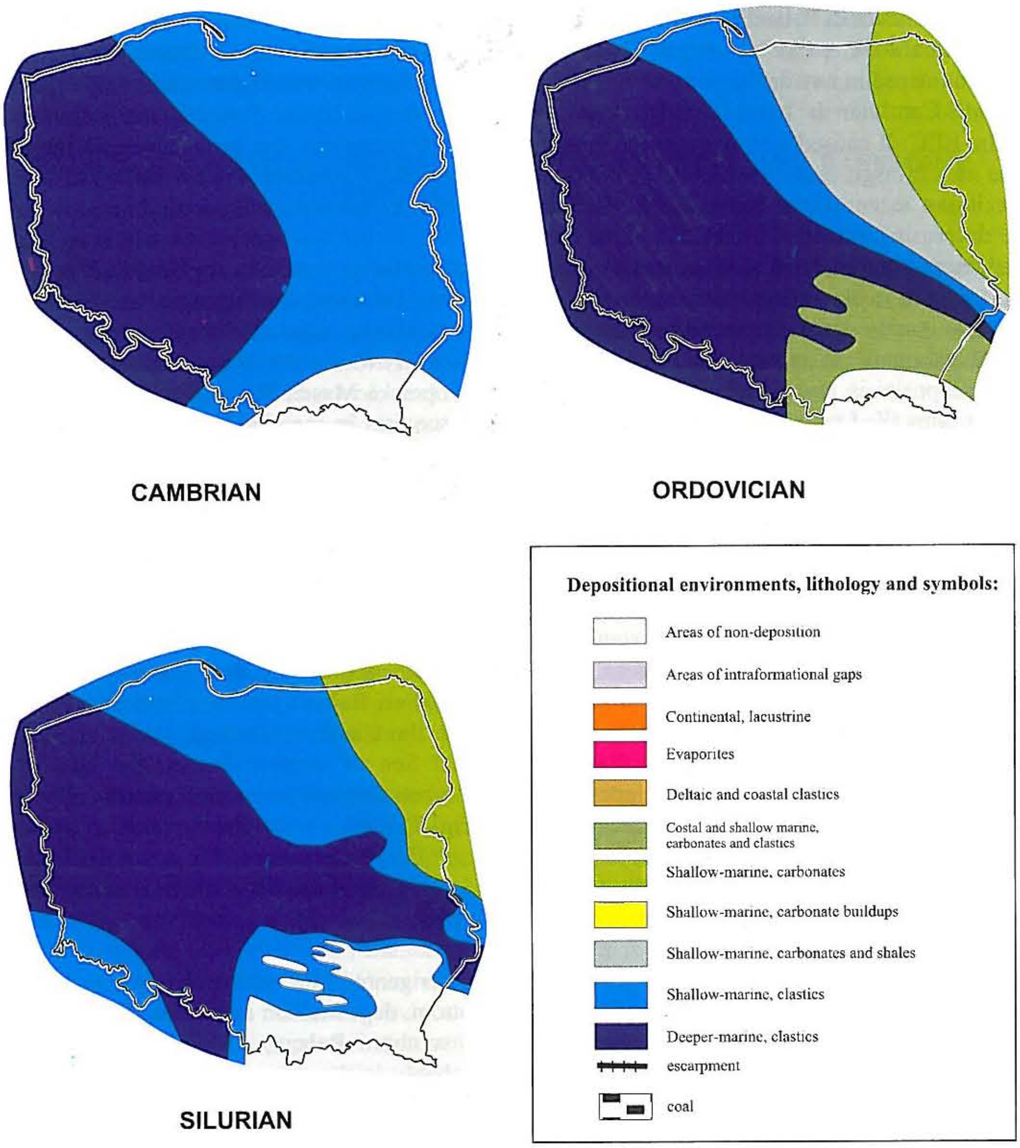

Fig. 5. Cambrian, Ordovician and Silurian palaeogeography of Poland (main sources: H. Tomczyk, 1963; Z. Kowalczewski, 1968; K. Lendzion, 1970; H. Tomczyk *et al.*, 1977; K. Jaworowski, 1979, 1982; Z. Modliński, 1982; S. Orłowski, 1988). No palinspastic restoration was made.

In the border zone of EEC a subsided zone existed; in southern Poland it was attributed to the Łysogóry region and Lublin area. The post-Ludlovian basin with shaly graptolitic facies continued to exist in the central and western Poland and in the northern part of the Holy Cross Mts., including the Lublin area. In the Łysogóry region there is a continuous transition between the Silurian and Devonian (H. Tomczyk *et al.*, 1977). New investigations on Upper Silurian–Lower Devonian rocks in the Kielce city area (J. Malec, 1993) indicate that continuous deposition of Upper Silurian greywacke sediments in the southern region of the Holy Cross Mts. (and undoubtedly in the whole Małopolska area) lasted uninterruptedly until the boundary between the Silurian and Devonian. Other studies also indicate (J. Malec, 1990) that in the northwestern part of Kielce city, the Miedziana Góra Conglomerates which overlie greywackes were most probably deposited as submarine fans in the declining Silurian basin with claystone-siltstone sediments. Source areas of clastic material for these conglomerates (quartzic sandstones of the Middle and Upper? Cambrian) were palaeohighs (horsts) situated close to deposition sites (J. Czarnocki, 1936; Z. Kowalczewski, 1968). A lack of the uppermost Silurian greywacke sediments corresponding to claystones and greywackes of both the Kielce Beds in the southern part of the Kielce region and in the Maopolska area, can be indicative of intense uplift and folding at the Silurian–Devonian boundary and a deep erosional truncation of that area before deposition of the Emsian sediments (J. Malec, 1990). In the Kielce region, the Variscan complex begins with the Lower Devonian (Emsian) terrigenous sediments that overlie, with a huge stratigraphical gap and angular discontinuity, the folded substrate composed of vari-aged rocks.

CALEDONIAN FRAMEWORK

A relation between the Polish Rotliegend Basin and Early Palaeozoic Basin in Poland is difficult and still under discussion. In the light of the plate tectonics theory, during the Early Palaeozoic, the wide Iapetus Ocean separated Gondwana from Laurentia–Greenland and Fennoscandia–Baltica. The Gondwana-derived continental fragments drifted northwards and accreted to the southern margin of the newly forming Laurassia mega-continent (P. A. Ziegler, 1982, 1986).

This assumption supports the W. Pożaryski *et al.* (1992) concept of four tectonostratigraphic terranes outside the edge of EEC in Poland. Two of them — the Pomerania and Łysogóry terranes — are questioned by R. Dadlez *et al.* (1994a). They consider these areas rather to be a part of the EEC passive margin (miogeocline) deformed in Late Caledonian times into a fold-and-thrust belt.

In the Pomerania region the presence of the Caledonian orogenic fold belt is not questionable. Its presence was suggested by J. Znosko (1962) on the basis of interpretation of magnetic and gravity anomalies and a general concept of the circum-Fennosarmatian Caledonides (H. Stille, 1948). Basing on seismic cross-sections and boreholes they were first identified there by W. Pożaryski (1964) and several hypothesis of their origin have been published since that time. R. Dadlez (1974) interpreted the Ordovician and Silurian of the Pomerania zone as a miogeosynclinal branch of the Caledonides, drawing a northern branch boundary in areas farther to WNW, at more or less half a way between Rügen Island and Bornholm; W. Pożaryski, Z. Kotański (1978) interpreted the zone of the folded Ordovician and Silurian, as an aulacogen; W. Brochwicz-Lewiński *et al.* (1981) and W. Pożaryski *et al.* (1982b) considered the Caledonian complex of Pomerania to be a megablock of the Grampianides and Taconides, displaced eastwards by large-scale strike-slip movements in the Caledonian epoch. It follows that there is no comprehensive opinion on the origin of the Caledonides, but it is proved by borehole data from North Germany, Denmark and the central North Sea that they extend from southern Norway through the southern North Sea to German–Danish border area and into northern Poland.

The existence of the Caledonides in southern Poland is suggested mainly by J. Znosko (1962, 1965, 1986), the main advocate of this concept. An opposite idea has recently been presented by W. Mizerski (1979, 1995) and E. Stupnicka (1992) as the main believers in Variscan folding of the Palaeozoic rocks in the Holy Cross Mts. W. Mizerski (1998) accepts differences between the Łysogóry and Kielce units. Within the Kielce Unit, Early and Late Caledonian folding occurred, whereas within the Łysogóry Unit only vertical movements took place during the Early Palaeozoic. Starting from the Devonian, both these blocks evolved together and the Variscan movements in the Holy Cross Mts. took place due to a tectonic stress of the Variscan orogen in western Poland.

A similar opinion is presented by J. Głazek (1995) who considers that the whole of the area disscused was affected only by the Caledonian and Variscan movements and it does not represent a typical orogen, but may be treated as a block-faulted (mobilized) region.

An idea of the absence of the Caledonides in southern Poland has lately been expressed also by E. Tomczykowa, H. Tomczyk (1994) and H. Tomczyk (1994). The most evident example of this opinion is presented in the Geological Atlas of Poland — Geological Maps of Horizontal Cutting (Z. Kotański, ed., 1997b).

From the above considerations it is concluded that the Polish Permian Basin is partially located on the Pomeranian Caledonides and does not cross the area of the Łysogóry and Kielce units where the presence of the Caledonides is questionable.

DEVONIAN

At the end of the Silurian and during Early Devonian, the Iapetus Ocean became closed. Borders of continental plates welded together and the Caledonian orogenic belt was folded and uplifted along a suture zone (P. A. Ziegler, 1984). Caledonian Europe formed the "Old Red Sandstone Continent" and arranged a new palaeogeographic pattern. The Old Red Continent was bordered from the south by numerous pericratonic basins and the Polish epicontinental Devonian Basin is one of them. Farther to the south, in Devonian and Early Carboniferous time, the Rea ocean spread so that in the present territory of southwetern Poland, the Rheno-Hercynian, Saxo-Thuringian and Silesia-Moravian deep oceanic basins existed.

Reconstructions of Devonian facies (Fig. 6) allow to assume that the Polish epicontinental basin was bordered from the east by the Mazury Land (part of the Belorussian Elevation), from the south by the sub-Carpathian Elevation and from the north by the Old Red Continent. Palaeoclimatic interpretations (B. J. Witzke, P. H. Heckel, 1988) indicate that northern Europe might have been located south of the equator, at latitudes between 10–30°. Observations from the area of Poland, whith the occurrence of evaporites (mainly sulphates) associated with red-coloured clastic deposits provide a proof for such a setting. Data for the Devonian palaeogeographic maps (Fig. 6) were collected mainly from the Pomerania region, Lublin area, Holy Cross Mts. (HCM) and southern Poland. A majority of them is derived from the boreholes located near outcrops within the HCM and the eastern margin of the Upper Silesian Coal Basin.

Marine sedimentation across the Silurian–Devonian boundary was continued within the area not affected by the late Caledonian movements. It firstly concerns the eastern part of the Rheno-Hercynian and Saxo-Thuringian Basin, but also the Lublin area and northern part of the Holy Cross Mts.

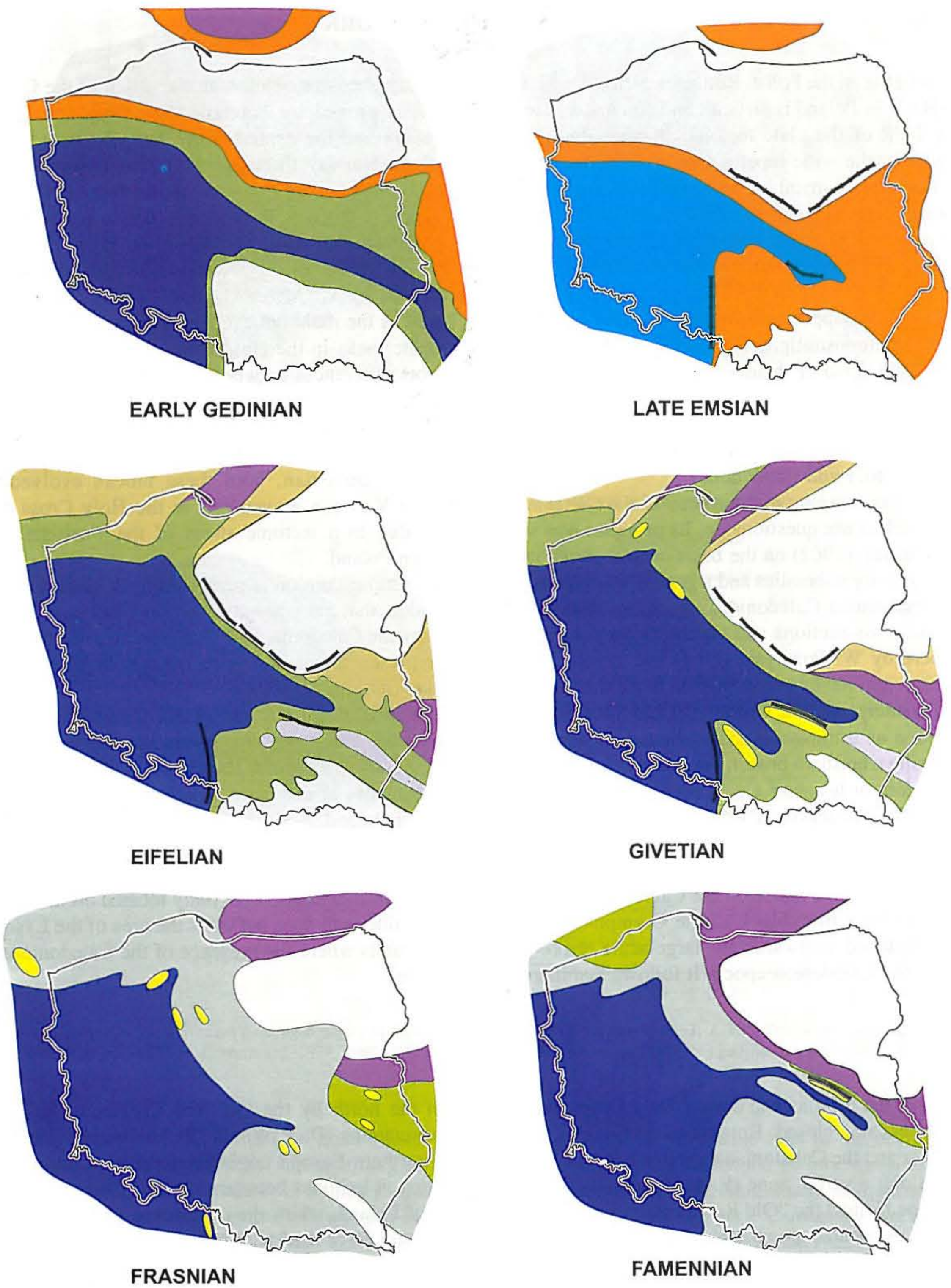

Fig. 6. Devonian palaeogeography of Poland (explanations in Fig. 5) (main sources: M. Szulczewski, 1977, 1995; R. Dadlez, 1978; L. Miłaczewski, 1981, 1987; M. Szulczewski, G. Racki, 1981; Z. Bełka, S. Skompski, 1988; M. Narkiewicz, 1985, 1987, 1988; H. Matyja, M. Narkiewicz, 1992; H. Matyja, 1993; G. Racki, 1993). No palinspastic restoriation was made.

(Fig. 6). In the Lublin Basin, open-marine Gedinnian shales are conformably overlain by deltaic Siegenian and continental Emsian clastics (L. Miłaczewski, 1981). In the Łysogóry region deposition of marine facies continued from the Silurian until earliest Devonian. They pronouncedly interfinger with the terrigenous complex and disappear westwards. Consequently, the lower boundary of the terrigenous complex is diachronous within the Gedinnian (M. Szulczewski, 1995).

Throughout the Early Devonian, the margins of the Polish epicontinental basin were occupied by deltaic complexes sourced by rivers. In shelf areas extending along the basin margin, the sequences were accumulated in shallow-marine and deltaic environments. The Emsian deposits reflect the maximum regression stage of the Early Devonian (Fig. 6).

In southern Poland the Lower Devonian is developed mainly as a distinct terrigenous sequence, composed predominantly of fine clastics accumulated in alluvial and marine nearshore environments. K/Ar age determinations carried out on detrital muscovites from Lower Devonian clastic formations of the HCM are indicative of cooling ages between 423 and 436 ± 10 Ma (Z. Belka *et al.,* 1997). Since there is no source of that age within the crystalline rocks of the EEP, the clastic material in the Emsian rocks was probably derived from Caledonian sources located to the northwest. In the Upper Silesia, detrital muscovites in the Lower Devonian series exhibit age of a Cadomian provenance (Brno Batholith?) (Z. Belka *et al.,* 1997).

In the Pomerania region, there is no data for a reconstruction of the Early Devonian facies pattern (L. Miłaczewski, 1987). Marine sedimentation began in the Middle Devonian epoch. It seems that Western Pomerania was a large, shallow-marine and coastal area at that time, which was subjected to marine ingressions during Eifelian time (Fig. 6). Distinctly marine conditions were established in Givetian time (R. Dadlez, 1978; L. Miłaczewski, 1987). Sediments were initially terrigenous in their character and, subsequently terrigenous-carbonate (claystones, mudstones and sandstones with lenses of limestones, sometimes of a reef type). Facies distribution changes from NE to SW. Shallow-marine facies (sandy intercalations and reef barriers) were developed in the NE area whereas deeper-water conditions were typical of the remaining parts of the basin. During the Givetian, temporal links between the Pomeranian Shelf and the Baltic Depression Basin were established which, by Late Givetian time, became inundated by transgressions advancing westwards from the Moscow Platform (V. Kurshs, L. Girst Stinkulis, 1998).

Middle Devonian time corresponds to a period of rising sea levels in the Rheno-Hercynian basins as well as in the Holy Cross Mountains and Lublin area. This is reflected by a progressive overstepping of the Early Devonian basin margins (Fig. 6). The carbonate deposition was established over the vast Fennosarmatian shelf, to which the area of the HCM belonged. A carbonate platform had been developing until the Frasnian and attained a thickness of about 1400 m (G. Racki, 1993). In the Middle Frasnian the external parts of the carbonate platform were covered with detrital carbonate deposits, containing skeletal debris and ooids (M. Szulczewski, 1971). This facies is evidently regressive in relation to the underlying deposits. It is especially evident in the area where these deposits overstep the peripheral Lower Frasnian quiet-water reef mound of the Kadzielnia Limestone Member (M. Szulczewski, 1981; M. Szulczewski, G. Racki, 1981). According to M. Szulczewski (1971), the Devonian reef from the HCM persisted until the Lower Famennian.

In the Lublin area of southeastern Poland, the Early Eifelian corresponds to a regional transgression. Accumulation of shelf carbonates and evaporites commenced during the Middle Eifelian. This carbonate platform contained reefal buildups; it extended westwards across the Małopolska uplift, encroached onto the East Silesia High and entered the area of the Upper Silesian Basin (L. Miłaczewski, 1981).

The Middle to Upper Devonian palaeogeographic evolution in the transition area between the Lublin region through HCM to Upper Silesia High is largely a history of intra-shelf basins separating carbonate platforms (**Fig. 6**). The basin depth did not exceed several hundred metres, but it was usually less. The lithology of basin-fill is dominated by clay and carbonate rocks, clastic rocks being exceptionally rare (Z. Bełka, S. Skompski, 1988; H. Matyja, M. Narkiewicz, 1992; G. Racki, 1993).

In the Late Frasnian the carbonate platforms developed along the continental shelf were completely drowned owing to the rapid Late Devonian transgressive episode (Fig. 6). In the Pomerania area the extremely shallow-marine Early Frasnian deposits were replaced by open-shelf marls or, in a proximal part of the Pomeranian epicratonic sea, by an extensive carbonate platform with stromatoporoid-coral limestones. Within this deeper environment, in front of the carbonate platform margin, isolated elevations were formed by organic buildups of a stromatoporoid-coral mud mound type. The carbonate platform was ultimately drowned and covered by deeper open-shelf shales and marls at the Frasnian–Famennian transition period (H. Matyja, 1993). The reappearance of shallow-water and coastal environments took place in Middle Famennian time. At the end of the Famennian, open-shelf conditions became prevalent almost over the whole Pomeranian area and continued until Early Tournaisian time.

In the area of HCM the shallow-marine carbonate platform was almost completely drowned in the Late Frasnian. The onlap of low-rate pelagic deposition over the shallow-marine carbonates was completed late in the Famennian (M. Szulczewski, 1981; M. Narkiewicz, 1988). A very similar scenario to the above presented could be adopted for the area of southeastern Poland (Fig. 6).

CARBONIFEROUS

Data on the Devonian sedimentation and palaeogeography of the Polish Rheno-Hercynian, Saxo-Thuringian and Moravo-Silesian Basins are scarce and thus, the reconstructions of the Upper Devonian sedimentary pattern in Poland must frequently refer to the basins located to the west (in Germany). The principal problem in a comparison of these basins is the continuity of the Mid-German High into the territory of Poland. The role, location and significance of the Mid-German High is well affirmed in Germany but in Poland it is difficult to recognize this element separating the Rheno-Hercynian Basin from Saxo-Thuringian ones.

Variscan Europe is often subdivided according to the F. Kossmat's (1927) classic pattern into the Rheno-Hercynian Zone, Saxo-Thuringian Zone and Moldanubian Zone. These zones were thought to represent external, internal and central parts of the Variscan orogen, respectively. It is easy to trace the Saxo-Thuringian Zone with its Palaeozoic metasediments eastwards to the West Sudetes as it was originally proposed by F. Kossmat (1927) and has recently been confirmed by W. Franke *et al.* (1993). However, it is more difficult to identify in the Sudetes the eastern continuation of a Variscan magmatic arc located in the west at the Mid-German Crystalline Rise (MGCR). In Poland, the Odra Fault System composed of medium-grade metamorphic rocks is comparable with the MGCR rocks (A. Grocholski, 1982, 1986, 1987). It has not been substantiated by A. Żelaźniewicz *et al.* (1997) because of the absence of Upper Devonian (meta)granitoids and lack of any extensive ductile fault movements recorded. For a sedimentary reconstruction of the Variscan Basin in this area, the Kaczawa Mts. sequences are used. They are composed of Palaeozoic rocks of an Ordovician–Lower Carboniferous succession. About 1000 m of Ordovician siliciclastic sediments of continental derivation (Z. Urbanek *et al.*, 1995) are associated with locally up to 300 m thick, shallow-water carbonate (algal) buildups (S. Lorenc, 1983) and bimodal volcanogenic rocks. The Silurian sequence is condensed (c. 100 m), mostly developed as pelagic clayey and siliceous shales, which are conformable with Ordovician strata (Z. Baranowski *et al.*, 1990). The Devonian is also represented by c. 100 m of condensed silicic shales. Upper Devonian and especially Lower Carboniferous turbidites and melanges contain, in a shaly matrix, olistoliths (>1 km) derived from the Ordovician–Devonian portion of the Kaczawa complex. This heralded the closure of the Palaeozoic basin which had remained undisturbed by any earlier event temporally related to the Acadian, Caledonian or Ligerian orogeny occurring elsewhere. The Ordovician–Upper Devonian sequence remained essentially undeformed and unmetamorphosed till the Late Devonian–Early Carboniferous (A. Żelaźniewicz *et al.*, 1997).

Farther to the north, beneath the Fore Sudetic Monocline, it is almost unknown what type of rocks actually occur below the Lower Carboniferous deposits which were documented by tens of hydrocarbon-prospecting wells. There are some positive evidences that the Kaczawa Mts. succession occupies a majority of the Wielkopolska Externides. The Sudetes are much better recognized and sedimentary, metamorphic and igneous complexes appear now as a mosaic of fault-bounded geological units of a different tectono-stratigraphic and metamorphic history. It is interpreted in terms of synorogenic long-distance strike displacements along regional-size ductile to brittle shear and fault zones (A. Grocholski, 1987; P. Aleksandrowski, 1995).

Other sedimentary model of the Sudetes-Variscan Basin, diametrically different from that proposed by J. Oberc (1972) and still widely accepted for a structural reconstruction, has been proposed by B. Wajsprych (1995, 1997). He suggests that the Sudetes and probably the whole Lugo-Sudetean Zone are not an internal zone of the Variscan orogen but, on the contrary, they constitute a part of the external zone of this orogen and originated in platform-to-foreland tectonic regimes. Both the platform and foreland basin evolution was governed by a crust-scale tectonic extension. During the Middle Famennian the platform area was affected by basic-ultrabasic plutonism associated in time and space with a rapid uplift of a deeper crust fragment to the Earth's surface (proto-oceanic crust?). In Late Visean time this platform was transformed into a foreland basin which was formed in front of the orogenic uplift. The foreland basin was infilled by flysch-olistosthrome-melange sediments. This was connected with a permanent rebuilding of the foreland basin and subsequent migration of the deformational front and depositional centres from NNE–NE–E to SSW–SW–W. Palaeogeological analysis defines a frontal part of this orogenic upgrowth as composed of an accretionary prism constructed of the trench-to-forearc basin successions.

The Moravo-Silesian Basin, located on the Brunnian-Upper Silesian Block (A. Kotas, 1982) reveals characteristic features of the Variscan Externides where Carboniferous rocks are in sedimentary continuity with underlying Devonian sediments (Fig. 7). They make up the top of pre-flysch sedimentary-volcanogenic and carbonate associations, and a flysch one. The transition from the pre-flysch to flysch sedimentation is diachronous in different parts of the basin spanning the Famennian to Visean (J. Dvořak, 1982). In the Opole-Silesian segment of the Moravo-Silesian Zone, Carboniferous sediments of the flysch type are only partly known from scarce exposures and boreholes. They are temporally and lithostratigraphically correlated with the well described Carboniferous of the Nízký Jeseník (J. Dvořak, 1982). Towards the north, these deposits pass into sediments ascribed to the Wielkopolska Externides.

The part of the Moravo-Silesian Basin, occupied by the Upper Silesian Coal Basin, was situated during the Early Carboniferous within a foreland of the Variscan system. Carboniferous rocks of the basin form a characteristic sequence terminating the sedimentary development of the whole Moravo-Silesian Basin, which was limited to a foredeep located within the Upper Silesian Block during the Upper Carboniferous (Fig. 7).

Carboniferous rocks of the basin located within the Upper Silesian Block are composed of two lithologic associations. They compose a top portion of pre-flysch carbonate complexes, and the whole profile of marine clastic sediments which correspond to flysch deposits of the Nízký Jeseník Zone (A. Kotas, W. Malczyk, 1972a, b; A. Kotas, 1982). In the western and northeastern parts of the basin, these are flysch sediments. They laterally pass towards the southeast into a molasse, featured by a cyclic structure and symptoms of a shallowing sea, spanning the Upper Visean and Lower Namurian A.

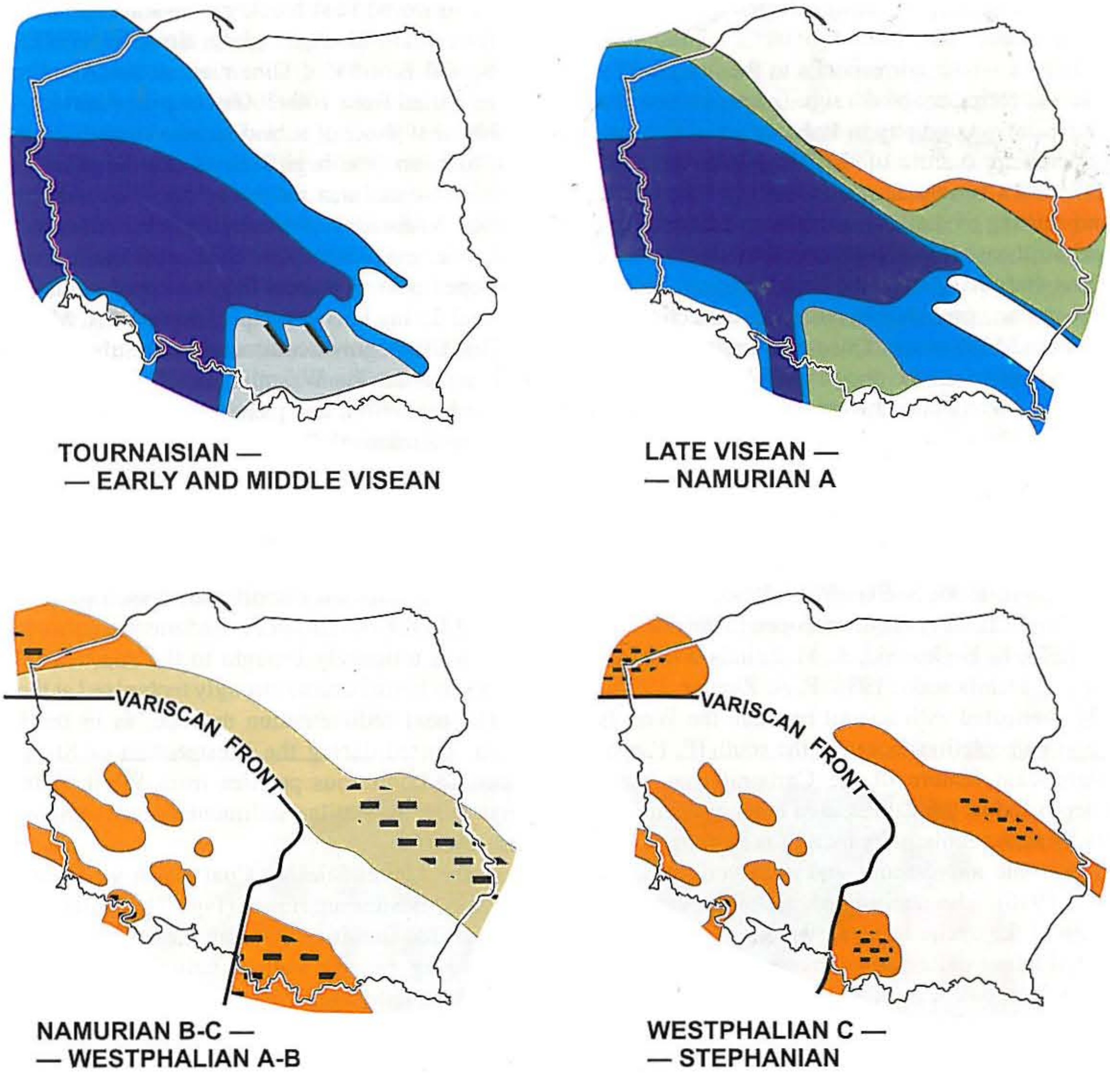

Fig. 7. Carboniferous palaeogeography of Poland (explanations in Fig. 5) (main sources: K. Bojkowski, 1978; K. Bojkowski, A. M. Żelichowski, 1980; A. Kotas, 1982; , H. Żakowa *et al.*, 1984; W. Pożaryski, Z. Dembowski, 1984; A. M. Żelichowski, 1987a, b; K. Bojkowski, Z. Dembowski, 1988; E. Paproth, 1989; M. Szulczewski, 1995; S. Skompski, 1996). No palinspastic restoriation was made.

During the Late Devonian, a subsequent break in sedimentation lasting until the Late Visean, took place in the Małopolska region. The extent of the Carboniferous sedimentation area was much larger than the Devonian one. This is evidenced by the presence of Carboniferous carbonate rocks progressively overlying different members embracing rocks from the Upper Devonian to the consolidated crystalline basement (Fig. 7). Lower Carboniferous sedimentation of varied intensity had continued until the Late Visean, when it ultimately terminated, and the area was uplifted as a result of tectonic movements assigned to the Sudetic phase. Palaeozoic rocks of the Małopolska Massif underwent erosion which continued until the Early Triassic. Carboniferous deposits were preserved within local depressions or troughs (M. Paszkowski, 1988; M. Paszkowski, M. Szulczewski, 1995).

General pattern of principal facies in the Holy Cross Mts. during the Early Carboniferous is relatively simple. The Famennian and Lower Carboniferous succession evidences progressing and stepwise foundering of the carbonate platform. The facies of the succeeding lithosomes reflect a progressive deepening, decreasing oxygenation and increasing rate of accumulation (Fig. 7). The Lower and Middle Visean was a period of the most unified and deepest depositional environments in the Late Palaeozoic history of the Holy Cross Mts. Hemipelagic noncarbonate clays were deposited at that time (M. Szulczewski, 1995). Tephra deposits were appreciably contributing to the accumulation of the above all described Carboniferous units (H. Żakowa *et al.*, 1984; Z. Migaszewski, 1995; R. Chlebowski, 1995). They appear as early as in the uppermost Famennian. Volcanic activity coincided with successive phases of basin drowning. It confirms that this mechanism was significantly affected by extensional tectonics.

The Lublin area which corresponds to the margin of the East European Platform occupied a significant position in the Carboniferous palaeogeography in Poland and in Europe as well. A characteristic feature of the late Visean pattern in Central and Western Europe is a broadening of the Laurussian shelf and shifting of shallow-water marine deposition to the north and northeast (Fig. 7). During the late Visean the sea invaded the marginal part of the East European Platform in the Lublin region, probably opening a connection with epeiric seas of the Moscow and Dneper–Donets basins. The sea occupied this area until the end of the Westphalian A (S. Skompski, 1996). Meanwhile, the area of mobile blocks extending from Cracow, on the eastern margin of the Silesian Coal Basin, to the Holy Cross Basin, was finally uplifted at the end of the Visean or beginning of the Namurian (K. Bojkowski, 1978; W. Pożaryski, Z. Dembowski, 1984; M. Paszkowski, 1988; W. Pożaryski *et al.,* 1992; M. Paszkowski, M. Szulczewski, 1995; S. Skompski, 1995). The Lublin area was either an isolated embayment, open to the northwest (H. Żakowa, 1970; K. Bojkowski, A. M. Żelichowski, 1980; K. Bojkowski, Z. Dembowski, 1988; P. A. Ziegler, 1990) or more broadly connected with a strait between the West European Sea and Palaeotethys Ocean in the south (E. Paproth, 1989). A significant feature of the Carboniferous paralic succession deposited in the Lublin area is its cyclicity governed mainly by such sedimentary factors as eustatic changes of sea level, tectonic movements, and autocyclic processes (S. Skompski, 1996). The analysis of cyclothems confirms a deltaic origin of the cyclic interval, which is typical of the river-dominated lobate deltas, and corresponds well with the scheme of the Yoredale cyclothem proposed by G. A. L. Johnson (1961).

In the Pomerania region, the Dinantian sedimentary basin was a continuation of that formed in the Devonian (Fig. 7). At the turn of the Devonian and Carboniferous a volcanic activity phase took place. It resulted in volcanic intrusions and extrusions of trachytes, rhyolites, diabases, and tuffites. Facies pattern in the Pomerania Basin is characterized by sandstones in a near-shore zone and oncolitic-oolitic rocks in deeper one. The deepest part of the Tournaisian and Visean basin in this area is notified by clay-marly and on a smaller scale, sandy rocks (A. M. Żelichowski, 1987b).

In Pomerania, the Dinantian sequences ended in the latest Visean or earliest Namurian. A denudation stage, corresponding to the Namurian and possibly lowermost Westphalian A followed next block movements resulted in both an uplift of some blocks, mainly along WNW–ESE oriented faults, and erosion of Dinantian strata. Amplitudes of the uplifts varied from 100–200 m to over 1000 m.

The next phase of subsiding movements took place in the Late Silesian (the beginning of the Westphalian). Clastic material (sometimes red in colour) was derived from the uplifted Variscides in the southwest. Alluvial fans (thick sandstone series with thin coal seam intercalations) which developed over vast areas began to predominate in a distant foreland during Early Westphalian time (A. M. Żelichowski, 1987b). Black-grey sediments (with subordinate, thin, red beds) represent the Westphalian–Early Stephanian episode (Wolin Formation) and pass into red clastic sediments (Stephanian–Autunian) already belonging to the Rotliegend (J. Pokorski, 1981b).

The Pomerania Basin formed the northeastern flank of the Rheno-Hercynian Basin during the Lower Carboniferous. A deeper part of this basin was located in the Wielkopolska area, where Lower Carboniferous flysch sedimentation terminated in the Namurian A. Sedimentation in the Variscan Basin was ultimately brought to the end and all sediments filling this basin became strongly tectonized at that time (Fig. 7). The next sedimentation episode, as in the Pomeranian region, started during the Westphalian or Stephanian. The Upper Carboniferous profiles from Wielkopolska and Pomerania show similar sedimentary environments in both these areas.

In the Upper Silesian Coal Basin which was a part of the Moravo-Silesian Basin (Fig. 7) paralic sedimentation changed into limnic one during the Early Namurian. Cyclic coal-bearing molasse sedimentation developed in this basin showing no sedimentary gaps or discordances (A. Kotas, W. Malczyk, 1972a, b). The sequences were formed on large alluvial plains under braided and meandering rivers conditions without any marine influences. The section is terminated by the Stephanian, coal-free fan sediments formed above a regional water level. The latest Carboniferous sedimentation in Poland was confined only to very small basins or grabens (Fig. 7).

From the above consideration it follows that in the whole territory of Poland, independently from a type of basin and sedimentary environment in each basin strong tectonic movements (the Sudetes phase) caused either a total termination of sedimentation or initiated alluvial coal-bearing sedimentation in the Upper Silesia and Lublin basins during the late Visean or Namurian A.

VARISCAN FRAMEWORK

Tectogenesis of the Variscides in western Poland, despite of long-term investigations in the Sudetes and their foreland, is still a matter of controversial interpretations. Additionally, the foregoing area is dissected by long NW-trending zones whose role and age are also variously interpreted. The best known and commonly used subdivision of the Variscides is given by F. Kossmat (1927) where the Rheno-Hercynian, Saxo-Thuringian and Moldanubian zones are attributed to the external, internal and central part of the Variscan orogen. Such an interpretation is widely exploited in the Polish references (*vide* J. Oberc, 1972; W. Grocholski, 1972; A. Grocholski, 1987; J. Don, 1995). In the recent years a few new concepts concerning Variscan tectogenesis in Poland were published.

P. Aleksandrowski (1995) underlines the role of long-distance strike-slip displacements of dextral sense, locally exceeding 300 km in magnitude, that existed in the Late Devonian–Early Carboniferous along regional-size ductile to brittle shear and fault zones trending NW–SE. They dissected and mutually displaced eastern portions of major structural units of the Variscan belt, e.g. the Rheno-Hercynian, Saxo-Thuringian and Tepla-Barrandian tectonic/facies zones. In the East Sudetes, representing a fragment of the Moravo-Silesian zone of the Variscides, regional-size ductile shear zones trending NNE–SSW to NE–SW showed a significant strike-slip component of motion during the Early through Late Carboniferous.

The Sudetes have been classically divided into Lugicum (Western Sudetes) and Moravo-Silesicum (Eastern Sudetes). Recent data (e.g. kinematic, isotopic, geochemical) put a new light on the geotectonic evolution of the whole Sudetes. Z. Cymerman (1998) concluded that the dominant displacement of ductile thrusting and wrenching was connected with a dextral transpressional regime in both the Lugicum and Moravo-Silesicum. A similar opinion about a significant role of major strike-slip fault zones in the European Variscides structure was also expressed by Ph. Matte (1986) and Ph. Matte *et al.* (1990).

Another interpretation is based on the deep seismic profile GB-2A situated in SW Poland where under the Western Sudetes there is visible a domal stack of well reflective lower crustal rocks, with the Moho easily identifiable at the base of the laminated lower crust (A. Żelaźniewicz *et al.*, 1997). Interpreting this profile it is suggested that the main crustal suture of the A-subduction type is located beneath the Góry Kaczawskie Mts., and the entire feature probably represents a Cadomian compressional event, then repeated during Variscan times, after the Early Palaeozoic crustal extension. The above mentioned authors are of the opinion that the seismic GB-2A line shows that the Odra Fault Zone cannot be taken as an eastern continuation of the Mid-German Crystalline Rise (MGCR).

Another opinion is based on a discovery — in the Sudetes — of the Middle Devonian platform with a passage to the Late Visean foreland basin (B. Wajsprych, 1995, 1997). The palaeotectonic model of this area in the Late Palaeozoic implicates that the Sudetes and probably the whole Lugo-Sudetean Zone are not an internal zone of the Variscan orogen, as it is commonly accepted. On the contrary, the Sudetes state a part of the external zone of this

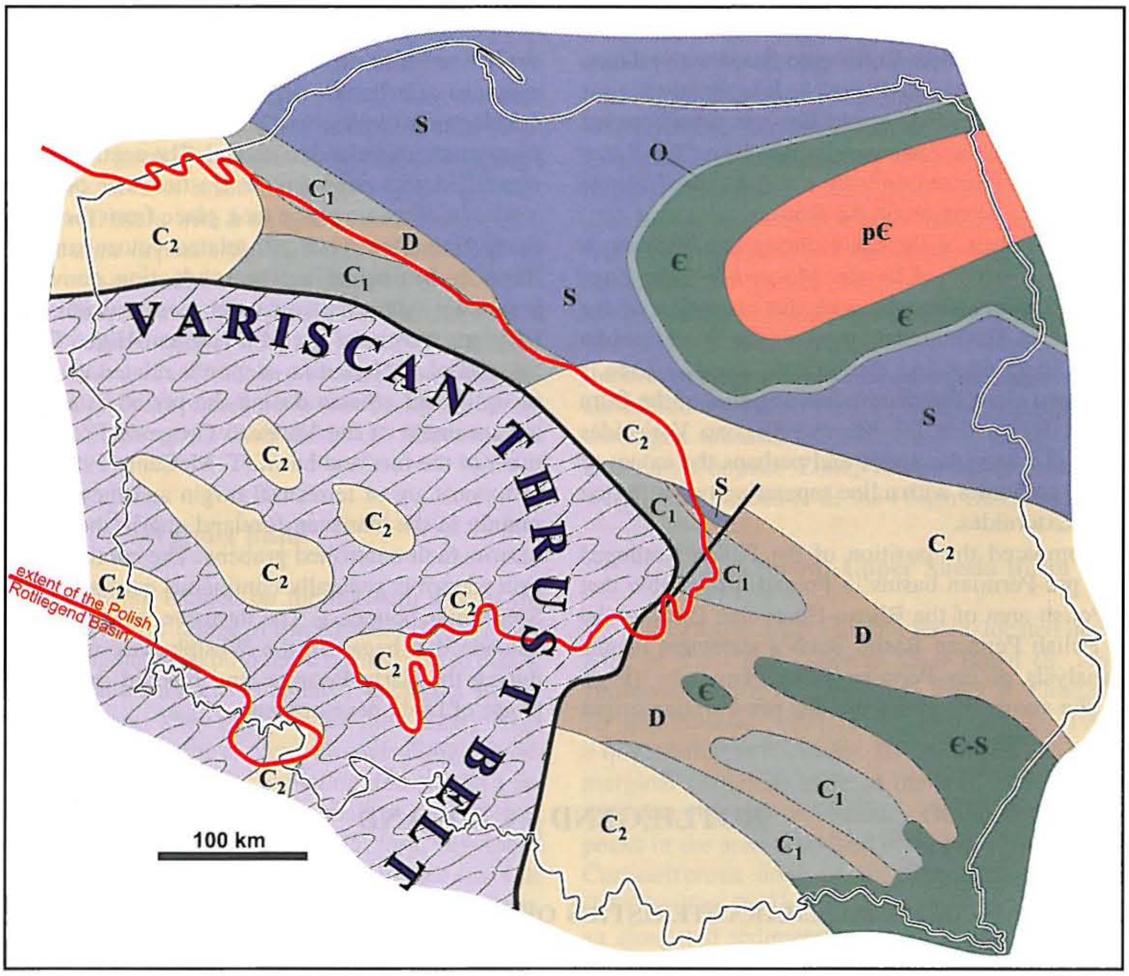

Fig. 8. Pre-Permian geological map of Poland (main sources: W. Pożaryski, Z. Dembowski, 1984; W. Pożaryski, P. Karnkowski, 1992).

orogen and originated in the platform-to-foreland tectonic regimes. It implicates that the Variscan orogen *sensu stricto* must be situated generally north of the Sudetes or Lugo-Sudetean Zone.

The above presented short review of the recent opinions on the Variscan tectogenesis in Poland should be completed by the opinion on the northern boundary of the Variscan Fold Belt. It is shown in the tectonic map of Poland during the Variscan time (W. Pożaryski, P. Karnkowski, 1992). The present author also examined all drilling cores from beneath the Rotliegend and taking into account lithology, tectonics and metamorphism of rocks, he accepts the extent of Variscides assumed for the map, except in the area located north of the Holy Cross Mts. (Fig. 8).

An opposite opinion, substantiated by some geophysical data and reconstructed mainly according to the posthumous tectonic structures within the Permian–Mesozoic cover is expressed by a position of the Variscan front extending farther south approximately along the line Gorzów–Poznań–Wieluń (K. B. Jubitz *et al.*, 1986; R. Dadlez *et al.*, 1994a).

Upper Palaeozoic rocks occurring outside the Variscan Thrust Belt are frequently folded to a different degree. It refers to e.g. the Pomeranian region, Holy Cross Mts., Małopolska Massif. The area of the folded Upper Palaeozoic rocks developed in epicontinental facies is proposed to be named "Peri-Variscicum" (Z. Kotański, 1997a).

The position of the Polish Rotliegend Basin with relation to the Variscides is shown in Figure 8. It is clearly visible that the major part of the Rotliegend Basin is superimposed on the Rheno-Hercynian Zone and its foredeep. The Saxo-Thuringian Zone is covered only by a few hundred metres thick deposits and volcanics of the Rotliegend and it constituted a marginal part of the basin during the Permian. A special position is occupied by the Moravo-Silesian Zone devoid of the Rotliegend rocks with the exception of the Laskowice Graben. The boundary between the Wielkopolska Branch of the Externides and the Moravo-Silesian Zone is sometimes drawn along the eastern prolongation of the Odra Fault Zone. It seems that the Moravo-Silesian Variscides cross this line (L. Sawicki, 1995) and perhaps the extent of the Rotliegend coincides with a line separating two different blocks of the Externides.

Having compared the position of the Polish Rotlieged Basin to the pre-Permian basins in Poland it is visible that the whole Polish area of the Rheno-Hercynian Basin is the site of the Polish Permian Basin. Such a statement results from the analysis of pre-Permian palaeogeography (Figs. 5–7). From the above it follows that the pre-Permian origin of the Polish Rotliegend Basin was involved in the interplay of the Caledonian and the Variscan events. The interplay of regional and local stresses, sea-level changes and volcanic activity produced a complex facies mosaic in this region. The Late Caledonian stresses strongly deformed bedding within the Ordovician and Silurian section of Pomerania. This is in a distinct contrast with the platform sediments located north of the Caledonian Deformation Front, which are essentially flat-lying and undeformed. Marine Ordovician and Silurian sandstones and associated mudstones and siltstones were deposited in a deep-marine basin before the final phase of the Caledonian orogenic activity.

Devonian deposition was governed by a crustal extension and development of the Rheno-Hercynian Basin in the area studied. Sedimentation along the northern basin margins was largely shallow marine or deltaic in its character, becoming deeper marine to the south. In the Late Devonian, transgression of the northern basin margin increased, as rift-related volcanic activity in the Rhenish Basin. Volcanic deposits are interbedded within clastic and carbonate successions along the basin margins. Termination of volcanic activity in the Famennian and the coeval increase in tectonic instability has been interpreted as being related to the beginning of subduction-related processes along the northern margin of the Mid-German High (K. W. Glennie, 1984a; P. A. Ziegler, 1990).

Depositional patterns in the Early Carboniferous are similar to those of the latest Devonian (also with volcanic episodes). Carbonate deposition was related to the regional development of a more or less continuous carbonate platform from southern Ireland to Poland. The central part of the basin was filled with deep-marine clastics. The onset of the main Variscan orogenic phase took place from the Late Visean to Early Namurian when rift-related volcanism ceased in the Rhenish Basin and active subduction commenced along a southerly-dipping subduction zone, which paralleled the northern margin of the Mid-German High. The absence of any complete Namurian section is related to periodic phases of uplift and erosion during the period associated with the advancement of the Variscan Orogenic Front and development of the foreland basin (T. McCann, 1996). Westphalian sediments are of terrestrial origin and they were developed mainly in the Variscan foreland and in the intra-mountains narrow fault-controlled grabens. The continental sedimentation pattern is generally continuous across the Westphalian-Stephanian boundary. The intrusive and extrusive magmatic episode that began in the Westphalian, reached its climax during the Early Permian and marked the onset of a new phase of basin development.

ROTLIEGEND IN POLAND

GENERAL CHARACTERISTICS OF THE ROTLIEGEND BASINS

The Rotliegend basins in Poland may be divided into two groups. The first one represents basins located in areas with a basement consolidated during the pre-Cambrian, such as the Słupsk Basin, Warmia Basin, Podlasie and Cracow–Upper Silesia basins. The second group comprises basins founded on a basement consolidated during the Caledonian or Variscian orogenies. The Polish Basin belongs to the latter, with several subbasins such as: the Intra-Sudetic Basin, North-Sudetic Basin, Eastern Fore-Sudetic Basin (Laskowice Graben), Lower Silesian Basin, Wielkopolska Basin, Central Basin and Pomerania Basin.

Basins location in areas of a Precambrian consolidation is strictly related to basement structures, whose tectonic activity and palaeogeographic influence have been recorded from the earliest Palaeozic. The major structural element is the Mazury High, being a part of the Belarus High. This elevation has been remarked as an uplifted structure since the earliest Palaeozic in the palaeogeographic images of the Polish epicontinental basins (Figs. 5–7). The Mazury High was characterized by a distinctly thinner sedimentary cover, lack of deposition or by a priority of erosion. Shallow sedimentary basins infilled with deposits up to 80 m thick were also formed during the Rotliegend on both sides of discussed high. The Warmia Basin developed on the northern side and the Podlasie Basin on the southern one.

Podlasie Basin

The Podlasie Basin is infilled with conglomeratic-sandy sediments derived mainly from the eroded Mazury High in the north and subordinately — from the Radom–Lublin area in the south (Devonian–Carboniferous clasts). These deposits are mainly alluvial in origin (J. Pokorski, 1971, 1974, 1978c). Low clast roundness, poor sorting and common chaotic distribution of coarse-grained components in sandstones as well as good preservation of easily weathered minerals are indicative of a short transport by flood flows. Sandstones prevail there with a repeated succession of conglomerate-sandstone deposits (J. Pokorski, 1978c), allowing to distinguish — basing upon sedimentological analysis — several alluvial fans. The Podlasie Basin was infilled with in clastic material derived mainly from the Mazury High, composed of magmatic and sedimentary rocks of the older Palaeozic. Seasonally a part of sediments was transported from this basin directly into the Polish Basin (H. Kiersnowski, 1997b).

Warmia Basin

The Warmia Basin, located on the northern side of the Mazury High, is a mirror image of the Podlasie Basin. Many similarities existing between both these basins refer to clastic composition, sedimentary environments, thickness of deposits and their extent. They indicate that the Mazury High became the principal structural element controlling the development of both basins and its evolution determined a sedimentary pattern within the adjacent shallow depressions. One of the evidences is a pattern of alluvial fans, developed around the Mazury High (J. Pokorski, 1974). On the east side of the high these fans are largest and they completely disappear westwards. It suggests a more intense uplift of the Mazury High in its eastern part compared with western one and such a tendency was also reflected by the magnitude of erosion of Lower Palaeozic deposits around the high. A dominance of silty facies in the western part of the Warmia Basin confirms the hypothesis on a general transport direction from the Mazury High towards the west, into the Polish Basin. Alluvial fans, recognized in the margins of the Mazury High and continuing into the Warmia Basin, have a general north-south orientation but such a transport direction was quickly modified in the western direction. The Rotliegend sediments are almost absent in the area between the Warmia Basin, Mazury High and Polish Basin. Sporadically, sandstones or conglomerates, several metres thick, which may be considered to represent a weathering waste of older basement rocks are noticed in some boreholes.

Słupsk Basin

The Słupsk Basin is located in west Pomerania, on the northeastern margin of the East European Platform. It is genetically related to the uplifts located within the Koszalin–Chojnice zone. They supplied clastic material into the Słupsk Basin and probably to the Polish Basin as well. A thickness of clastic deposits in the basin is up to 80 m. These are sandstones (Darłowo Beds) and conglomerates (Miastko Beds — after J. Pokorski, 1976b). The sandstones are commonly located within the upper part of lithologic sections but completely sandy profiles are also known. These sandstones are fluvial or aeolian in origin; the conglomerates are fluvial. The location of the basin is strictly related to the Palaeozic basement. This basin was founded in the central part of a large syncline-shape structure called the Peribaltic Syneclise. Likewise in a case of the Podlasie and Warmia basins an immediate relation between dynamics of the Peribaltic Syneclise and adjacent areas is also visible here. Stronger erosion around the future Słupsk Basin must have taken place before the basin came into existence that is reflected by erosion of lower Palaeozic deposits, covered by Rotliegend sediments. The earlier mentioned elevations, bounding this basin from the southwest, also limited a direct drainage from the Słupsk Basin into the Polish Basin. Probably the Słupsk Basin was drainaged towards the southeast, as far as the end of the Koszalin–Chojnice Zone, where the outflow turned westwards, into the center of the Polish Basin.

Cracow–Upper Silesia Basin

The Cracow–Upper Silesia Basin, located in the marginal zone of the Upper Silesian Coal Basin (S. Doktorowicz-Hrebnicki, 1954; A. Siedlecka, 1963; R. Gradziński, 1982; H. Kiersnowski, 1991; P. H. Karnkowski, 1992), was of a quite different character. Its development is related to the marginal (external) zone of the Variscan foredeep but the time-forming and sedimentary character of Rotliegend deposits in the area described distinctly differ from the Upper Carboniferous ones of the Upper Silesian Coal Basin (USCB). The Rotliegend deposits were accumulated within an elongated sedimentary basin, located in the eastern and northeastern margin of USCB and showing tectonic foundations of a tectonic graben type. This graben, as an individual tectonic-sedimentary structure, began to develop in the Early

Stephanian. The arkose from Kwaczała is a rock recording this moment. Above it — according to location — volcanites, conglomerates, sandstones or siltstones occur. Such a mosaic distribution of various lithological types gave rise to some controversial opinions on the lithostratigraphy and cyclicity in this region (see P. H. Karnkowski, 1992). The age of Karniowice travertine occurring in the lower part of the Rotliegend profile, is defined by J. Lipiarski (1971) as the Autunian whereas conglomerates from the Sławków graben are of the Thuringian age (S. Dybowa-Jachowicz *et al.*, 1991). This illustrates a long duration of processes and environments, existing there during the Permian. Moreover, according to A. Siedlecka (1963) and H. Kiersnowski, A. Maliszewska (1985) the characteristic clastic facies were connected with particular parts of the Permian graben. *Caliche* horizons, visible within the conglomerates, tuffites or travertines from Karniowice (M. Paszkowski 1987) are indicative of sustained breaks in sedimentation (A. Siedlecka, 1963; H. Kiersnowski, 1991). Relations between lithologies and their position within the sedimentary basin during the Permian were presented by P. H. Karnkowski (1992) in the case of the Sławków graben. This interpretation is based on differences between litho- and allostratigraphic subdivisions of the Permian succession in the Silesia–Cracow region. A lithostratigraphic method enables to distinguish main lithological types as well as to show them on both surficial and subsurface maps. A method of sedimentary cycles analysis and study of genetical relations between various types of deposits (depositional systems, allostratigraphic units) is necessary to reconstruct a complete development of the Sławków graben (P. H. Karnkowski, 1992). Its history corresponds to those of the Sudetic basins, located just in the Variscides area.

Polish Rotliegend Basin

The Polish Rotliegend Basin (Fig. 9) is composed of several sub-basins which in the Polish geological bibliography are referred to as basins. According to the tradition all their names are used here with a term *basin*.

In the Late Carboniferous the Eastern Fore-Sudetic Basin (Laskowice Graben) came into existence in the eastern part of the Fore-Sudetic Block. Its structural-sedimentological development is similar to both the Intra-Sudetic and North-Sudetic basins. The basin described became a deep, narrow, and curved tectonic graben with its axis oblique to the Odra Fault Zone. Orientation of its axis highly corresponds to the regional shear zone of Brzeg–Nysa. The basin infill predominantly consists of coarse clastics, forming a vast alluvial megafan, which invaded onto the Lower Silesian subbasin in the last phase of its development. A sedimentary depocenter was located in the southern part of the basin with 1100 m thick deposits. Three depositional megasequences were distinguished there, representing mainly alluvial fan facies and subordinately — fluvial and lacustrine sediments (H. Kiersnowski, 1983, 1995). Deposional architecture, characterized by a variability of depositional systems, reflects a multiphase tectonic evolution as well as the internal structure of the graben. These tectonic stages are recorded by a basin subsidence combined with extension. Depositional phases, separated by erosional periods, characterize a tectonic development of the basin. The following depositional sequences in a form of incomplete sedimentary megacycles frequently without uppermost fine clastic elements, composed of clay and carbonate deposits may be distinguished there: Ist sequence — Late Carboniferous–Early Permian (Late Stephanian–Early Autunian); IInd sequence — Early Permian (Late Autunian) and IIIrd one — Late Permian (Saxonian–Thuringian). Good examples of such successions are visible in the Intra-Sudetic and North-Sudetic basins.

The Intra-Sudetic Basin, located in the northern periphery of the Bohemian Massif (Fig. 9) closely corresponds to the Eastern Fore-Sudetic Basin. Its origin is probably related to tectonic movements of the Bretonian phase. During the Hercynian orogenesis several small intramountain basins were formed within the Bohemian Massif, among which the Intra-Sudetic Basin is the oldest one. It forms a geological structure about 60 km long and 25 km wide. Its infill consists mainly of Carboniferous sediments. Permian rocks compose up to 10% of the whole sedimentary succession of the basin. It is important that the Rotliegend basin in the Intra-Sudetic Basin was overlapped onto the older, Carboniferous intramountain basin (K. Dziedzic, A. K. Teisseyre, 1990). The Glinik Beds are considered here to represent the onset of Rotliegend deposition and they constitute a transitional member between the typical coal-bearing deposits of Namurian–Westphalian age and Stephanian–Autunian red sediments.

The Rotliegend sediments in the Intra-Sudetic Basin compose three megacycles with thickness of 250–300 m. Bases of megacycles are defined by distinct erosional contacts and differences in a grain size. A complete megacycle succession consists of several elements as follows: alluvial fan deposits (occurring only in the basin margins), fluvial deposits and lacustrine sediments (K. Dziedzic, 1961; J. Wojewoda, K. Mastalerz, 1989). The above mentioned megacyclothems are interpreted as a product of unequal episodical subsidence related to tectonic events. Autocyclic processes influenced a deposition rate during the periods of tectonic stability, when the basin bottom gradually and slowly subsided. Effects of slow climatic changes, well manifested by successive horizons of lacustrine deposits, indicate a gradual climate drying (K. Dziedzic, 1961; J. Wojewoda, K. Mastalerz, 1989). Intensive volcanic activity in the Autunian significantly influenced the development of the Intra-Sudetic Basin. After volcanism cessation the whole area of the Middle Sudetes was relatively highly uplifted and its landscape was rejuvenated. Seismites and redeposited fossil colluvia evidence a tectonic activity and differentiated morphology at that time (K. Mastalerz *et al.*, 1993). At the end of the Saxonian the climate became more arid and the basin area with its surroundings was significantly peneplenized. Desert flood sheets sediments as well as soils of *caliche* type are sediments typical of this period. The post-volcanic Rotliegend succession in the Intra-Sudetic Basin is characterized by ephemeral sedimentary episodes interrupted by long non-

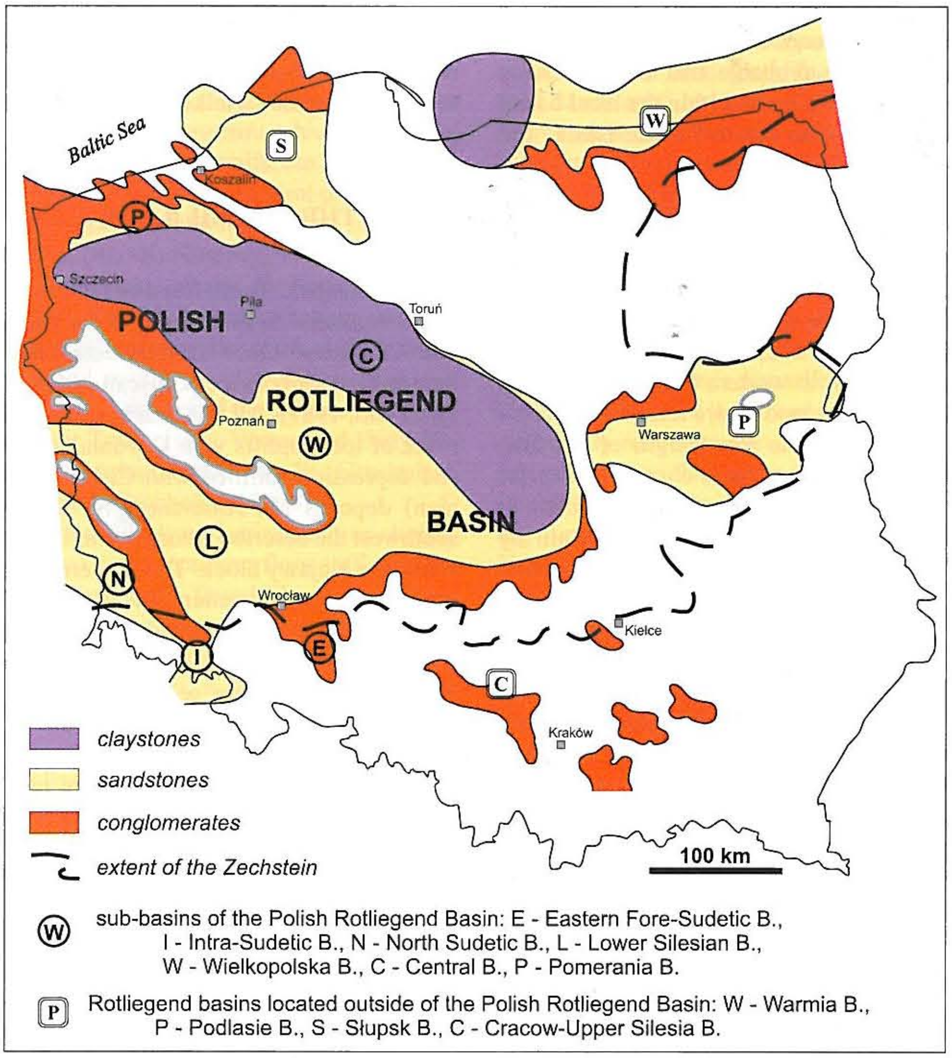

Fig. 9. Rotliegend basins of Poland (main sources: A. Siedlecka, 1963; J. Pokorski, 1976a, 1978b, 1989; S. Depowski, 1978; P. Karnkowski, 1979; P. H. Karnkowski, 1987a, 1994; J. Wojewoda, K. Mastalerz, 1989; K. Dziedzic, A. K. Teisseyre, 1990).

deposition periods manifested — among others — by the occurrence of *caliche* horizons.

Although the North-Sudetic Basin formed much later than the Intra-Sudetic one, the features of Stephanian and Lower Permian infills of both the depressions are very similar (K. Mastalerz *et al.*, 1993). Also here, beneath the volcanic complex, two megacycles of normal grading and bounded at the top with lacustrine facies — the so called Lower and Upper Antracosia Shales (Świerzawa Formation) have been distinguished. The fundamental part of both these megacycles is composed of coarse clastic fluvial sediments and subordinarily — of alluvial fan deposits (K. Mastalerz, 1990). The volcanic complex (Wielisławka Formation) consists mainly of volcanic rocks with intercalated sediments devoid of such a distinctive cyclicity (S. Kozłowski, W. Parachoniak, 1967). The post-volcanic sedimentary complex (Bolesławiec Formation) is composed of dominating fluvial conglomerates and sandstones with numerous *caliche* horizons (J. Milewicz, 1976, 1985). Aeolian sandstones locally occur at the top of the formation (J. Mroczkowski, C. Skowronek, 1980).

The Lower Silesian Basin is located north of the North-Sudetic Basin, between the Fore-Sudetic Block and the Wolsztyn Ridge. In the pre-volcanic period of the Rotliegend, when the Wolsztyn Ridge and Fore-Sudetic Block did not manifest themselves yet in palaeomorphology, similar sedimentary conditions probably existed in the areas of both the basins mentioned above. Megacycles distinguished in the Lower Silesian Basin are not so evident but this may result from later erosion or from incomplete drilling core data. But also there, at the beginning of the Rotliegend sedimentation in the Late Stephanian, a gradual replacement of grey and black deposits by red and brown ones is clearly visible.

Other subbasins are distinguished also within the Polish Rotliegend Basin area. There are the Wielkopolska Basin, Central and Pomerania basins. In all these regions, under volcanic rocks, successions of grey and black clastics, gradually changing their colour upward into red and brown, have been found. Recently they occur very fragmentarily but it is quite probable that they primarily occupied a larger area and originated within the local basins comparable in their sizes to the North-Sudetic Basin. The volcanic episode and a concurrent tectonic rebuilding barely caused the formation of the Polish Basin, the first stage of which was reflected by the deposition of the volcanites and sediments of the Wielkopolska Subgroup (Upper Rotliegend).

BASEMENT OF THE ROTLIEGEND IN THE POLISH BASIN

The Polish Rotliegend Basin was founded within two tectonic zones of the Variscian orogene and the epi-Caledonian platform. The front of the Variscan orogene exhibits an almost latitudinal orientation in western Poland but it turns towards the south in central Poland where it assumes a NW–SE orientation, nearly parallel to the margin of the East European Platform. Such an orientation change causes the northern and northeastern basin margins have a basement of folded deposits of the Caledonian orogene, overlain by Devonian and Carboniferous sediments (Fig. 8). The latter deposits originated within the marginal part of the Rheno-Hercynian basin (compare previous chapters). The Lower Carboniferous sediments of flysch type and subordinarily — the Devonian and older series are observed within the Variscan orogene. A discussion on the Rotliegend basement within the Polish Basin refers to its two main structural regions: the Variscan part (including Wielkopolska, Lower Silesia and Sudetes areas) and epi-Caledonian one (Western Pomerania and Kujawy).

Tectonic studies of the Pomerania and Kujawy areas have been conducted by many scientists (J. Znosko, 1962, 1965; W. Pożaryski, 1964, 1987, 1991; R. Dadlez, 1974, 1978, 1990; A. M. Żelichowski, 1987b; L. Kieszner, W. Solawa, 1980; W. Brochwicz-Lewiński *et al.*, 1981; L. Antonowicz *et al.*, 1994; Z. Kotański, 1997a, b). Studies are based on over 100 deep boreholes, that drilled the sub-Permian Palaeozoic rocks, numerous seismic and refraction sections as well as on gravity and magnetic data. Tectonics of these regions is characterized by blocky structures bounded with huge fault zones. Slip values of pre-Zechstein faults vary from 500 m to several thousands of meters and they are dated as pre-Devonian, Devonian/Carboniferous, Late Carboniferous, Early and Middle Permian (W. Pożaryski, 1987). Blocky structure enables distinguishing of four megablocks, described in Polish geological literature as follows (from the east to west): the Koszalin–Chojnice zone, Szczecinek massif, Czaplinek and Szczecin blocks. The Koszalin–Chojnice zone is characterized by a pattern of parallel antythetic faults, oriented NW–SE, throwing down their south-western footwalls by 300–2000 m (R. Dadlez 1974, 1980a, b, 1993; W. Pożaryski 1987; L. Antonowicz *et al.*, 1994). At the margin of the East European Platform the Devonian and Carboniferous cover is discontinuous, thinner and faulted. Its thickness increases gradually towards the southwest. The area with few fault zones and a continuous Devonian–Carboniferous cover, described as the Szczecinek massif, is located southwest of the Koszalin–Chojnice zone. At the Baltic Sea coast, where the Koszalin–Chojnice zone turns to WNW direction, this massif becomes narrower and ends at a coastal line. To the southwest it is bounded — along a fault zone — by the Czaplinek block. These framing faults of a NW–SE orientation are parallel to the margin of the East European Craton. The Czaplinek block is intersected by numerous faults, founded probably in the Variscan or Caledonian epochs (W. Pożaryski, 1987). All this area is characterized by the occurrence of local uplifts with Devonian sediments on their top and depressions infilled with Carboniferous (up to Stephanian) deposits (L. Knieszner, W. Solawa, 1980). To the southwest the described block continues into a structural unit called the Kujawy block. The westernmost large structure of the Rotliegend basement in Western Pomerania is the Szczecin block, being a depression, wedged between the Variscan orogene front and Czaplinek block.

Variscan foredeep sediments are preserved probably within this structure. The area of the described blocks is limited from the south and southwest by folded and probably overthrusted Variscides, known from rare boreholes (comp. map of W. Pożaryski, P. Karnkowski, 1992, and discussions by R. Dadlez *et al.*, 1994a). More data on the nature of the Rotliegend basement within the Variscan orogene were supplied by boreholes from the Wielkopolska and Lower Silesia regions.

The oldest rocks of the Rotliegend basement in the Wielkopolska area are sericitic-chloritic shales, quartzites and phyllites. Their tectonic dips are of about 40–90 degrees. In drilling cores, the intensive tectonic deformations of these rocks manifested themselves by fine folds, and rare tectonic crenulation are often observed. These rocks from southern Wielkopolska have been lithologically compared with the older Palaeozoic series of the Sudetes (W. Grocholski, 1972). H. Krawczyńska-Grocholska (1978) has described sporomorphs there, dated to be older Palaeozoic. The whole area occupied by this metamorphosed complex was proposed by W. Grocholski (1972) to be called "the metamorphicum of southern Wielkopolska", not being a synonym of the Wolsztyn Ridge. Devonian (Givetian–Lower Frasnian) deposits were locally found directly north of this metamorphicum (J. Kłapciński *et al.*, 1975, 1978) and the Upper Devonian series with conodont fauna have been found in the basement of the southern part of the Fore-Sudetic Monocline (M. Chorowska, 1978).

The occurrence of older Palaeozoic rocks in the Wielkopolska region is limited to its southern part (P. Karnkowski, K. Rdzanek, 1982; Z. Kotański, 1997b). These rocks contact, both from the south and north, with series of intercalated sandstones and shales, dark grey and violet in colour. These sediments are of Late Palaeozoic age (mainly Carboniferous), they are strongly transformed diagenetically and silty-clay series indicate a strong sheet jointing. Their dips vary from 20 up to 90 degrees; intensive tectonic deformations are visible in some profiles. Such a strong tectonism of some rock series results probably from a higher competence for deformation of silty-clay intervals. These rocks, due their characteristic colour and lithology, are quite easily recognizable in the whole area, outside the metamorphicum of southern Wielkopolska. The Lower Carboniferous deposits are dated mainly after goniatites fauna. In several profiles from the southern part of the Fore-Sudetic Monocline, the Visean (K. Korejwo, L. Teller, 1967; K. Korejwo, 1969) and Lower Namurian (A. M. Żelichowski, 1964a; K. Korejwo, 1969) deposits were found. In the Wielkopolska region the sediments contain goniatites (J. Kapciński *et al.*, 1978), documenting Late Visean and possibly — Early Namurian age. The results of palynological studies of the series commented above indicate also their Tournaisian, Visean and Early Namurian age (H. Krawczyńska-Grocholska, W. Grocholski, 1976a, b; H. Krawczyńska-Grocholska, 1978).

Dark grey to black deposits, lying horizontally or slightly inclined (15–20 degrees) and containing flora sufficient for palynological studies have been found above the folded Lower Carboniferous rocks, in several places of northern Wielkopolska. Palynological results (T. Górecka *et al.*, 1977a, b, 1978; P. H. Karnkowski, K. Rdzanek, 1982) suggest Late Carboniferous (Westphalian–Stephanian) age of the deposits. Many boreholes from the southern part of the Fore-Sudetic Monocline have also drilled through Upper Carboniferous (Westphalian–Stephanian) series, frequently dipping up to 25 degrees (A. M. Żelichowski, 1964a, b; H. Krawczyńska-Grocholska, W. Grocholski, 1976a; T. Górecka *et al.*, 1977a; J. Jerzykiewicz, 1977).

The presented examples illustrate an angular discordance existing here and there between the Lower (including Namurian A) and Upper (Westphalian–Stephanian) Carboniferous. A similar discordance (up to 30 degrees) is also sometimes observed between the Upper Carboniferous and the red sub-volcanic series of the Rotliegend. It is possible that tectonic deformations visible in the Upper Carboniferous succession are limited to small areas only. In a dozen or so boreholes above highly tectonized Lower Carboniferous deposits dark grey shales, lying almost horizontally, are found. It is possible that a tectonic activity at the turn of the Carboniferous and Permian manifested itself mainly as block tectonics or a selective activation of particular zones. Consequently the Upper Carboniferous deposits usually lie horizontally and they are concordant with the overlying Rotliegend series, or an angular discordance is sometimes visible between the Upper Carboniferous and Permian. The occurrence of a local angular discordance or a change in grain size (so called "basal conglomerates") at the Upper Carboniferous/Permian boundary, recorded in several small basins of Western Europe (e.g. Meisdorf, Ilfeld and Mansfeld depressions — D. Andreas *et al.*, 1975; the Autun Basin — S. Feys, C. Greber, 1972), complicates additionally a distinction of the lower boundary of the Rotliegend. Detailed biostratigraphic studies indicate that these basal conglomerates frequently lie below or above the Carboniferous/Permian boundary.

The relation of the lower limit of the Rotliegend to the Carboniferous/Permian boundary becomes a quite individual problem. The term "Rotliegendes" was created in Germany to define continental red deposits, underlying marine Zechstein sediments. In England these deposits were called "New Red Sandstone" because of their similarities to the Lower Devonian series. The idea of Rotliegend, primarily of only lithostratigraphic character, was later adapted to chronostratigraphic subdivisions. But stratigraphic studies evidenced that red sediments could represent a part of the Lower Permian or the whole Permian and, in some cases, also the Upper Carboniferous. So the term "Rotliegend" began to be applied for such sediments, whose lower limit corresponds to a floristically defined Carboniferous–Permian boundary while the upper one is demarked by marine Zechstein series.

The problem of the lower boundary of the Rotliegend is genetically related to the concept of the Carboniferous/Permian boundary. The latter one was accepted during the Ist International Stratigraphic Congress in Heerlen (1972) basing on the range of the genera *Callipteris* and *Valchia*. Numerous specimens of flora nad microflora, defining the turn of the Carboniferous and Permian (Stephanian/Autunian) are known from the Intra- and North-Sudetic depressions (see T. Górecka, 1969, 1970; J. Jerzykiewicz, 1973, 1975) and from Silesian-Cracovian area (J. Lipiarski, 1971). The palynological associations distinguished are characterized by a gradual decline of the spores of hygrophilous Carboniferous flora and dominance of xerophytic (Permian) elements. The youngest (dark) grey sediments from southern Poland already contain spore assemblages indicating their Autunian age. The most complete sections of the Carboniferous–Permian transition from southern Poland are documented in the North-Sudetic Basin, where the Stephanian sediments (laid on the folded Kaczawa orogene) pass gradually upward into the Lower Permian series (J. Jerzykiewicz, 1973, 1975). An angular discordance between the Upper Carboniferous and the sub-eruptive depositional Permian series is absent there. In the Wielkopolska region the grey sediments of this transition are already devoid of Autunian microflora (P. H. Karnkowski, K. Rdzanek, 1982), suggesting that the youngest grey deposits of this area are limited in age to Stephanian. The appearance of red-coloured deposits at the Carboniferous–Permian boundary is not a rapid phenomenon but a gradual transition from black deposits is visible in both outcrops in the North-Sudetic Basin and in borehole sections from the Wielkopolska area.

Similar interbedding of grey and red deposits is observed in Western Pomerania, where red deposits occur just in the upper part of the Strzeżewo series (Upper Westphalian). The Strzeżewo section consists of dark grey siltstones and claystones, occasionally brownish in colour, with sandstones and thin coal intercalations. The Wrzosowa series occurs above these deposits. It is composed of red-brown sandstones, siltstones and claystones overlain by volcanic rocks (J. Ryba, 1979). The Western Pomerania section could be comparable with profiles of the Carboniferous–Permian transition known from the Wielkopolska area and North-Sudetic Basin. The only difference between them is an earlier appearance of red colour in the Western Pomerania sections.

Concluding, the nature of sedimentation at the turn of the Carboniferous and Permian in the Wielkopolska area suggests its transitional position between the Western Pomerania and Sudetic basins. In Pomerania red colour of deposits appeared already in the Late Westphalian, in the Wielkopolska region — at the turn of the Stephanian and Autunian, and in the Sudetic area — not before Autunian. A similar process is known from Western Europe where, in its southern part, a coal-bearing formation already developed in the Autunian (e.g. coal centres of the Central Massif) whereas in the northern one (e.g. England, the Netherlands) — the red sediments developed just in the Stephanian. Such a diachroneity can be explained by a regional climatic change caused by the northward drift of Europe from the equatorial to tropical zone (E. Paproth, 1987).

A criterion of mapping ability should be realized because the Rotliegend should be considered first of all as a lithostratigraphic unit. In the case of Poland, where most of the Rotliegend deposits are documented with borehole sections, possibilities of distinction of lithostratigraphic units have been adapted to a resolution of logging methods. The folded Variscan basement is clearly distinguished from upper sedimentary or volcanic series in well logs. In such a situation, it was assumed for the Wielkopolska and Lower Silesia areas — for practical reasons — that the lower boundary of the Rotliegend will be defined by the top of the folded basement, and the oldest lithostratigraphic unit (Dolsk Fm.) will also include the Uppermost Carboniferous deposits. In Western Pomerania, where Upper Carboniferous sediments overlie the epi-Caledonian platform, the lower limit of the Rotliegend is demarked at the bottom of red facies including also the Uppermost Carboniferous series.

The present-day distribution and tectonic development of the Rotliegend basement rocks result from a multiphase tectonic activity combined with intensive erosion. Generally, in the Wielkopolska and Lower Silesia areas this basement is composed of Variscan deposits, and in their foreland — of series of the epi-Caledonian platform. A significant element within Variscan sediments is a belt of older Palaeozic rocks, called "metamorphicum of southern Wielkopolska" (W. Grocholski, 1981; Z. Kotański, 1997b). In Western Pomerania the Rotliegend basement is dominated by Lower Carboniferous or Devonian rocks (Koszalin–Chojnice zone, Szczecinek and Czaplinek blocks) as well as by Upper Carboniferous series (Szczecin block).

STRATIGRAPHY OF THE ROTLIEGEND

Rotliegend stratigraphy in Western Europe

Prospective studies of the European Permian basins enabled a good recognition of their geological structure as well as elaboration of several Rotliegend stratigraphic schemes. The main distinctive criteria are lithological features, being a basis of lithostratigraphic divisions, because the Rotliegend deposits are almost completely devoid of guide fossils. Sedimentological data are also applied for a distinguishing and classification of Rotliegend series; they enable to distinguish units basing on a depositional cyclicity (sedimentary cycles, cyclothems and sequences).

A great number of current subdivisions of the European Rotliegend results from a recognition of many local fragments of individual Permian basins (H. Kiersnowski *et al.*, 1995). Stratotype profiles are often represented by borehole sections, located in different countries, so that the units distinguished have a limited extent, although it is quite possible now to elaborate a common and unified stratigraphic subdivision of the Rotliegend for Central and Western Europe. A review of the hitherto applied Rotliegend subdivisions in Europe, presented here, illustrates the evolution of methodology in solving complex stratigraphic problems by introducing allostratigraphic units.

Lithostratigraphy: the Netherlands and England

At the beginning of the seventhies the prospective works in the Netherlands and England supplied many data for establishing still applied lithostratigraphic subdivisions (see Nederlandse..., 1980; Stratigraphic..., 1980). Their basis was the Schlochteren Sandstone Formation, distinguished in the basin margins and corresponding to the Leman Sandstone Formation in England and to the Silverpit Claystone Formation in the basin center. Repetitive claystone and sandstone horizons observed in lithologic sections are called from bottom to top as follows: the Lower Schlochteren Sandstone Member, Ameland Claystone Member, Upper Schlochteren Sandstone Member and Ten Boer Claystone Member. Several evaporitic horizons, distinguished as a single evaporitic member, occur in the basin center. All these members and formations, described in detail in the Netherlands (Stratigraphic..., 1980) are still in use, evidencing the universal character of a properly constructed lithostratigraphic subdivision. In 1993, the paper of T. D. J. Cameron (1993) was published. This presented the Rotliegend subdivision from the North Sea area. The sandstone formations distinguished there: Auk Sandstone Fm. and Findhorn Sandstone Fm., correspond to the Schlochteren and Leman Sandstone Fms. The monography was perfectly prepared and edited, and acclaimed as a fundamental work on the Rotliegend lithostratigraphy from the North Sea. The southern part of this region was separately described by H. Johnson *et al.* (1994). Both these publications are a perfect example of properly edited and published papers on lithostratigraphic subdivisions of sedimentary basins. They comprise lithological descriptions of individual units and their contacts with adjacent members, vertical and horizontal extent of units, stratotype profiles with well logs and analysis of depositional environments as well as correlations of units with distinctions from other parts of the same basin or neighbouring ones. The time of the edition should also be appreciated, it was published forty years after the first wells were drilled in the Southern Permian Basin, so the authors selected and presented the unquestionable, widely accepted schemes of the Permian stratigraphy from the North Sea, the Netherlands and England areas. Regardless of new sedimentological works, applying mainly allostratigraphic subdivisions, the lithostratigraphic sub-divisions elaborated and used by oil companies become the fundamental stratigraphic subdivision based on clear lithological criteria.

Stratigraphic subdivisions in Germany

The definition *stratigraphic subdivisions*, used in the title, refers to subdivisions based on different citeria of stratigraphic units distinction (chronostratigraphic, lithostratigraphic and allostratigraphic ones). The second title element, *Germany*, requires an explanation. Historically, Germany was divided till 1990 into two parts: the German Democratic Republic and Federal Republic of Germany. In geological literature on the Rotliegend stratigraphy this geographic-political division existed till 1993 and just in the period of 1993–1995 the stratigraphic subdivisions of both these parts of Germany were unified. Such a situation refers only to the Southern Permian Basin, whose large part is located in Germany and the whole basin is called the North-German Basin in German literature.

A discussion on the Rotliegend stratigraphic subdivisions in Germany concentrates on historical analysis of different Rotliegend stratigraphic schemes in different parts of Germany before the union, and of a final, universal Rotliegend scheme, constructed after 1990. This remark is important because the opinions on distinction criteria for Rotliegend subdivisions are variable although the unit terminology is often the same. In such a case some geologists could be impressed that unchanged name indicates a lack of evolution of opinions.

The papers published by H. Falke (1976) and H. A. Hedemann *et al.* (1984) are the fundamental works on the Rotliegend deposits in Germany. They described in details sediments from both the South-German Basin and western part of the North-German Basin. The publication of G. Katzung (1968) was the first synthesis of the Rotliegend from Eastern Germany, commented and supplemented in his later works (G. Katzung, 1982, 1988). The scheme (G. Katzung, 1988) presents a distribution of the Late Carboniferous–Permian molasses in the Saxo-Thuringien zone through the Rheno-Hercynian zone as far as the external Variscides zone. The North-German Basin in this scheme is considered to be a foreland basin. Such an opinion, arised from studies of small intramountain basins from the Rheno-Hercynian and Saxo-Thuringien zones. It dominated the whole knowledge of the East German Rotliegend development. It was well expressed in the stratigraphic table (TGL 25234/12, 1980), presenting the Rotliegend units distinguished in different parts of East Germany. For the North-German Basin two unit categories were proposed: *Folge* and *Schicht.* Their eqivalents are: *series* and *bed.* The Vulkanit-Folge is the oldest unit and the Havel-Folge and Elbe-Folge were distinguished above it. Geographical terms of these units come from river names like for the Zechstein stratigraphic terminology. Such relations between the Rotliegend and Zechstein subdivisions result from cyclothem criteria (diastrophic-sedimentary cycles), applied in both stratigraphic schemes. In the Rotliegend these cycles are observed only in clastics; they are determined by tectonic movements and each one starts with coarser material (G. Katzung, 1982; E. Pleine, 1993). The *Folgen* and *Schichten* are considered to represent lithostratigraphic units. W. Lindert *et al.* (1990) divided stratigraphic units into two categories: lithostratigraphic and lithogenic ones. The lithogenic units have been distinguished according to lithological features, that are reflected in their names, for instance: Elbe-Wechselfolge, Elbe-Basissandstein, Mirow-Wechselfolge, Mirow-Sandsteinfolge, etc. Other units, called e.g. Elbe-Folge, Havel-Folge, Eldena-Schichten, represent the group of lithostratigraphic units. But the above scheme (W. Lindert *et al.*, 1990) indicates explicitly that the so-called lithostratigraphic units are chronostratigraphic ones. Their boundaries continue across the whole basin, cutting different lithological complexes. Some of them cross sandstones in the basin margin, farther away they pass through siltstones and in the basin center — through evaporites. It is stricking that the Elbe-Folge belonging to lithogenic units, was distinguished without any cyclic principles. According to the international stratigraphic codes such complications clearly evidence that the lithostratigraphy, created and applied in East Germany, really represents the allostratigraphic or chronostratigraphic category and the lithogenic subdivision corresponds to the proper lithostratigraphic one. Comparison of lithostratigraphic schemes from the North Sea, England and the Netherlands perfectly indicates that the lithogenic subdivision proposed by W. Lindert *et al.* (1990) refers to the above discussed examples.

The basis of the Rotliegend subdivision in East Germany became — as it was mentioned earlier — the tectonically generated cyclothems distinguished in clastic rocks. Phases of tectonic movements during the Late Rotliegend were named Altmak I, II, III and IV (N. Hoffmann *et al.*, 1989; U. Gebhardt *et al.*, 1991; J. Schneider, U. Gebhardt, 1993). These papers also contained some attempts to correlate the Rotliegend deposits between the eastern and western parts of the North-German Basin. The correlation proposed there assumed that the supravolcanic series from the West Germany area correspond strictly to the Upper Rotliegend II and the tectonically controlled cyclothems were the basic criterion for unit distinction. These cyclothems are normally graded and represent normal fining upward cycles. In both the eastern and western parts four Altmark tectonic phases and several minor tectonic episodes, responsible for a depositional cyclicity in the North-German Basin were defined.

The Rotliegend stratigraphic subdivision in the western part of this basin refers to lithostratigraphic schemes well known for the Netherlands (comp. Stratigraphic..., 1980). But this type of subdivision is not commonly used due to good recognition of basin center, where salinary facies occur. These well marked salty horizons enabled the Rotliegend subdivision, starting from the basin center towards its margins.

The comprehensive paper by P. Gralla (1988) suggests that the intracratonic Southern Permian Basin contained playa sediments in its center and alluvial fan and wadi systems as well as aeolian fields in its margin. Climatic changes, considered to represent repetitive humid and dry periods, highly influenced the sedimentation of expanding playa lake, involving distinct facies migration. Each development of a halite layer reflected an initial stage of basin configuration. Migration of facies zones was expressed in vertical sections by sedimentary cycles with transgressive and regressive stages. This cyclicity was of various scale and the cycle boundaries corresponded to transgressive episodes. Thick halite horizons recorded the beginning of transgressive phases of sedimentary cycles and they were replaced upwards by fine clastics. In a transtional zone between the basin margin and its center the transgressive phase was preserved as clay with anhydrite replaced upwards by claystones. The regressive phase was marked by sandstone sequences coarsening upwards. Along basin margins transgressive events were reflected by claystone intercalations within commonly occurring sandy facies. During a regression this zone was dominated by aeolian facies. Assuming such a depositional pattern, P. Gralla (1988) has presented an evolution scheme of the North-German Basin and sedimentary cyclothems, distinguished basing upon transgressive-regressive events within the lake area, occupying the basin center. The cycle defined this way begins with a halite layer passing upwards into claystones (in the basin center) or it starts with claystones and is terminated by sandstones in the basin margin. In such successions, well illustrated in numerous figures and correlation schemes (P. Gralla, 1988; P. Gralla, C. Visser, 1995), halite beds correspond with claystones from the basin margin, whereas claystones of the basin center are equivalents to marginal sandstone layers.

A different interpretation of the same material was presented by R. E. Gast (1991, 1993). He assumed that a halite layer reflects a final phase of a regressive stage but thick claystone horizons mark the beginning of a transgression. In the basin margin claystone beds also indicate a transgressive episode, while sandstone layers — a regressive one. So the dissent between both the authors mentioned are reduced to different lithological evidences which mark the beginning of the transgression. R. E. Gast (1991, 1993) is of the opinion that each claystone appearance in a lithologic section indicates a transgression outset, whereas P. Gralla (1988) distinguished correlative horizons just in sections interpreted lithologically and he introduced a correlation of depositional systems in various parts of the basin instead of simple lithostratigraphic correlations. R. E. Gast (1991, 1993) practically correlated characteristic lithostratigraphic horizons (but it does not mean the standard lithostratigraphic procedure). R. E. Gast (1991, 1993) has obtained about twenty transgressive-regressive cycles, generated by climatically controlled water level changes within a central playa saline lake. H. J. Helmuth, S. Süssmuth (1993) also suggested the application of methodology similar to the above discussed for the Rotliegend deposits from the eastern part of the North-German Basin. These sediments are lacking of any sedimentological analyses but they have been correlated with the West-German subdivisions.

All the above discussed German stratigraphic subdivisions, from both the eastern and western parts of Germany, became — after Germany unification — analysed to obtain a single universal stratigraphic scheme for the Rotliegend in the North-German Basin (L. Schröder *et al.*, 1995). The authors (*op. cit.*) remarked that "... data from many boreholes as well as results of lithostratigraphic, biostratigraphic and magnetostratigraphic studies and of sequence stratigraphy were detaily considered. Such analysis enabled creation of the new stratigraphic table of the Rotliegend in the North-German Basin and several enclosures, containing also correlation of stratotype profiles."

Unification of two stratigraphic schemes, primarily created in two parts of Germany, required some settlements. At first it relates to the name: "*New stratigraphic division.*" This title did not precise which type of division was applied there: litho-, bio- , chrono- or allostratigraphic one. Names of the units distinguished are of a lithostratigraphic provenance (subgroup, formation, member) but they are not true lithostratigraphic units because their boundaries cross thick complexes of varied lithology. To compensate such discrepancies other names are also used, for instance: Elbe-Sandstein, Dethlingen-Sandstein, Hannover-Sandstein, but it was not explained which category and range they represent. Cyclothems, distinguished by R. E. Gast's (1991, 1993) methodology in the central part of the North-German Basin, become fundamental elements of this subdivision. Only the names, Elbe and Havel, have an East-German provenance but recently they are completely unrelated to methodology, used in the former GDR. The East-German methodology of subdivision, based on tectonically generated cyclothems with normal grading (i.e. finining upwards), were totally ignored and clastic cyclothems, distinguished by R. E. Gast (*op. cit.*) and characterized by reversed grading, were applied. The most important was a refusing of all elaborated in the eastern part of the North-German Basin comparisons basing on tectonic principles because now also in former East Germany the correlation methods founded on sequence stratigraphy were introduced.

Sequence stratigraphy in the Netherlands and England

Sequence stratigraphy is used mainly for analysis of sediments accumulated within sedimentary basins located on passive continental margins so they are commonly shelf deposits. Continental sediments have been occasionally studied by this method until now. But the opinion that climatic changes may controll a supply of fluvial systems in a similar way as relative sea level oscillations is now more frequently accepted (K. W. Shanley, P. J. McCabe, 1994). Change of erosional base position caused by eustatic or climatic factors, always involves a change of groundwater level. Especially sedimentation of aeolian deposits is controlled by this phenomenon (R. P. Langford, 1989; R. P. Langford, M. A. Chan, 1989; G. Kocurek *et al.*, 1991; G. Kocurek, G. Havholm, 1993). In the seventies and eighties, modern ideas in sedimentology of aeolianites developed independently from concepts of sequence stratigraphy. Sedimentary processes, boundary surfaces and possibilities of eolianites preservation became the principal problems to recognize. The ascertained, climatically determined oscillations of groundwater levels, as well as climatic influence on the varying extent of a giant perennial lake in the center of the Southern Permian Basin in Europe enabled a detailed sedimentological analysis, applying sequence stratigraphy.

Previously commented papers of P. Gralla (1988) and R. E. Gast (1991, 1993) assumed periodical changes of water level in the Permian lake as a principle of the Rotliegend subdivision. In England, the southern part of the North Sea and in the Netherlands similar subdivisions were attempted (G. T. George, J. K. Berry, 1993, 1994). A similar methodology as for the Germany studies was applied in the above publications. However, they differ in a territory studied. The mentioned authors (G. T. George, J. K. Berry, 1993, 1994) assumed hypothetical, ideal sequences in individual parts of the sedimentary basin. These examples were named "conceptional models". Each sedimentary association is characterized by its own, specific assemblage of features and sedimentary environments, related to all cases possible to found in a geological section. Their works have wide theoretical assumptions, verified by numerous examples from fossil and modern sedimentary environments. The schemes enabled interpretation of well sections. Cored sections became more easily and confidently compared. Sections with some lithological variability also show a better observable cyclicity than monotonous ones, e.g. sandy sections, in which cyclic sedimentation is very controversial and the interpretation is commonly adjusted to an ideal model. Stratigraphic methodology is simple, each cycle consists of two parts: a lower one — "wet", and upper one — "dry", reflecting a transition from a pluvial to arid period. Application of such a procedure allowed to distinguish five cycles, correlable over a vast area (from England to the Netherlands). Although the earlier authors frequently emphasized a strong palaeotectonic influence (synsedimentary tectonics) on the Rotliegend deposition, this phenomenon has never been considered as a factor. The methodology applied by G. T. George, J. K. Berry (1993, 1994) assumed constant subsidence, proportional to section location within basin. But in their discussions it was underlined that sequence boundaries are very often difficult to define in aeolian sediments, and completely impossible within resedimented ones. Facies assemblages, composing depositional systems, cannot be to defined basing on commonly used well logs instead of rare drilling cores. The most disputable and false is a definition of such stratigraphic units named as lithostratigraphic ones. In the paper from 1993 this term was used in the title — "*New lithostratigraphy...*" (G. T. George, J. K. Berry, 1993). A comparison of the above commented papers with simultaneously published comprehensive studies on the same areas (T. D. J. Cameron, 1993; H. Johnson *et al.*, 1994), with formal lithostratigraphic units created by oil companies after many years studies, exactly indicates that G. T. George, J. K. Berry (1993, 1994) improperly used the fundamental criteria and stratigraphic nomenclature.

The exact example of such a good stratigraphic methodology and nomenclature were the papers of C. S. Young, Y. A. Baumfalk (1990) and C. S. Yang, S. D. Nio (1993) in which the Rotliegend deposits from the Netherlands have been analysed in terms of sequence stratigraphy principles, but at the beginning the allo- and lithostratigraphic units were separated. The title "Application of high-resolution sequence stratigraphy to the Upper Rotliegend in the Netherlands Offshore" (C. S. Yang, S. D. Nio, 1993) clearly shows the category of stratigraphic units applied there. Nevertheless, also in these papers a cyclicity was related to climatic changes but a single cycle was interpreted contrary to a model of G. T. George, J. K. Berry (1993, 1994). The lower part of cycle represents an arid period, the upper one — a humid episode. Consequently the facies assemblages and correlation were treated in a different way but five supersequences or twelve sequences were distinguished in the Rotliegend section. These sequences lasted probably about 0.9 mln years according to the Milankovich cyclicity scale.

The above presented review of stratigraphic subdivisions of the Rotliegend from the Southern Permian Basin in Western Europe illustrates an evolution of stratigraphic concepts. It is symptomatic that after improvement of stratigraphic subdivision, almost simultaneously many proposals of another, more detailed subdivision of the Rotliegend were created. While in Germany such a subdivision based on allostratigraphic methodology was established, similar schemes were independently prepared for the England, North Sea and the Netherlands areas. So two Rotliegend subdivisions are related to Germany (P. Gralla, 1988; R. E. Gast, 1991) and also two for the North Sea area (G. T. George, J. K. Berry, 1993, 1994; C. S. Yang, S. D. Nio, 1993). All these elaborations have a common assumption — climatic variations became a main deposition factor in the Rotliegend Basin, but each author proposed a slightly different criteria of sequence distinction, from both genetic and lithofacial point of view. These new subdivisions resulted from a real necessity of more detailed anticipation of promising reservoir rocks or occurrence of lithofacial patterns with stratigraphic (lithofacial) trap characteristics. Such stratigraphic studies were necessary to extend a knowledge of character and origin of the Rotliegend deposits by distinction of depositional systems, formed during numerous cyclic depositional episodes. Although, all of authors have emphasized the importance of the tectonic factor in sedimentary processes, until now the climatic factor has been considered as a dominant one. This traditional opinion should change soon when the general stratigraphic schemes will be tested in areas of numerous boreholes and geophysical data. Analysis of the European Rotliegend basins has undoubtedly reached a new phase of its development, which started in the late eighties. First of all, this stage includes detailed sedimentological studies applying the newest technics (e.g. dipmeter, acoustic scanner, 3D seismics, highly processed seismics — acoustic impedance, amplitude extraction).

In Poland the attempts of more precise sedimentological analysis of the Rotliegend sediments have also been carried on to prospect gas lithofacial traps (P. H. Karnkowski, 1995c; P. H. Karnkowski *et al.*, 1996, 1997a, b) and predict promising reservoir rocks in top parts of the Rotliegend succession.

Rotliegend stratigraphy in Poland

A more detailed recognition of the Rotliegend in the Polish Basin started at the beginning of the sixties. The stratigraphic divisions established for the Intra- and North-Sudetic basins, based on sedimentary-diastrophic cycles were used at that time. This principle is still successfully applied for the Rotliegend stratigraphy in small basins of the Thuringen Forest and Saale Depression (Eastern Germany). In the late sixties and seventies several hundreds of boreholes were drilled in the Polish Permian Basin. They supplied a lot of analytical data. Simultaneously in 1975 the principles of stratigraphic classification and nomenclature (based on international stratigraphic codes) were published in Poland (Zasady..., 1975). They recommended to create new stratigraphic units according to presented rules, and proposed a revision of hitherto existed units. The author (P. H. Karnkowski, 1977) proposed a new subdivision of the Rotliegend from Wielkopolska basing on lithological criteria only. A widely accepted subdivision based on diastrophic-sedimentary cycles existed at that time. Two proposals (P. H. Karnkowski, 1981; J. Pokorski, 1981a) to formalize a lithostratigraphic subdivision of the Rotliegend in Poland, according to the rules introduced by the Polish instruction for classification of stratigraphic units (Zasady..., 1975), were published parallely in 1981. J. Pokorski (1981a) proposed to distinguish the Rotliegend units according to diastrophic-sedimentological criteria while P. H. Karnkowski (1981) applied only lithological features for subdivision. Concluding, J. Pokorski (1981a) methodologically related his subdivision directly to schemes, criteria and unit categories described in the German Democratic Republic but the present author (P. H. Karnkowski, 1981) attempted to relate his scheme to lithostratigraphic subdivisions established in the Netherlands, England and the Federal Republic of Germany. Later on this author (P. H. Karnkowski, 1987a, 1994) formalized the units. The scheme of J. Pokorski is still composed of informal units (J. Pokorski, 1988b) and it has been used in comparisons of the Polish and East-German Rotliegend basins (N. Hoffmann *et al.*, 1997). Nowadays, when the subdivision criteria of the Rotliegend from the North-German Basin has drastically changed after Germany unification, and when analysis of climatically generated sequences became a principle for distinguishing units, this traditional scheme will surely be of minor importance.

In his previous papers the present author emphasized the role of climate and tectonics in the Rotliegend Basin development and consequently proposed to distinguish in the Rotliegend succession allostratigraphic units, independently of lithostratigraphic ones (P. H. Karnkowski, 1986b, 1987b) that seems to be the optimal methodological and formal solution. The last attempt of Rotliegend stratigraphic analysis was presented by H. Kiersnowski (1997b) who arbitrarily distinguished depositional sequences mainly on "the basis of vertical lithological changes interpreted in terms of changing sedimentary environments distinguished in the course of sedimentological core material". Sedimentary environments, defined by him in vertical sections, were correlated within the central part of the Polish Rotliegend Basin. This scheme will be verified practically in the future.

Formal lithostratigaphic subdivision of the Rotliegend in the Polish Basin

The papers summarizing the state of art of the Rotliegend stratigraphy in Poland and proposal of its normalization and formalization were published by J. Pokorski (1981a) and P. H. Karnkowski (1981). Up to date only the Karnkowski's proposal was formally established and published (P. H. Karnkowski, 1987a, 1994).

Since clastic, red deposits are almost devoid of index fossils, the stratigraphic subdivisions have to base on lithological criteria as the essential principle in establishing lithostratigraphic units (Fig. 10). The application of cyclic sedimentation and geological processes (i.e. tectonics, climate) could be introduced using allostratigraphic units (P. H. Karnkowski, 1987b). Since comprehensive papers considering the Rotliegend lithostratigraphy have already been published (P. H. Karnkowski, 1987a, 1994), only a short draft of the Rotliegend formal lithostratigraphic units in the Polish Basin will be presented here.

The oldest unit of the Rotliegend subdivision is the Dolsk Formation, located between the folded Variscan basement and volcanics (Fig. 10). Now it occurs only locally but primarily it may have extended over larger areas of the Rotliegend Basin. The lower part of the formation contains grey and black sandy deposits; upward red-brown siltstones prevail. The Dolsk Formation is overlain by volcanics and pyroclastics (W. Ryka, 1978a, b; E. Jackowicz, 1994) of the Wyrzeka Formation. Occurrence of the volcanic rocks in the Polish Permian Basin is limited to its western part (Fig. 11). A thickness of volcanics exceeds occasionally one thousand meters and normally varies between 100–200 m. Comparing this thickness with that of East Germany volcanics (Fig. 11) there is a great difference visible: in East Germany this maximum thickness exceeds 2500 m and the average value is of 1000–1500 m, while in the Polish Permian Basin the thickness is ten times smaller. This difference could not be explained only by erosion of the lava covers. The Rotliegend volcanism in Western Poland was less developed than in East Germany. The volcanic event was related to the Saalian movements which in the first phase ceased sedimentation and later caused great erosion of the Dolsk Fm. The main phase of these movements involved lava extrusion and eruption of pyroclastic rocks.

After volcanic activity, the Saalian tectonic movements produced displacements of basement blocks covered by volcanics. Erosion of these blocks initiated the coarse-grain sedimentation of the Wielkopolska Subgroup (especially Książ Wlkp. Conglomerate Fm. and Polwica Conglomerate Mb.). Petrographic assemblages of these conglomerates often provide the only evidence of the volcanism, and the quantification of clasts in the sequence informs about lava covers removed. Generally, the volcanics contain a low admixture of acid volcanic rocks (rhyolites, rhyodacites). Locally, trachytes and trachybasalts occur in a large amount.

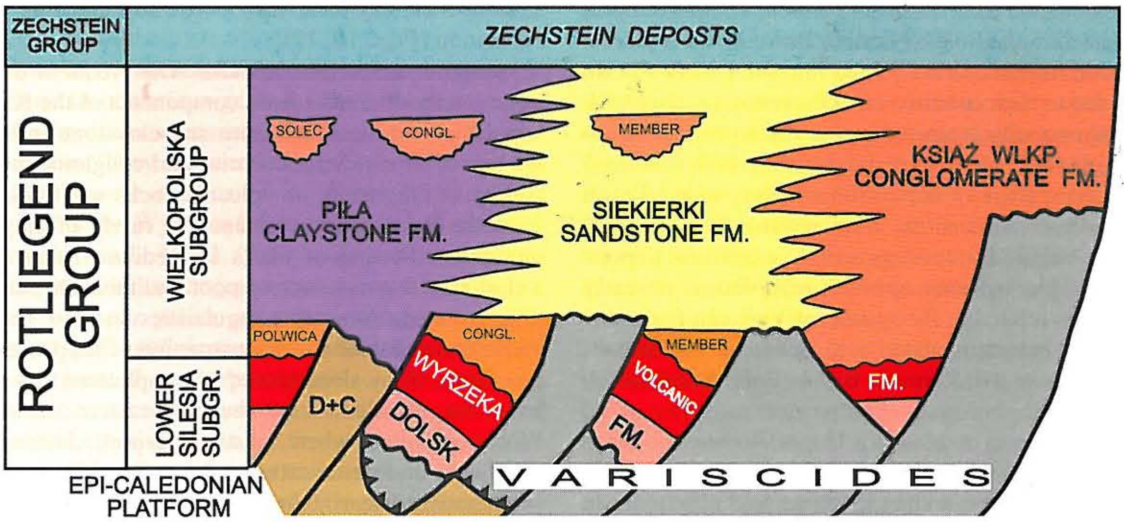

Fig. 10. Formal Rotliegend lithostratigraphic units in the Polish Basin (P. H. Karnkowski, 1987a, 1994).

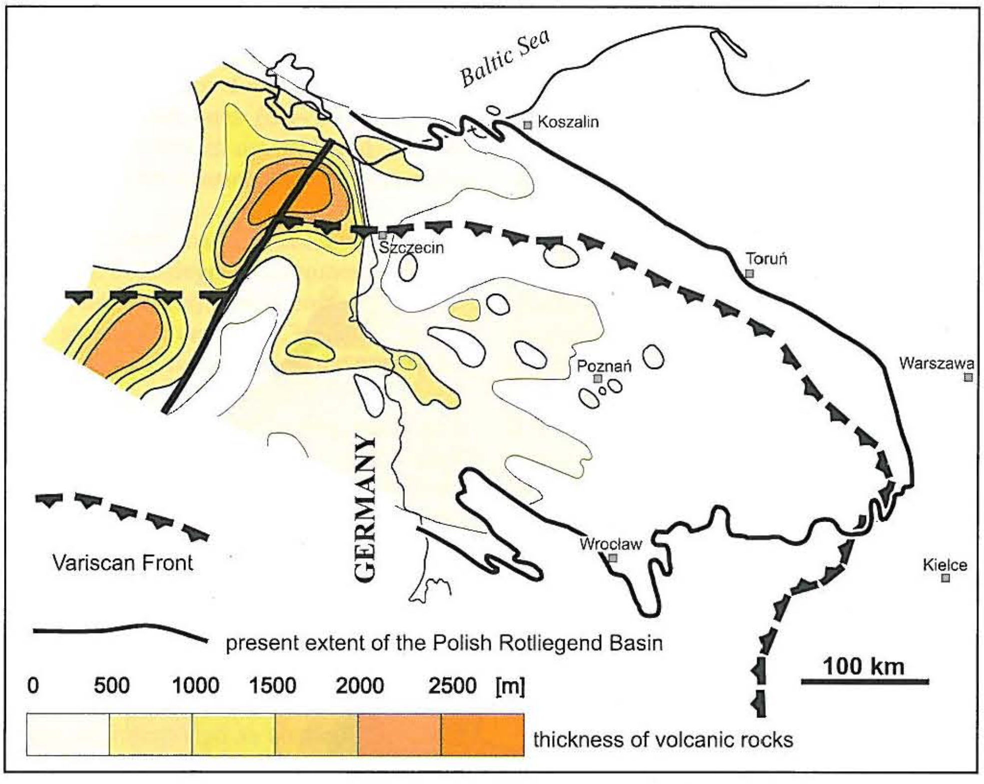

Fig. 11. Present extent and thickness of the Rotliegend volcanics in Poland and Eastern Germany (main sources: W. Ryka, J. Pokorski, 1978; E. Jackowicz, 1994; N. Hoffmannn *et al.*, 1997).

Analysis of these profiles indicated that in the places where the thickness of volcanics is greater than the average value (centres of volcanism), the lower part of profile is built of neutral volcanic rocks, and the upper part of acid ones. In other places, where the thickness of volcanics is lower than average value the acid volcanic rocks occur commonly. This regularity suggests only one volcanic cycle of neutral volcanism at the beginning, and an acid event at the end of cycle. Basic-neutral lava occurs mainly in the small areas with higher thickness of volcanic rocks. Acid lava covered a larger area outside the volcanism centres. These examples are documented in the Polish Permian Basin in a few places.

Both these formations are joined into the **Lower Silesia Subgroup** due to their common co-occurrence, i.e. the Dolsk Formation is normally protected by the volcanic cover of the Wyrzeka Fm. (Fig. 10). Accordingly, they both indicated a very important stage of depositional history of the Polish Permian Basin — a transition from sedimentary style, induced by the Variscides development, to a platform depositional mode. This volcanic episode, regarded as an early platform one, is related to the system of Variscan faults and deep fractures but rejuvenated and activated by stresses generating the new Rift Permian Basin (P. H. Karnkowski, 1995a).

The volcanics are overlain by Upper Rotliegend siliciclastics, developed as conglomerates at the basin margins and around palaeohighs, and as siltstones and claystones in the basin centre. In the transitional zones sandstones prevail (Figs. 9, 10). These three lithofacies are classified as individual formations: the Książ Wielkopolski Conglomerate Formation, Siekierki Sandstone Formation and Piła Claystone Formation (Figs. 10, 12).

Conglomerates and breccias with frequent thick sandstone interbeds are the main components of the Książ Wielkopolski Formation. Siltstone and claystone intercalations are less common there. Breccias and conglomerates usually consist of fragments of volcanic rocks and rocks derived from the Palaeozoic basement and rarely of clay-siltstone intraclasts. Sorting of clasts is medium, frequently poor, a clast size selection is very poor and their lithology is very differentiated. Some fine regularities in clast composition and content enabled the reconstruction of supposed transport directions. They documented a complicated transport systems, for instance — of the northeastern margin of the Wolsztyn Ridge, where clastic transport, directed initially northward and northeastward, turned rapidly eastward and southeastward nearby the Poznań–Kalisz tectonic zone, parallel to the basin axis. This resulted from the activity of ephemeral rivers, transporting coarse clastics just nearby the Wolsztyn Ridge. The vast sandy fields of distal alluvial fans,

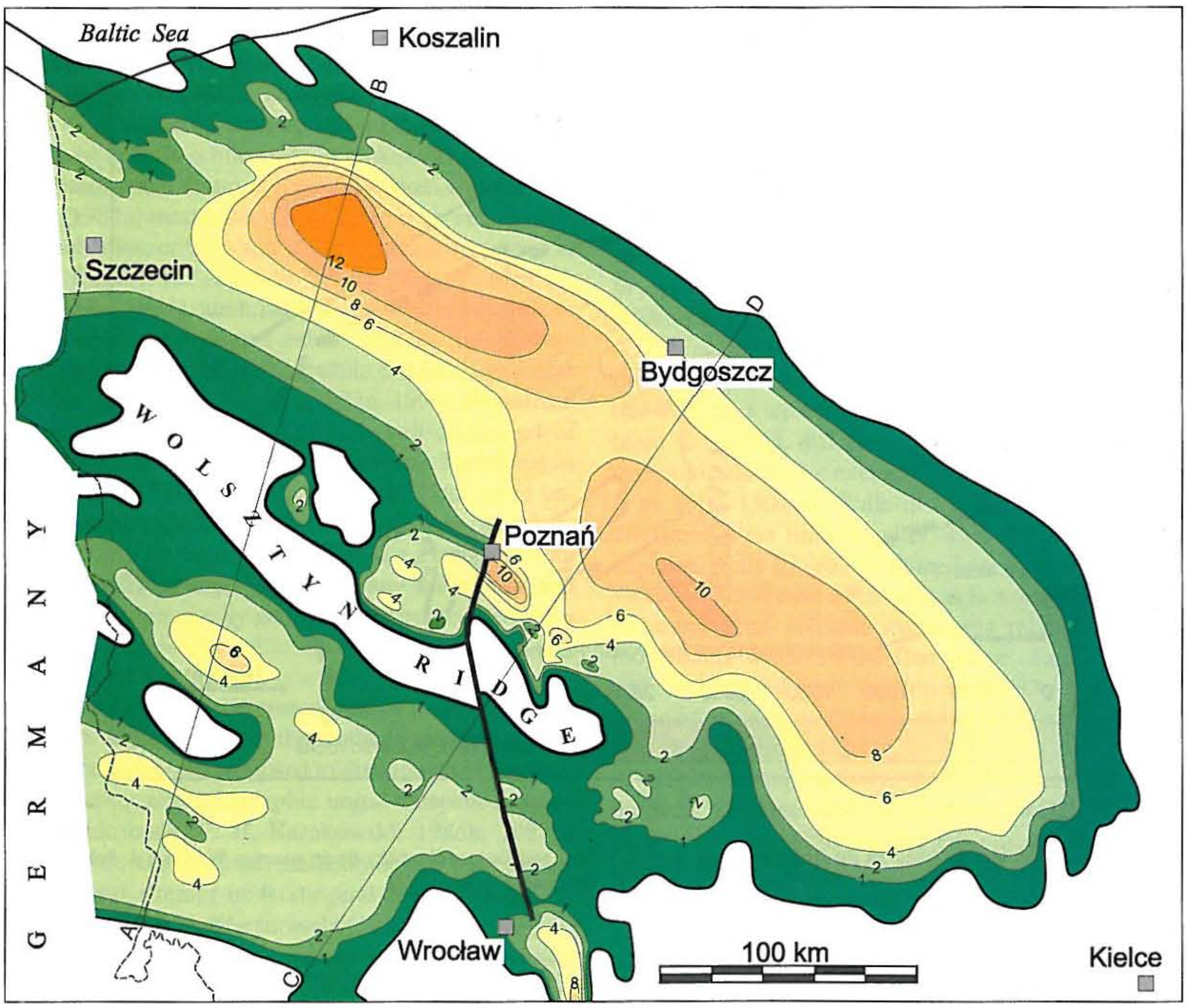

Fig. 12. Restored isopach map (in hectometres) of the Wielkopolska Subgroup (Upper Rotliegend) in the Polish Permian Basin (A–B, C–D — location of cross-section lines presented in Figs. 16, 17).

easily modified by eolian processes developed farther away from it.

Sandstones of the **Siekierki Formation** are petrographically uniform but of various genesis. They directly overlie the Lower Carboniferous basement, the Dolsk Fm. or Wyrzeka Fm. volcanics. They are surrounded (Figs. 9, 10) by the occurrences of coarse clastics of the Książ Wielkopolski Fm., volcanics of the Wyrzeka Fm. or older basement rocks (P. Karnkowski *et al.,* 1978). Their main components are quartz grains of varied sorting and roundness, feldspars and plagioclases. Feldspar grains are poorly preserved due to carbonitization and kaolinization. Particles of sedimentary rocks are represented by cryptocrystalline fine quartzose sandstones, siltstones and claystones; smaller fragments of acid and neutral effusive rocks are frequent. Sandstones of the lower part of this formation are characterized mainly by clay matrix, the upper part is dominated by carbonate matrix, with varied anhydrite admixture. Siliceous matrix occurs in a varied amount within the whole section, commonly forming rims of quartz grains or void infills. Hydrated iron oxides coexist with clay minerals of the matrix or create delicate rims on sandy grains.

Fine-medium sandstones are predominant with varied grain sorting and roundness. A second group consists of coarse and varigrained sandstones of bimodal sorting, expressed by two grain populations: finer grains (0.06–0.2 mm), less rounded and coarser ones (0.4–1.5 mm), well rounded. Conglomeratic sandstones are included into the sandstones if they contain rare coarser (5–6 mm) particles dispersed.

Most of the sandstones are characterized by cross-bedding (laminae inclination: 0–30 degrees), commonly marked by variations of grain size and clay matrix content. A thickness of lamine vary strongly from 0.1–0.3 mm to several millimetres. In the top part of the formation the sandstones are often structureless.

Locally, within the Siekierki Fm. profile, especially in its lower and middle parts, conglomerate intercalations occur. These lowest interbeds were distinguished as the **Polwica Conglomerate Member** and those upper ones as the **Solec Conglomerate Member**. Both units being of local range could be included into marginal parts of lava-pyroclastic sheets or related to activated tectonic zones, with strong subsidence and/or tectonic movements.

Claystones and siltstones with parallel, flaser and lenticular bedding, composing the **Piła Formation**, prevailed in the basin centre and they are interpreted as continental sabkha (playa) deposits. The bedding type is often marked by coarser grain lamination and hence, small scale sedimentary structures are visible. Sandstone horizons within this formation occur sporadically — they are mainly of fluvial origin. Sandstones of aeolian genesis also exist. Interbeds of claystones and sandstones allow us to conclude that this is the result of migration of aeolian sand fields along the shore of an inland lake (playa). Since the origin of sandstone horizons within the Piła Claystone Fm. could be aeolian or fluvial, it is difficult to regard them, without reliable evidence, as the equivalents of conglomerates and conglomeratic sandstones. Currently, thick sandstone horizons could be distinguished as informal members (for instance — Lower or Upper Siekierki Sandstones Member). In some profiles of the formation distinguished, conglomeratic and sandy-conglomeratic horizons occur. Their position and sedimentological similarity are comparable to coarse clastic members and undoubtedly they can be classified as the Polwica Conglomerate Member and the Solec Conglomerate Member (Fig. 10). The pebbles composition of the Polwica Mb. is differentiated, for instance in the Pomeranian region clasts of sedimentary rocks prevail and in the other area — pebbles of volcanic rocks are dominant.

Analysis of the map of both volcanics extent and the Polwica Mb. showed that the occurrence of coarse clastic facies well correlates with the marginal parts of lava covers or, moreover, with the zones of a high tectonic activity (Resko–Czaplinek region). The Solec Conglomerate Mb. commonly occurs in the middle part of the Piła Fm. The mosaic of clast composition and distribution of this member indicate that coarse material was supplied from both eroded lava covers and the eastern margins of the basin lacking of any volcanics.

The Piła Fm. is combined with the Siekierki Fm. and Książ Wlkp. Fm. into the Wielkopolska Subgroup (Fig. 10). The thickness distribution of the Wielkopolska Subgroup (Fig. 12) indicates that claystones-dominated area well correlates with the greatest depocenter of the Polish Rotliegend Basin, although in Wielkopolska there are also several areas of exclusively sandy facies with a few hundred metres thick sections.

Wielkopolska is the best recognized region of the Polish Rotliegend Basin (northern margin of the Wolsztyn Ridge). The main geological source data are drilling cores because Zechstein evaporites cause bad seismic images for Rotliegend strata. Facies differentiation in each profile and sedimentological features enable the reconstruction of sedimentary environments. One of the most useful parameters is the composition of clasts forming breccias and conglomerates. The main transport direction of coarse material during sedimentation of the Wielkopolska Subgroup shows that from the beginning of the Late Rotliegend, the Wolsztyn Ridge was the main source area (Fig. 12). At present, in the western Wielkopolska, Palaeozoic rocks outcrop on the surface of the Wolsztyn Ridge (mainly Lower Carboniferous). Basing on the composition of conglomerate clasts from the Książ Wlkp. Fm. it may be concluded about the primary presence of volcanic rocks (quartz porphyry) in the Wolsztyn Ridge. In the eastern Wielkopolska, the pattern was more complicated: conglomerates occur around the Wolsztyn Ridge and also in the area of the Poznań–Kalisz tectonic zone. Transport directions were divergent from a hypothetical volcanic centre in the Wyrzeka region (P. H. Karnkowski, 1987c, 1997a). The analysis of clast assemblage within the Polwica Mb. and the lower part of the Książ Wlkp. Fm. proved that transport direction was southeastwards, along the Poznań–Kalisz tectonic zone. The middle stage of the Wielkopolska Subgroup sedimentation is correlated with the Solec Mb. and the middle part of the Książ Wlkp. Fm. Transport directions for this period were approximately the same as for the previous ones. The Late Rotliegend was characterized by sedimentation of conglomerates around the Wolsztyn Ridge, claystones in the central part of basin and sandstones — in the transitional zone between the two last. Aeolian transport also took place and in some areas it prevailed. The nature of the uppermost Rotliegend Group is a subject of controversy. Undoubtedly, the clastic sediments resting below the Kupferschifer are partly reworked in some places by the transgressing Zechstein Sea, but from the lithostratigraphical point of view all clastics below the black marine shales are included into the Rotliegend.

DEPOSITIONAL ENVIRONMENTS IN THE POLISH ROTLIEGEND BASIN

The Rotliegend is characterized by clastic-dominated continental sedimentation. In the Lower Rotliegend (Lower Silesian Subgroup a relatively humid climate) prevailed whereas in the Upper Rotliegend — relatively arid one. These climatic-palaeogeographic frames determined types of sedimentary environments: there were mainly fluvial, aeolian and lacustrine ones. Their extent was also controlled by the boundaries of the Polish Basin and palaeotectonic elements such as the Wolsztyn Ridge. The above mentioned factors divide the development of Rotliegend sedimentary environments into two stages. The first one — corresponding to a relatively humid period and without a distinctly remarked pattern of the Polish Basin — and the second one (Wielkopolska Subgroup), post-volcanic, when the design of the Polish Basin was clearly expressed and climate became more arid than during the previous periods.

Information on sedimentary environments of early stages of the Rotliegend in Poland are barely sufficient. It is known that the Uppermost Carboniferous and Autunian deposits mainly originated within small basins. Good examples of them are the Sudetic basins: the Eastern Fore-Sudetic, Intra-Sudetic and North-Sudetic ones. The Dolsk Fm. sediments drilled by boreholes in the Polish Lowlands are lithologically comparable with the Sudetic basins deposits but due to pre- and post-volcanic erosion they have been preserved only fragmentarily. It seems to be quite probable that in Early Rotliegend time the lakes, developed within local sedimentary basins and occasionally joining together, became a dominant depositional environment. A common occurrence of clay lithofacies evidences the lacustrine environments, controlled by tectonic subsidence in local sedimentary basins.

The simplest recognition of a sedimentary environment type is based on a grain size of deposits. Consequently, conglomerates represent fluvial environments, sandstones — alluvial or aeolian ones but claystones and siltstones — lacustrine conditions. Since the Rotliegend studies from the Polish Basin are based on limited borehole data the methods of well logging, defining lithology of drilled series are so important. There are only several fully cored sections of the Rotliegend successions. According to the author's observations, a proper examination of lithology of Upper Rotliegend rocks is quite easy and it is correct in most cases. Only breccias and conglomerates may be mistaken for volcanic rocks. Most of conglomerate clasts were derived from volcanic rocks so in radiometric logs volcanoclastics have similar characteristics as volcanics. Such a mistake will be immidiately corrected if there is a piece of core to be examined. Described diversity of interpretation is important in distinguishing of coarse clastic units, which — in case of the absence of core material — may be defined as volcanic or pyroclastic rocks.

Sandstones are quite properly distinguished in sections lacking of cores. A definition of their sedimentary environment is more difficult. Without direct observations of a core or without dipmeter data such an interpretation is often ambiguous and it is diffucult to decide what kind of facies the sandstones represent: aeolian or fluvial one. Fortunately, in the seventies many wells, drilled through the Rotliegend of the Polish Basin, had been cored in frequent intervals and later a dipmeter measurements were widely applied.

The simplest interpretation relates to clay lithofacies. Sandy or conglomerate interbeds are easily defined within them, enabling univocal determination of siltstone and claystone packages. No evaporites occur within the Polish Rotliegend Basin — in contrast to the central part of the Southern Permian Basin in Western Europe which are a principle for distinguishing sedimentary cycles and sequences. So it is difficult to compare Polish sections with sequences defined basing upon a model of rapid multiple climatic changes (R. E. Gast, 1991, 1993; P. Gralla, 1988; C. S. Yang, S. D. Nio, 1993).

Sedimentary environments of clay deposits in the central part of the Rotliegend Basin are best defined by a term "playa". It was a perennial lake existing under an arid and semiarid climate, with water discharged by a closed drainage system, and limited mostly to the Polish Basin area. Tectonic and climatic influences controlled the playa extent by invading of dune fields or fluvial sediments onto the playa. It is reflected by intercalations of pure clay series with sand admixtures. These admixtures may result from a distribution of fine material by water flows but they also may be windblown into the playa from adjacent contemporary deserts. Most common stratification types observed in claystones are horizontal lamination, wavy, lenticular and ripple bedding. Structures indicating playa dessication as well as traces of evaporites are almost completely lacking there. When a seasonal emersion of playa surface took place a new water flood completely removed any traces of such ephemeral dessication. Only more significant breaks in lacustrine deposition, resulted from dominant aeolian and fluvial processes, are possible to define and correlate over wider areas. Within the playa sedimentation area in the Polish Basin, two fluvial horizons corresponding to the Polwica Conglomerates Member and the Solec Conglomerates Member, and a single aeolian sandstone horizon are distinguished. The latter may be informally named the Siekierki Sandstones Member, according to the Siekierki Sandstones Formation, composed mostly of aeolian sandstones.

Clay deposits of the Rotliegend Basin center are commonly bordered with sandstones. Such a regional regularity of distribution of both major Rotliegend lithofacies indicates that clastic material was transported from the basin margins towards its center. This type of selection is best realized in a fluvial environment when clastics are transported by rivers. Sedimentological analyses of sandy profiles also inform that some sections show fluvial features, but in many cases sedimentary structures and facies associations such as dunes and interdune series are observed, confirming their aeolian origin (comp. K. W. Glennie, 1970, 1972, 1984b; M. E. Brookfield, 1977; S. G. Fryberger *et al.*, 1979, 1983; G. Kocurek, 1981, 1988). Aeolian and fluvial environments are distinguishable if core or dipmeter data are available but in other cases such an interpretation is doubtful. Dipmeter results are especially useful. They continuously record variations in a sedimentary dip and a primary dip direction of sedimentary units, helping to reconstruct directions of aeolian transport. Basing on dipmeter data the author has stated that dominant wind directions in an initial phase of aeolian deposition in the Polish Rotliegend Basin were from the south and southwest and at the end of aeolian period winds blew from the east and southeast. Such a direction change possibly resulted from a climate evolution at that time.

Fluvial processes were the basic transport type of material into the Rotliegend Basin and also within it. Variations of hydrological regime were typical of an arid and hot climate. Under such conditions only sporadic seasonal rainfalls supplied water to the fluvial system. Naturally, palaeotectonic processes modified the drainage system but its general pattern became unchanged during the whole Late Rotliegend (Wielkopolska Subgroup).

Sandy material was derived from the eroded areas surrounding the Rotliegend Basin but frequently breccias and conglomerates are found on the basin margins or elevated palaeotectonic structures, e.g. the Wolsztyn Ridge. Coarse material is also noticed in sections distal from source areas. These coarse lithofacies were distinguished as the Książ Wlkp. Conglomerate Formation, Polwica Conglomerate Member and Solec Conglomerate Member. All these sediments are fluvial, showing features of short transport. They are best documented by breccias with low sorting and clast roundness and with clay-sandy matrix, interpreted as mud flows deposits (P. H. Karnkowski, 1986a, 1987c). Sandstone or siltstone series are also found within the coarse clastics. Such a lithological variability combined with sedimentological observations enabled grouping of these rocks into several assemblages, representing an alluvial fan environment. Data from many boreholes well cored in the Wielkopolska region allowed to recognize the extent and development of suspected fans (P. H. Karnkowski, 1997b). On the northern side of the Wolsztyn Ridge these coarse clastics are visible not far than 15 km from the ridge. On the distal part of alluvial fans, conglomerates very frequently interfinger with sandy facies and a thickness of sandy interbeds increases outside the ridge. These regularities enabled estimation of a height difference between distal margin of fan and its backland. In many papers (W. B. Bull, 1964; R. J. Steel, 1974; C. R. Twidale, 1978, 1979) the average fan surface inclination is estimated at 1–2°. In the piedmont zones this value is higher, up to 10 or 25 degrees but these zones are relatively narrow and constitute a minimum percent of total fan surface. With inclination of one degree and fan length of 15 km the estimated height difference is about 250 m whereas for two degrees of inclination — 500 m. Assuming this second value one should be conscious that such parameters are extremal existing for a short time, because only single fans extended so far. These calculations suggest that a maximum relative height of the Wolsztyn Ridge was about 100–400 m and it seemed to become more or less constant for a longer time. Accumulation of clastic deposits and decreasing surface inclination of the ridge foreland were accompanied by the ridge uplift. This process was discontinuous, with periods of a higher tectonic activity which uplifted the ridge and/or dropped sedimentary basin bottom. During these episodes also tectonic grabens probably formed, like within the Poznań–Kalisz or Czaplinek tectonic zones. The arising of such grabens favoured a distribution of clastic material from source areas and — in a case of higher subsidence within grabens — trapping of coarse clastics.

The top part of the Rotliegend profile is often called "Weissliegendes" due to its frequent grey and white colour. The nature of the uppermost part of the Rotliegend Group and the question of a character of the Zechstein transgression are the subject of a significant controversy. In the case of the area of southern Poland this problem was discussed in extensive studies by T. Jerzykiewicz *et al.* (1976), W. Nemec, S. Porębski (1977a, b, 1981), J. K. Błaszczyk (1981) and in the Wielkopolska area by P. H. Karnkowski (1986a, 1995a). A character of transgression and earliest stages of Zechstein deposition supply some information on sedimentary environments at the end of the Rotliegend.

The Wielkopolska region, comprising the more central part of the basin, exhibits the best predisposition to show a regional palaeogeographic image at the end of Rotliegend time and at the beginning of the Zechstein transgression. In the Wielkopolska area, the upper part of the Rotliegend succesion is represented by sediments which may be assigned to three facies. Breccias, conglomerates and conglomeratic sandstones are the lithological types predominating around the Wolsztyn Ridge, claystones and siltstones predominate in the Obrzycko area, and sandstones in the remaining areas. Medium- and coarse-clastic sediments display as a rule a change in colour from red to white or grey (Weissliegend) towards the base of the Kupferschiefer or Zechstein Limestone whereas mudstones remain brown-red.

Coarse-clastic facies undoubtedly represent fluvial sediments formed by a short-distance rapid transport. This is best evidenced by breccias characterized by poor sorting and clay-sandy cement. Such breccias may be interpreted as mud flows. The Wolsztyn Ridge acted as a source area, around which fanglomerates were originated in a zone of alluvial fans, partly as a result of seasonal torrential rains. Sediments of claystone facies represent a lacustrine environment under conditions of a warm and dry climate (playa). Sandstones occurring in the areas extending between facies of claystones and conglomerates display features indicative of an aeolian sedimentary environment. It may be assumed that dunes

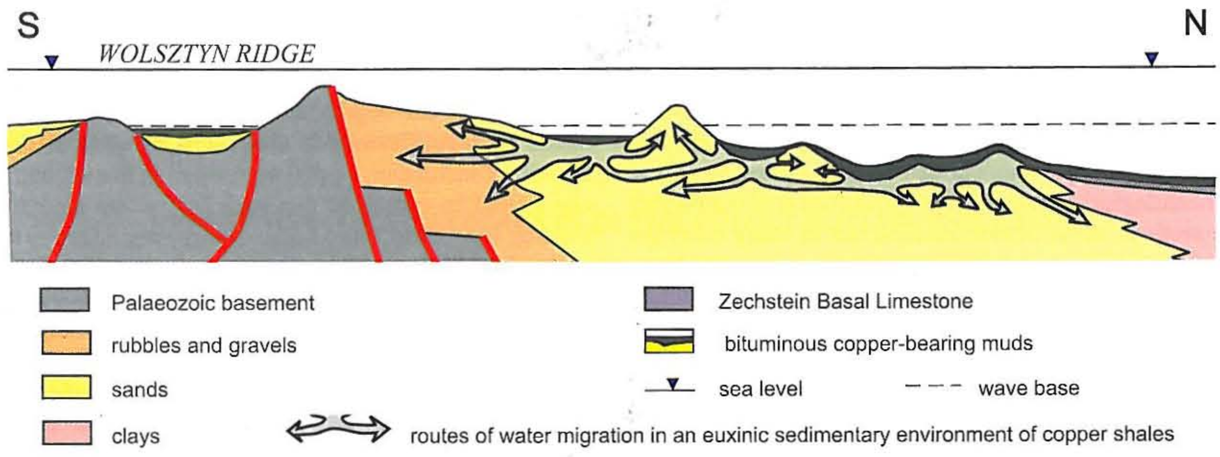

Fig. 13. Palaeofacies cross-section sketch for the Kupferschiefer depositional period. Not to scale.

from a few to about a dozen meters in height were predominant in the areas of sandy facies. Direct studies on the Weissliegend deposits in copper mines in the Lubin area confirm the hypothesis of a palaeomorphological differentiation of the sandy facies at the end of Rotliegend time (J. K. Błaszczyk, 1981).

At the end of Rotliegend time, the Wielkopolska area was affected by the transgression of the Zechstein sea, as was the whole European Permian Basin. Sedimentological studies on the Kupferschiefer and Zechstein Limestone have shown that the invading sea attained its maximum depth during the initial phase of the Werra basin development (T. M. Peryt, 1978; T. M. Peryt, H. Ważny, 1978). Increase in water depth was controlled by the relief of bedrock. In several places the basin was shallower than the wave base depth i.e. the level beneath which an exchange of waters poor in oxygen and oxidized surface does not exist (Fig. 13). Decay of organic compounds and reduction of sulphides by bacteria resulted in the origin of copper shales in an anoxic environment. The Kupferschiefer directly lies on clastic sediments which suggest increase in water depth, i.e. a rapid transgression.

A change in colour of coarse clastic sediments and sandstones from red to white takes place in the upper part of the section, resulting in the origin of the Weissliegend horizon. Such a process is absent in the case of clay facies, being red-brown up to their contact with carbonates. Moreover, thin mudstone intercalations found within the Weissliegend deposits developed in coarse clastic facies retain their red-brown colour. Therefore, it may be assumed that the red colour was primary and omnipresent at the time of sedimentation of Rotliegend deposits (P. H. Karnkowski, 1986a).

The Zechstein transgression made possible the onset of reducing conditions in an anaerobic sedimentary environment of bituminous copper shales, impeding precipitation of iron oxides. Percolating marine bottom waters with negative potential Eh (Fig. 13) began to reduce iron trivalent to bivalent. The percolation was selective, depending on porosity and permeability of individual layers, and it was proceeding both in the vertical and horizontal direction.

The interpretation presented above shows that the author belongs to the adherents of the idea of postdepositional decolouring of red sediments. The author suggests that along

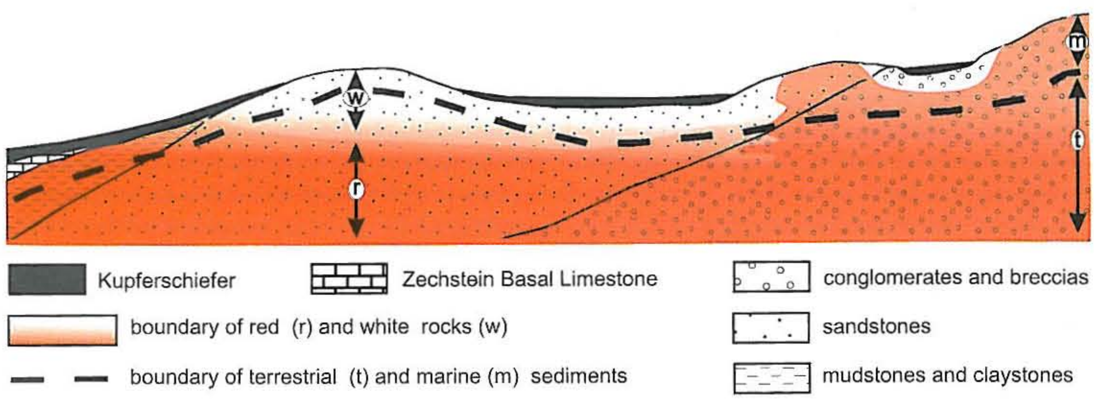

Fig. 14. Relationships between terrestrial and marine environments versus red and white coloured rocks in the uppermost part of the Wielkopolska Subgroup.

with the onset of Zechstein copper shales sedimentation, conditions have changed to highly reducing. Moreover, both concentration of H_2S and content of oxigenic matter were sufficiently high at that time to make possible reduction of such large amounts of hematite in iron coatings of sand grains. Therefore, there still remains the question of depth to which reducing solutions could percolate. Percolation, or more precisely, a mixing of oxidized marine and reducing waters was related to the porosity and permeability of rocks. It was negligible in clay rocks which explains why they were unaffected by decolouring processes. This is especially visible in the case when red-coloured claystone intercalations are found within the Weissliegend deposits. In sandstones and conglomerates, the effectiveness of decolouring processes decreased with depth, which is reflected by a gradual change of colour from white to red (P. H. Karnkowski, 1986a). Differences in thickness of the decoloured zone and thickness of the Kupferschiefer shales also appear to be related to the morphology of the top surface of Rotliegend deposits (Fig. 14). Direct examples of this phenomenon may be found in Polish copper mines (J. K. Błaszczyk, 1981).

The opinion presented in this paper does not support the hypothesis of postdepositional colouring of the Rotliegend deposits but rather an opposite view, i.e. that assumed decolouring of strata is consistent with the proposed model of rapid progress of the Zechstein transgression. The uppermost part of the Rotliegend Group consists of continental and clastic marine deposits. Part of them may be decoloured. Relationship between marine and continental deposits and between red and white ones is shown in Fig. 14. The top surface of the Rotliegend Group is the principal geological subject of natural gas investigation in the Polish Permian Basin. Some of the gas traps could be connected with the palaeorelief of flooded dunes.

MANIFESTATION OF CLIMATE IN THE POLISH ROTLIEGEND BASIN

The climate of Rotliegend time is commonly considered as hot and arid, especially contrasting with the Carboniferous climate, favourable for development of rich vegetation producing coal seams. So, the transition from Carboniferous to Permian is manifested by significant climatic changes, distinctly influencing the sedimentary conditions within the Rotliegend basins. What factors of such changes are an important problem? The first responsible factor was a foundation of the Pangea supercontinent, drifting between both poles. This supercontinent was surrounded by only a single global ocean Panthalassa (C. R. Scotese, W. S. McKerrow, 1990). This unique global pattern of continental and marine areas was one of the most important reasons of such a worldwide occurrence of continental climate over very vast contemporary terrestrial areas.

The second reason for a climatic change during the Late Carboniferous–Early Permian period was a decline of huge glaciations known from the Gondwana area. The reasons of such giant glaciations still become hypothetical but these phenomena have been unquestionably recorded and influenced global climatic variations. In many cases mechanisms of Late Carboniferous sedimentation are related to an effect of the giant Gondwana glaciations. It was best observed on shelf areas, where precisely recorded eustatic sea level oscillations may have resulted from water volume variations in oceans due to expansions or declines of continental ice sheets. Geological data indicate that such phenomena slowly deceased during the Permian and finaly disappeared before the end of the Permian (J. C. Crowell, 1995).

The Polish Basin, in a wider sense — the basins of Central and Western Europe, was located during the Carboniferous in a circumequatorial position. Lithosphere plates in this zone moved northwards. Continental plates of Gondwana and Laurasia were displaced northwards and a collision of both continents became a crash of more quickly moving Gondwanaland with Laurasia. The Variscides, developed due to this process, formed the largest mountain belt in global history. The process of drifting of lithosphere plates, consolidated them into a single Pangea supercontinent, and continued later, after their collision, involving the displacement of Central and Western Europe areas from the equatorial into the subequatorial zones during the Late Carboniferous and Permian. Stable global distribution of climatic zones determined by astronomic factors influenced decisively sedimentary conditions according to the geographical position of individual areas. At the moment when Central and Western Europe began to drift towards the subequatorial zone due to a northward migration of lihosphere plates they were subjected to climatic conditions characteristic of such latitudes, i.e. desert environments. An additional factor, favouring increased influence of continental climate, was the giant extent of the single Pangea supercontinent. This specific distribution of marine and land areas (a single supercontinent and single ocean) during the Late Carboniferous and Permian is still an important problem for climatologists and geologists, who attempt to reconstruct — using computer simulations — contemporary patterns of winds, ocean currents, rain and snow falls and temperature distribution according to the seasons of the year and area position (J. E. Kutzbach, R. G. Gallimore, 1989; W. T. Hyde *et al.*, 1990; E. J. Barron, P. J. Fawcett, 1995). Results of modelling indicate that most of the contemporary continental area was characterized by arid climate in the size of the Pangea supercontinent and its position according to the equatorial and both poles determined climatic parameters.

A geological evidence of climatic conditions and their variations are characteristic deposits defined only for climatic zones, such as evaporites and aeolian sediments. Their occurrence in the Rotliegend profile, especially in its upper part, univocally document arid desert continental climate. Between the Late Carboniferous and Permian it is possible to find more geological data, illustrating varied climatic conditions resulting in accumulation of coal-bearing formations as well as desert sedimentation.

In the Early Rotliegend (Autunian) red colour of sediments evidences a climate drying. Such colour never appears rapidly but at first thin red intercalations within grey and black sediments are commonly noticed and they successively increase in thickness upward a section up to a final dominance of redish colour. The second proof are the results of palynological analyses indicating a slow decline of humid-preferable flora and domination of more arid plant species (J. Jerzykiewicz, 1975). Such climatic changes (Westphalian –Stephanian) took place earlier in the northern part of the Polish Basin (Pomerania area) and later (Stephanian–Autunian) in its southern region. Similar analogies are known from Western Europe, where in England the first red-coloured deposits are visible in Westphalian rocks (J. D. Collinson *et al.,*, 1993). In the Central Massif a phytogenic accumulation still continued in the Autunian (e.g. the Autunian Basin – P. Marteau, R. Feys, 1989). This diachroneity of red colour occurrence within deposits according to their geographical location could result from a gradual displacement of Central and Western Europe northwards, e.g. towards the equatorial zone. Such a process was slow and gradual. In Poland the Lower Rotliegend was characterized by a humid and warm climate favouring oxidation of iron compounds and red-brown colouring of sediments. Gradual climate drying was probably accompanied by the disappearance of Carboniferous flora, which could not adapt to new more arid climatic conditions although, it evolved slowly and gradually. Deposits accumulated at that time were characterized by brownish colour and high content of pelites. A good example are the Dolsk Fm. deposits changing their colour gradually upward from grey and black to brownish. They are dominated by claystone and siltstone interbeds. The coarse sediments observed are well sorted and contain a high amount of clay matrix.

During the volcanic episode some sedimentological evidences are also visible suggesting an occurrence of large amount of atmospheric water directly in volcanic and post-volcanic processes (low hydrothermal transformations) and in accumulations of volcanoclastics from eroded lava sheets.

The significant moment in the history of Rotliegend climate evolution in the Polish Basin was the development of aeolian sediments within the basin center (P. H. Karnkowski, 1994; H. Kiersnowski, 1997a). From that time until the Zechstein transgression the results of continuous aeolian deposition are observed in some places. The onset of aeolian deposition in the Polish Rotliegend Basin may be correlated

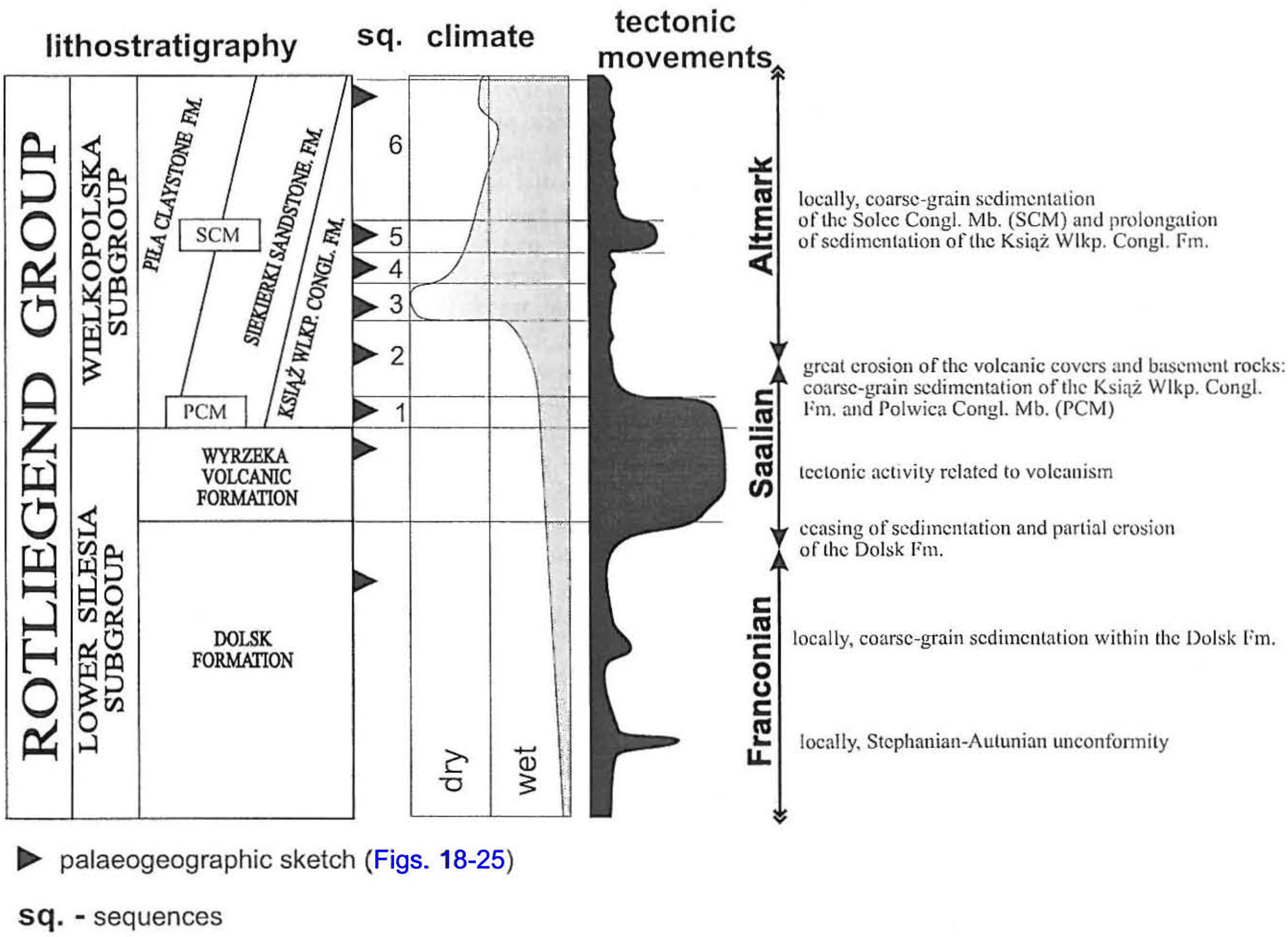

Fig. 15. Relationship between climatic and tectonic events during Rotliegend time in the Polish Permian Basin.

with a development of evaporites in the central part of the Southern Permian Basin. There are no evaporites in the Polish Rotliegend Basin and more detailed correlation of Polish Rotliegend units with evaporitic horizons of the German Basin seems almost impossible. After a significant arid episode, distinctly reflected in profiles of the central part of the Polish Basin, a little humidity increase took place, manifested itself by more frequent fluvial and alluvial deposits. But it was a subtle climatic oscillation which only limited aeolian sedimentation. A perennial playa lake occupied the basin center during the whole Rotliegend, without any evidences of dessication; only several horizons with a higher content of anhydrite nodules are noticed there. Climatic fluctuations, illustrated on the chart (Fig. 15), indicate the significant differences between the Lower and Upper Rotliegend, and show a moment of distinct drying of climate and beginning of aeolian deposition together with relatively small climatic oscillations during the Upper Rotliegend. Several flood horizons are recognized in the uppermost part of the Rotliegend profile around the Wolsztyn Ridge. This subtle humidity increase is reflected by a small peak on a climatic curve but it is not considered to be a sequence because much more similar episodes had earlier taken place. Their deposits were eroded and only the youngest ones have been preserved. Concluding, the significant humidity increase at the end of the Rotliegend seems groundless because the termination of Rotliegend sedimentation corresponds to the maximum extent of aeolian accumulation.

ROTLIEGEND TECTONIC MOVEMENTS IN THE POLISH BASIN

During the eighties and nineties in Polish publications related to Rotliegend palaeogeography, palaeotectonics and cyclicity the following terms have been used: the Saalian phase, main subphase of Saalian phase, early Saalian phase, late Saalian phase, Saalian diastrophism, movements of Saalian phase (J. Sokołowski, 1967; J. Kłapciński, 1971; J. Pokorski, 1976a, 1981b; P. H. Karnkowski, 1977, 1991; H. Kiersnowski, 1983, 1995; J. Tomasik, 1988). Application of these names resulted from a geological tradition of the frequent usage of the term "Saalian phase". In the Saale Basin a discordance within the Rotliegend sediments, regarded by H. Stille (1924) as a product of an orogenic phase which occurred before the Upper Rotliegend (*voroberrotliegende Gebirgsbildung*) and called by him the "Saalian phase" is observed. However, later stratigraphic studies have evidenced that between the Hornburg and Mansfeld Formations there is a significant stratigraphic gap, representing the Stephanian C and a part of the Lower Permian.

Another opinion is represented by H. Haubold, G. Katzung (1975), who reconsidered the Hornburg Fm. and included it to the Autunian period. To retain the position of the Saalian phase between the Autunian and Saxonian they displaced it from the bottom to the top of the Hornburg Fm. But such a procedure is inconsistent with the definition of H. Stille, after whom the Saalian phase must be placed between the Hornburg and Mansfeld Fms. As it was earlier mentioned, a large stratigraphic gap exists between both these formations. At that time in other places Lower Rotliegend sediments or volcanic rocks, up to 1000 m thick, were accumulated, e.g. in the Thuringian Forest. Several formations were formed, including volcanics and numerous discordances. Movements responsible for such phenomena were locally so intensive that sometimes the Oberhof Formation may directly overlie the Gehren Formation (H. Lützner, 1987). In other areas, e.g. the Saar-Nahe Depression, almost continuous tectonic impulses, expressed by block tectonics, controlling development of sedimentation and deposit thickness are observed (H. Falke, 1974).

The examples presented above indicate that the Saalian phase could not be considered to be widespread, short-lasting and synchronous over the whole area under discussion. The discordancy described by H. Stille could not be identified (as well as other discordances from the Saale Basin – see H. Lützner, 1987, p. 165) with the boundary between the Autunian and Saxonian or with the boundary between the Lower and Upper Rotliegend. In such a case it is better to speak of the Saalian movements (H. Falke, 1972, 1974, 1976; G. Katzung, 1988; H. Kozur, 1988) but a question appears if these movements should be extended into all Rotliegend time.

G. Katzung (1988) postulated an occurrence of the so called "Franconian movements" in the basal part of the Rotliegend succession. He is of the opinion that their activity started from the Stephanian C in the Bohemian Massiff area; from latest Stephanian in the Saxo-Thuringian zone and from the beginning of the Autunian in the Rheno-Hercynian zone. In such a scheme the intra-Stephanian phase, recognized by J. B. Miecznik (1981) in the Intra-Sudetic Basin may belong to the Franconian movements. Local tectonic discordances from the Laskowice Graben, dated at the turn of the Carboniferous and Permian (H. Kiersnowski, 1983) or similar ones from the Wielkopolska area (P. H. Karnkowski, K. Rdzanek, 1982) may also be related to these movements.

According to G. Katzung (1988) the Franconian movements preceded the Variscian volcanism. They were followed by the Saalian movements, initiated in the Late Autunian. The second maximum of Variscian subsequent volcanism was related to these movements (G. Katzung, 1988) and a peak of the Saalian activity took place at the turn of the Autunian and Saxonian.

The discussion on tectonic movements in Rotliegend time in Poland is based on the division of clastic-volcanic sediments of the Uppermost Carboniferous and Lower Permian into diastrophic-sedimentary cycles. A principle for a distinction of such cycles are mostly lithological variations, gradational changes in monofacial profiles or local angular discordances. This principle is quite simple but its application by other authors in the same areas and to the same materials gives different results (comp. J. Sokołowski, 1967; J. Kłapciński, 1971; J. Pokorski, 1976a, 1981b; P. H. Karnkowski, 1977, 1991; H. Kiersnowski, 1983, 1995; J. Milewicz, 1985; H. Kiersnowski, A. Maliszewska, 1985; J. Tomasik, 1988).

These differences result from a nature of tectonic movements in the Rotliegend. These movements lowered or uplifted basement blocks, initiating erosion of elevated structures and deposition within depressions. Authonomic behaviour of individual blocks determined a large thickness and facies differentiation of the Rotliegend sediments.

The Wielkopolska region, in which the Rotliegend succession is well recognized by numerous boreholes, supplies good examples illustrating the nature of the discussed tectonic movements. Previous studies in the Wielkopolska area defined the age of the major Variscan folding as younger than Namurian. J. Oberc (1987) referred them to the late Sudetic phase but A. M. Żelichowski (1964a) — to the Erzgebirge phase. At that time the Lower Carboniferous deposits of the Culm facies and the older ones were strongly folded and open marine sedimentation finished. During the terrigenous period of the Late Carboniferous, clastic facies grey and black in colour (lower part of the Dolsk Fm.) dominated. These deposits are sometimes deformed and in core sections their inclination at about 25 degrees is observed but in other places they lie almost horizontally on an older basement (P. H. Karnkowski, K. Rdzanek, 1982). Because the grey deposits are dated palynologically (*op. cit.*) the supposed age of the deformation is estimated at the turn of Carboniferous and Permian (intra-Stephanian phase?, Franconian movements?). Red sediments without any biostratigraphic evidences occur above grey deposits up to a contact with the Zechstein series. All tectonic and stratigraphic distinctions were established by a comparison with better recognized areas (Sudetic basins and Germany area).

It seems that the intra-Stephanian phase influenced neither the facies character nor deposits thickness, and clay sediments red-brown in colour successively developed. They were probably widespread in the area studied and attained a significant thickness. Despite such a common occurrence of clay facies in some profiles, the conglomerate interbeds resulting from a distinct tectonic activity are visible. They are not common and seem to be related to some tectonic zones. Significant erosion of the Dolsk Fm. that occurred before the beginning of volcanism, suggests radical palaeogeographic modifications.

Volcanic rocks overlie various deposits of the Dolsk Fm., the Lower Carboniferous basement or older Palaeozoic series. Basing on the results of lithological studies of the basal part of the Książ Wlkp. Fm. in western Wielkopolska it may be supposed that the Wolsztyn Ridge first time manifested itself as an elevated structure probably after the termination of volcanic activity. Its northern margin is demarked by the Dolsk fault systems. They favoured movements of basement blocks and, consequently, more intensive erosion of uplifted elements. These faults also enabled lava outflows and development of volcanoes. Other faults, generated or renewed at that time in western Wielkopolska, became paths for numerous acid lava extrusions. These data seem to confirm a significant tectonic activity at the end of the Dolsk Fm. deposition, which manifested itself by intensive volcanic phenomena.

The next increase in tectonic activity took place during a post-volcanic period, dominated by intensive erosion and sedimentation of coarse clastics. This tectonic episode is compared by J. Pokorski (1978b) with the Saalian phase. Large thickness, poor sorting and clast roundness as well as a distinct extent of both the Książ Wlkp. Fm. and Polwica Conglomerate Member clearly evidence a participation of a tectonic factor in the orgin of horsts, which later discharged clastic material into adjacent grabens.

Similar intensive tectonic episodes manifested themselves also during deposition of the middle part of the Wielkopolska Subgroup, producing the Solec Conglomerate Member (P. H. Karnkowski, 1977, 1987a, 1994).

The tectonic events described, except those of the main phase of Variscan folding, have one feature in common: they have never been recognized in the whole Wielkopolska area and they generally related to specific tectonic zones, such as the Dolsk or Poznań–Kalisz fault zones. It seems a rule that during the Rotliegend only tectonically predisposed zones controlled a facies and thickness pattern. In the areas located outside these zones there is no evidence for a tectonic activity. Synsedimentary faults, inducing a distinct thickness differentiation within individual formations, indirectly confirm a significant role of tectonics during Rotliegend time. The **Figure 15** includes all tectonic activity evidences noticed in the Rotliegend succession within the Polish Rotliegend Basin.

The examples from Germany and Poland indicate that much more tectonic impulses took place during the Rotliegend than it was stated in the previous studies. So in such a case it is difficult to use the term "Saalian phase". But referring to older tradition of Polish researchers who apply names connected with the Saalian phase to describe tectonic movements during the Rotliegend it is better to speak about Saalian movements (early, main and late ones).

It is also reasonable to propose another version, referred to opinions of some German scientists (G. Katzung, 1988; N. Hoffmann, 1990):

1. The so-called "Saalian phase", distinguished in Poland, may be assumed as an evidence of the last impulses of Saalian tectonic movements. Their beginning should be located at the end of the deposition of sub-volcanic series.

2. Older tectonic movements, including the intra-Stephanian phase, tectonic movements of a similar character as in the Laskowice Graben or in Wielkopolska area as well as a factor of cyclicity of clastic sedimentation during the Early Rotliegend — may be named the Franconian movements.

3. Referring to the East-German proposal (N. Hoffmann *et al.*, 1989) the Late Rotliegend tectonic movements may be classified as the Altmark movements.

In the case of the Rotliegend profiles from Poland, characterized by rare or absent biostratigraphic datings, the correlation of local tectonic events on an interregional scale is difficult. As it was demonstrated above, evidences of tectonic movements during the Rotliegend were mainly related to particularly active tectonic zones (grabens, half-grabens, fault zones), and their influence on facies and thickness characteristics as well as on generation of local discordances can not be observed at some distance from such structures.