The Polish Permo-Mesozoic Rift Basin

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ABSTRACT

Evolution of the Polish Permo-Mesozoic Rift Basin commenced during the Permian (late Rotliegend) in northern and central Poland, and presumably not earlier than during the Jurassic further southeast. It was terminated during the Palaeocene with the inversion of the axial rift zone, giving rise to the Mid-Polish Anticlinorium that extends from the Baltic Sea to the Carpathian front in south-eastern Poland and the western Ukraine, where it plunges beneath the Carpathian nappes. The multistage evolution of the Polish Rift Basin reveals several phases of extension, the last during the Albian. An asymmetrical mode of evolution of the Polish Rift Basin is evidenced by its stratigraphic and structural asymmetry, as well as by the decrease of crustal thicknesses, and higher heat flow, recorded southwest of the zone of strongest syn-rift subsidence.

RÉSUMÉ

Le bassin de rift permo-mésozoïque polonais.

L'évolution du bassin de rift permo-mésozoïque polonais a débuté durant le Permien (Rotliegend supérieur) en Pologne centrale et septentrionale. Plus au sud-est, elle n'a probablement pas commencé avant le Jurassique. Elle s'est terminée durant le Paléocène avec l'inversion de la zone de rift axiale, donnant la surrection de l'anticlinorium Médio-Polonais qui s'étend de la Mer baltique au front des Carpates dans le sud-est de la Pologne et l'ouest de l'Ukraine, où il plonge sous les nappes carpatiques. L'évolution polyphasée du bassin de rift polonais montre plusieurs phases d'extension, la dernière durant l'Albien. Un mode asymétrique d'évolution du bassin de rift polonais est mis en évidence par son asymétrie stratigraphique et structurale, aussi bien que par la diminution des épaisseurs crustales et par un flux thermique supérieur, enregistrés au sud-ouest de la zone de subsidence syn-rift la plus élevée.

INTRODUCTION

The Central European Basin, also referred as the Northwest European Basin (ZIEGLER, 1990), extends from North Germany into northern and central Poland. The concept of the Danish-Polish Furrow as a broad zone, with a NW-SE trend and converging dips of Permo-Mesozoic deposits, was introduced by POŻARYSKI (1957). Because of the individuality of the Polish part of this furrow, it is

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currently referred to as the Polish (or Mid-Polish) Trough. At first, this term was applied to regions in northern and central Poland, but it could be demonstrated that southeastern Poland was also included in this trough (KUTEK & GŁAZEK, 1972). The longitudinal extent of the Polish Trough is reflected by the Mid-Polish Anticlinorium (Fig. 1), a product of the Laramide inversion of this trough.

Only the zone now occupied by the Mid-Polish Anticlinorium, or a zone but slightly broader, was interpreted by several authors as a rift, or aulacogen (e.g., KUTEK & GŁAZEK, 1972; POŻARYSKI, 1977). This zone, which was usually the site of strongest subsidence within the much broader Polish Permo-Mezozoic Basin during the Permian and Mesozoic, is referred to in this paper as the Mid-Polish Furrow (MPF).

A fairly large number of deep refraction-seismic profiles, but not of reflection-seismic profiles, is available in Poland. Much information from boreholes is available in some regions, but the interpretations of faults, especially of their geometry, are hindered by the paucity of hitherto published, commercial high-quality reflection-seismic profiles. This is one of the reasons why faults are not indicated in several published palaeotectonic maps and cross-sections, and also in those reproduced herein.

PRESENT TECTONIC PATTERN

Most of the tectonic units revealed by the pre-Cainozoic geological map of Poland (Fig. 1) are chiefly the result of the Laramide inversion of the Polish Permo-Mesozoic Basin, and to some degree also of earlier Late Cretaceous tectonic events. The inversion of the axial zone of the Polish Basin (the Mid-Polish Furrow) gave rise to the Mid-Polish Anticlinorium (MPA), from which Upper Cretaceous sediments were totally removed by erosion. As a consequence of the uplift of this anticlinorium, two flanking depressions were individualized, notably the Border Depression to the northeast, and the Szczecin-Łódź-Miechów Depression to the southwest. The Border Depression includes the Pomeranian (PD), Warsaw (WD), Lublin (LbD) and Lviv (LD) depressions. The southwestern depression is composed of the Szczecin (SD), Łódź (ŁD) and Miechów (MD) depressions. Upper Cretaceous deposits, ranging up to the Maastrichtian, are preserved in the Szczecin-Łódź-Miechów Depression and in the Border Depression. The latter also contains some lower Palaeocene sediments (not indicated in Fig. 1), displaying a NW-SE trend, and thus also the Laramide tectonic pattern.

The Cracow-Silesian Monocline (CSM) and the Fore-Sudetic Monocline (FSM) are situated further southwest. They can be traced as belts of Jurassic, Triassic and Permian deposits in outcrop, and in the subsurface beneath Tertiary sediments. No Cretaceous deposits occur within these monoclines, except for some relics of Upper Cretaceous sediments found in down-faulted position within the Fore-Sudetic Monocline. These sediments, resting unconformably on Triassic deposits, testify to the presence of a widespread base-Cenomanian unconformity.

Three fairly small depressions, containing Upper Cretaceous deposits, occur in south-western Poland. These are the Opole Depression (OD), the North Sudetic Depression (NSD), and the Intrasudetic Depression (ISD), that extends into the Nysa Graben (NG). Upper Cretaceous deposits range in age from Cenomanian to Coniacian in the Opole and Intrasudetic depressions, and from Cenomanian to Santonian in the North Sudetic Depression.

Much of the Polish Platform is covered by Tertiary sediments, resting unconformably on earlier tectonic units (Fig. 2A). In northern and central Poland, a fairly thin Tertiary cover includes middle and upper Eocene, Oligocene, Miocene and Pliocene sediments. The Holy Cross Mountains (HCM) can be regarded as a large portion of the Mid-Polish Anticlinorium that is not covered by Tertiary sediments (Figs 1, 2A).

Most of the Polish portion of the Carpathians is formed by the flysch nappes of the Outer Carpathians. A typical peripheral foreland basin, the Carpathian Foredeep (CF), developed contemporaneously with the Miocene nappe emplacement (Figs 1, 2A). North of the Carpathian front, the

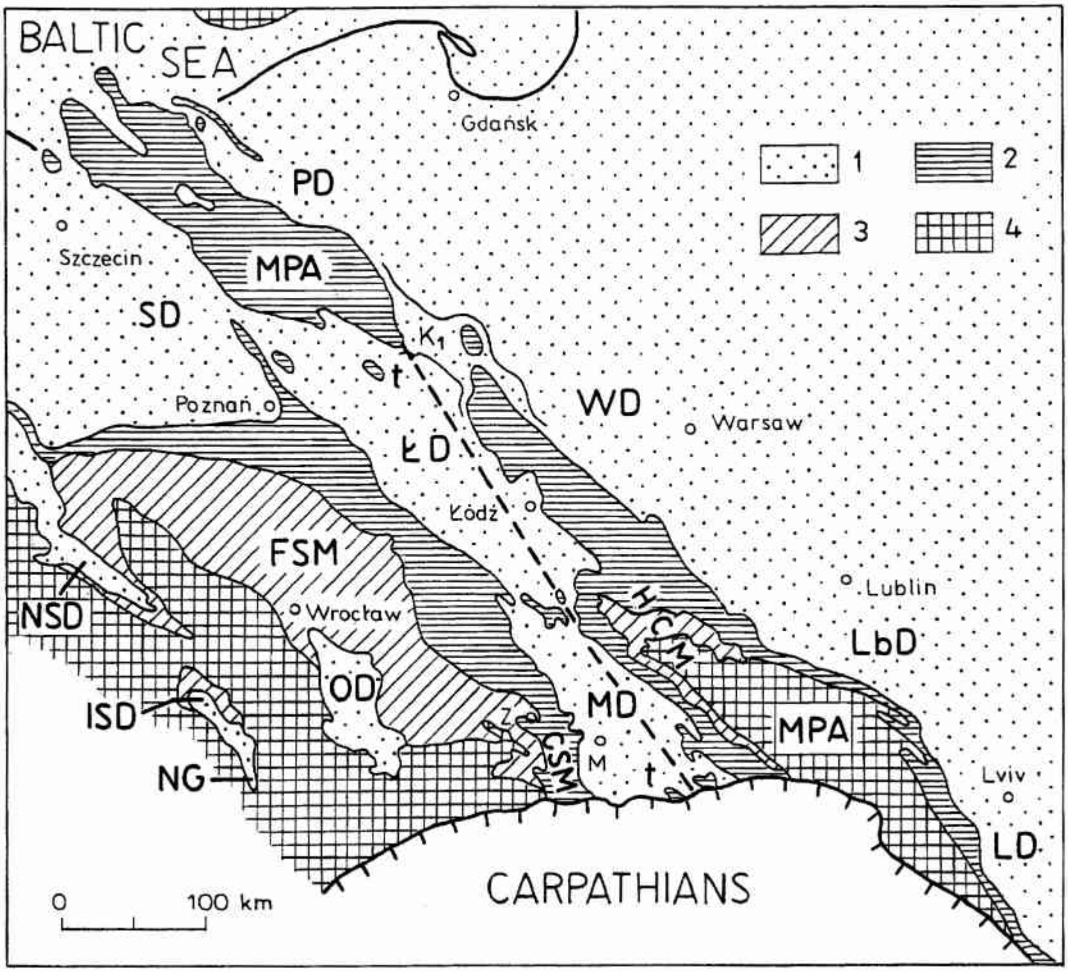

FIG. 1.— Geological map of Poland and adjoining areas, without Cainozoic deposits (after POŻARYSKI, 1979, strongly simplified). **1**, Cretaceous (K_1, Lower Cretaceous); **2**, Jurassic; **3**, Triassic and Permian; **4**, pre-Permian rocks. Tectonic units: PD, WD, LbD and LD, Pomeranian, Warsaw, Lublin and Lviv depressions; MPA, Mid-Polish Anticlinorium; SD, ŁD, MD, Szczecin, Łódź and Miechów depressions; FSM, Fore-Sudetic Monocline; CSM, Cracow-Silesian Monocline; OD, Opole Depression; NSD, North Sudetic Depression; ISD, Intrasudetic Depression; NG, Nysa Graben; M, Miechów; t-t, location of cross-sections of figure 3.

FIG. 1.— Carte géologique de la Pologne et des régions voisines, sans les dépôts cénozoïques (d'après POŻARYSKI, 1979, fortement simplifié). 1, Crétacé (K_1, Crétacé inférieur) ; 2, Jurassique ; 3, Permien et Trias ; 4, roches pré-permiennes. Unités tectoniques : PD, WD, LbD et LD, dépressions Poméranienne, de Varsovie, de Lublin et de Lviv ; MPA, anticlinorium Médio-Polonais ; SD, ŁD, MD, dépressions de Szczecin, Łódź et Miechów ; FSM, monoclinal avant-Sudète ; CSM, monoclinal de Cracovie-Silésie ; OD, dépression Opole ; NSD, dépression nord-Sudète ; ISD, dépression intra-sudète ; NG, Graben de Nysa. M, Miechów ; t-t, localisation des coupes de la figure 3.

basin is filled with Badenian and Sarmatian sediments, but older Miocene sediments are involved in, or overridden by, the nappe system.

Outside the Carpathians, Quaternary sediments are widespread in Poland. Hence, extensive outcrops of Permo-Mesozoic deposits can only be found in the belt of the South-Central Polish Uplands, roughly corresponding to the Lublin Depression, the Holy Cross Mountains, the Miechów Depression and the Cracow-Silesian Monocline. Further north, in the Polish Lowland, the Permo-Mesozoic strata are almost totally hidden beneath Tertiary and/or Quaternary sediments.

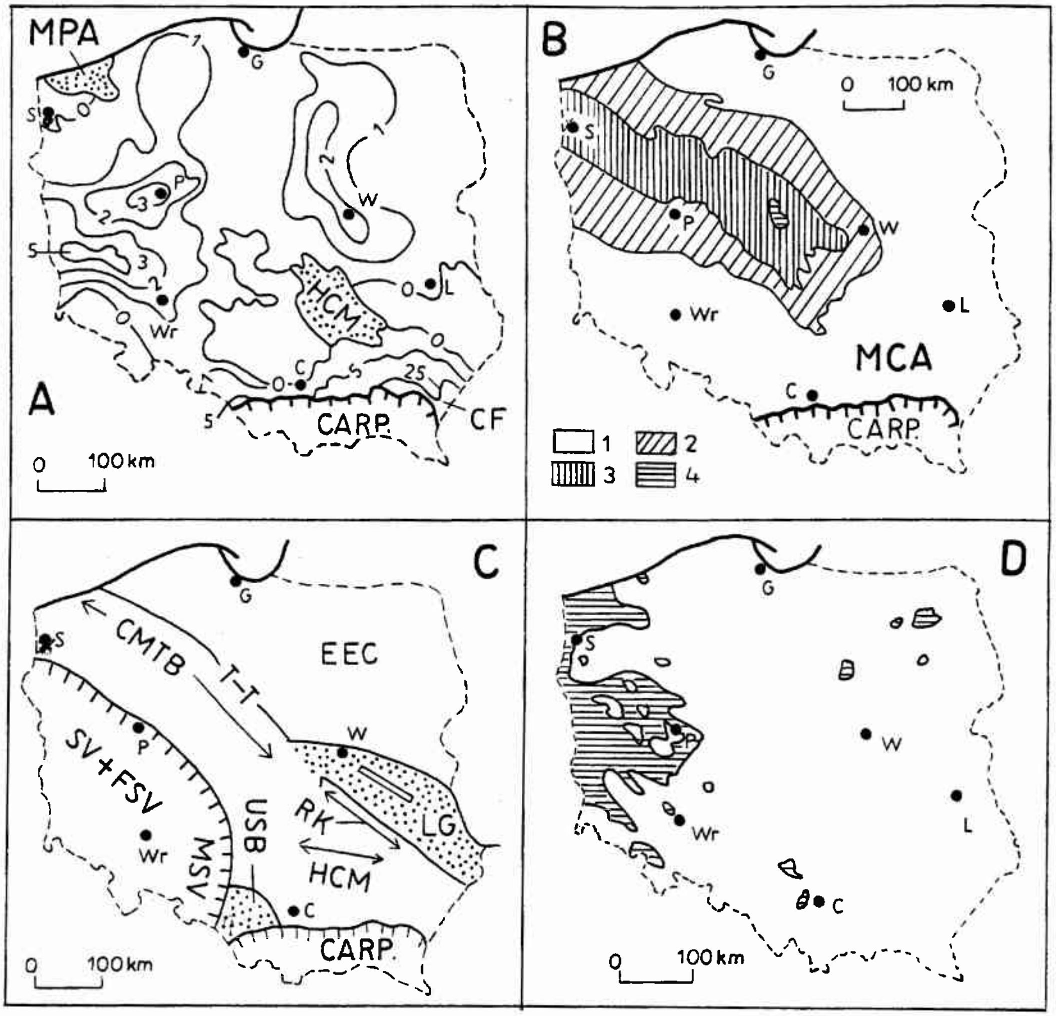

FIG. 2.— **A**, thickness of Tertiary deposits in Poland (chiefly after AREŃ *in* ZNOSKO, 1968); isopachs in hectometres. MPA, Mid-Polish Anticlinorium, stippled; HCM, Holy Cross Mountains; CF, Carpathian Foredeep. **B**, thickness of Permo-Mesozoic deposits (after SOKOŁOWSKI, 1972). **1**, 0-2500 m; **2**, 2500-5000 m; **3**, 5000-7500 m; **4**, over 7500 m. MCA, Meta-Carpathian Arch. **C**, sketch of pre-Permian tectonic units. EEC, East-European Craton; T-T, Teisseyre-Tornquist Line; CMTB, Caledonian Marginal Thrust Belt; LG, Lublin Graben; RK, Radom-Kraśnik Uplift; HCM, Variscan structures of the Holy Cross Mountains; USB, Upper Silesian Basin; MSV, Moravo-Silesian Variscides; SV+FSV, Sudetic and Fore-Sudetic Variscides. **D**, occurrences of lower Rotliegend volcanics in Poland (after POKORSKI *in* MAREK & PAJCHLOWA, 1997). C, Cracow; G, Gdańsk; L, Lublin; P, Poznań; S, Szczecin; W, Warszawa; Wr, Wrocław.

*FIG. 2.— **A**, épaisseurs du Tertiaire en Pologne (principalement d'après AREŃ* in *ZNOSKO, 1968) ; isopaques en hectomètres. MPA, Anticlinorium Médio-Polonais, en pointillés ; HCM, Montagnes de Sainte Croix ; CF, Avant-pays carpatique. **B**, épaisseur des dépôts Permo-Mésozoïques (d'après SOKOŁOWSKI, 1972). **1**, 0-2500 m ; **2**, 2500-5000 m ; **3**, 5000-7500 m ; **4**, plus de 7500 m. MCA, Arc Méta-Carpatique. **C**, esquisse des unités tectoniques pré-permiennes. EEC, Craton Est-Européen ; T-T, Ligne de Teisseyre-Tornquist ; CMTB, ceinture de chevauchement marginal calédonienne ; LG, Graben de Lublin ; RK, bombement de Radom-Kraśnik ; HCM, structures varisques des Montagnes de Sainte Croix ; USB, bassin de Haute Silésie ; MSV, Variscides Moravo-silésiennes ; SV+FSV, Variscides Sudètes et avant-Sudètes. **D**, présence de roches volcaniques du Rotliegend inférieur en Pologne (d'après POKORSKI* in *MAREK & PAJCHLOWA, 1997). C, Cracow ; G, Gdańsk ; L, Lublin ; P, Poznań ; S, Szczecin ; W, Warszawa ; Wr, Wrocław.*

META-CARPATHIAN ARCH

This traditional term is applied to a zone of uplift or lesser subsidence, which, during Permian and Mesozoic times, and also during the Palaeogene, separated structurally, and at some times also palaeogeographically, the easternmost part of the Central European Basin from the basins of the Carpathian domain. As a consequence, Permian and Mesozoic successions are strongly reduced in south-eastern Poland and the western Ukraine, where they are still preserved west and east of the Mid-Polish Anticlinorium (Figs 1, 2B, 3).

During the Permian, Triassic and Early Jurassic, the axis of the Meta-Carpathian Arch was located south of what is now the Carpathian front (Figs 7A-D, 8A; KUTEK, 1994). This arch was strongly downwarped during the Late Jurassic (Figs 3, 5C, 9A), but came into evidence again in post-Neocomian-pre-Albian time in the region of the Holy Cross Mountains (CIEŚLIŃSKI, 1976). By the Middle Albian, the axis of the Meta-Carpathian Arch shifted back to its usual southern position.

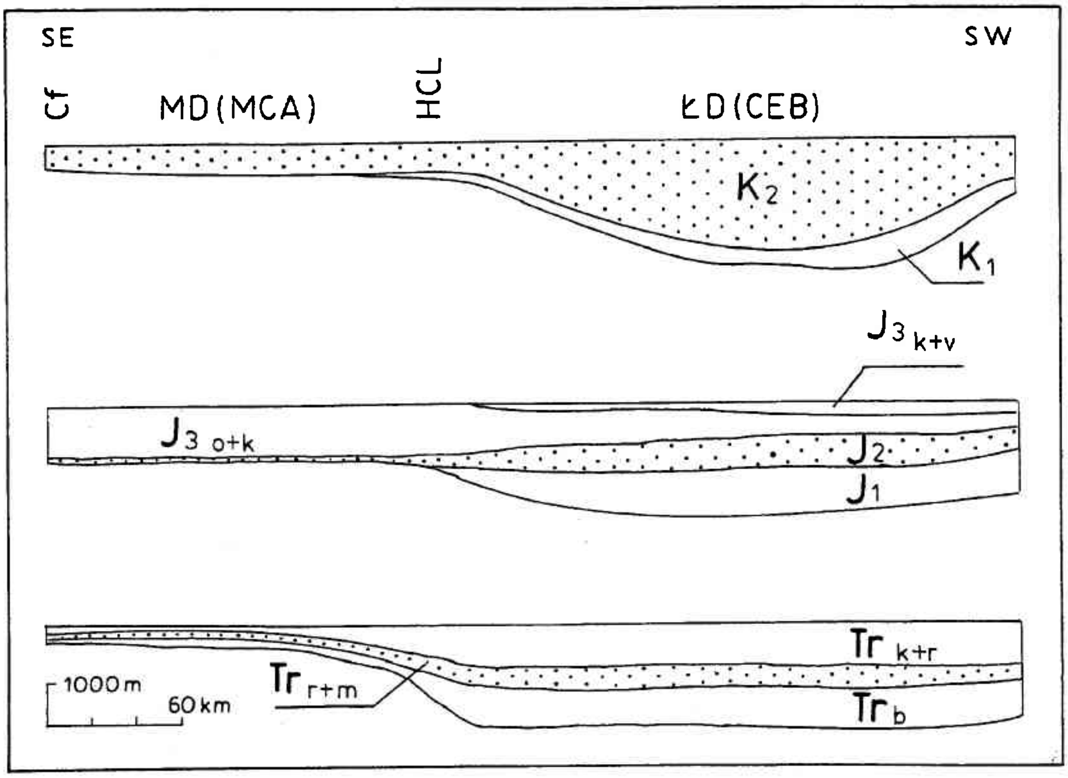

FIG. 3.— Generalized cross-sections through Triassic, Jurassic and Cretaceous deposits of the Łódź and Miechów depressions (after KUTEK, 1994); for location see figure 1. Tectonic structures: Cf, Carpathian front; MD, Miechów Depression; MCA, Meta-Carpathian Arch; ŁD, Łódź Depression; CEB, Central European Basin. Stratigraphic units: Tr_b, Buntsandstein; Tr_{r+m}, Röt and Muschelkalk; Tr_{k+r}, Keuper and Rhaetian; J_1, Lower Jurassic; J_2, Middle Jurassic; J_{o+k}, Oxfordian and Kimmeridgian; J_{k+v}, Kimmeridgian and Volgian; K_1, Lower Cretaceous; K_2, Upper Cretaceous.

FIG. 3.— Coupes synthétiques à travers les dépôts du Trias, Jurassique et Crétacé dans les dépressions de Łódź et Miechów (d'après KUTEK, 1994) ; pour la localisation voir la figure 1. Structures tectoniques : Cf, front carpatique ; MD, dépression de Miechów ; MCA, Arc Méta-Carpatique ; ŁD, Dépression de Łódź ; CEB, bassin Central Européen. Unités stratigraphiques : Tr_b, Buntsandstein ; Tr_{r+m}, Röt et Muschelkalk ; Tr_{k+r}, Keuper et Rhétien ; J_1, Jurassique inférieur ; J_2, Jurassique moyen ; J_{o+k}, Oxfordien et Kimmeridgien ; J_{k+v}, Kimmeridgien et Volgien ; K_1, Crétacé inférieur ; K_2, Crétacé supérieur.

As the Meta-Carpathian Arch developed as a long-wave crustal deflection, its evolution should presumably be explained , at least in part, in terms of crustal or lithospheric folding. In southeastern Poland and the western Ukraine, the Polish Rift Basin is superimposed on the Meta-Carpathian Arch. However, evidence for an independent development of the arch, largely governed by tectonic processes in the Carpathian domain, is provided by the fact that the Meta-Carpathian Arch was uplifted once more during the Palaeogene (HELLER & MORYC, 1985; KUTEK, 1994), after the Laramide inversion of the Polish Rift Basin.

The northern and central parts of the Polish rifted basin, that form part of the Central European Basin, are characterized by a thick Permo-Mesozoic sedimentary sequence (Fig. 10), including thick Zechstein salts that were halokinetically mobilised during Mesozoic times. During phases of crustal extension, these salts acted as decoupling layers causing strain dissipation to the end that extensional structures are difficult to identify in post-salt series. Morever, latest Cretaceous and Palaeocene inversion of the Polish Basin strongly modified its pre-existing extensional structure. In contrast, the southern parts of the Polish Basin, that are superimposed on the Meta-Carpathian Arch, are devoid of Zechstein salts. Therefore, extensional structures are more readily recognizable, particularly in the non-inverted Miechów Depression and in the northern part of the Craco-Silesian Monocline, but also in the Holy Cross Mountains area. In the southern parts of the Cracow-Silesian Monocline, Mesozoic extensional features were strongly overprinted by Miocene extensional faults that developed during the subsidence of the Carpathian foreland basin.

PRE-PERMIAN TECTONIC UNITS

The Teisseyre-Tornquist Zone is a zone characterized by anomalously thick crust (Fig. 4A) that transects Poland in a northwest-southeast direction, forming part of the Trans-European Suture Zone (BERTHELSEN, 1993; DADLEZ, 1997a). The former is some 50 to 100 km wide, and underlies the inverted Permo-Mesozoic Polish Basin.

In the northern part of Poland, the Teisseyre-Tornquist Line (TTL), which coincides with the northeastern limit of the Teisseyre-Tornquist Zone, forms the boundary between the Precambrian East-European Craton (EEC) and the area of Palaeozoic crustal consolidation of Central and Western Europe (Fig. 2C). In north-eastern Poland, the EEC is overlain by essentially flat lying Cambrian to Silurian sediments that increase in thickness to the south-west. These sediments are eroded over the Mazury-Byelorussia Arch that separates the Peri-Baltic Depression from the Podlasie Depression (Fig. 7B). On the EEC, the Palaeozoic sediments, and where missing, the Precambrian basements, are unconformably overlain by thin Mesozoic series (POŻARYSKI, 1977).

In southeastern Poland, the Teisseyre-Tornquist Zone slightly encroaches onto the East-European Craton, encompassing the Lublin Graben (Figs 2C, 11), where an epicratonic sedimentary succession begins with Vendian series (DADLEZ, 1993, 1997a).

Borehole and geophysical data show that the TTL marks the northeastern limit of a Caledonian thrust belt, developed in northern Poland (Fig. 2C). This structure was buried beneath Devonian and Carboniferous sediments that were partly deformed during the Variscan orogeny and again during the Stephanian-Early Permian post-orogenic phase of wrench faulting. The Variscan thrust front is well defined in south-western Poland where the Moravo-Silesian thrust belt (MSV) faces the Upper Silesian Coal Basin (USB), a Variscan foreland basin containing thick Namurian and Wesphalian sediments. Further to the north, the thrust front of the Sudetic (SV) and Fore-Sudetic (FSV) Variscides is less well defined due to a thick Permo-Mesozoic overburden (DADLEZ *et al.*, 1994; DADLEZ, 1997a, b). In the foreland of the Sudetic-Moravo-Silesian thrust belt, the Variscan structures of the Holy Cross Mountains (HCM) developed in response to Middle Carboniferous compression, and can thus be compared with similar structures, for instance, in the foreland of the Alps (ZIEGLER *et al.*, 1995). In the HCM, both Caledonian and Variscan structures strike WNW-ESE.

During latest Westphalian to Early Permian times, the TTL, and areas located to the southwest of it, were affected by a phase of late syn- and postorogenic wrench faulting that correlates with a

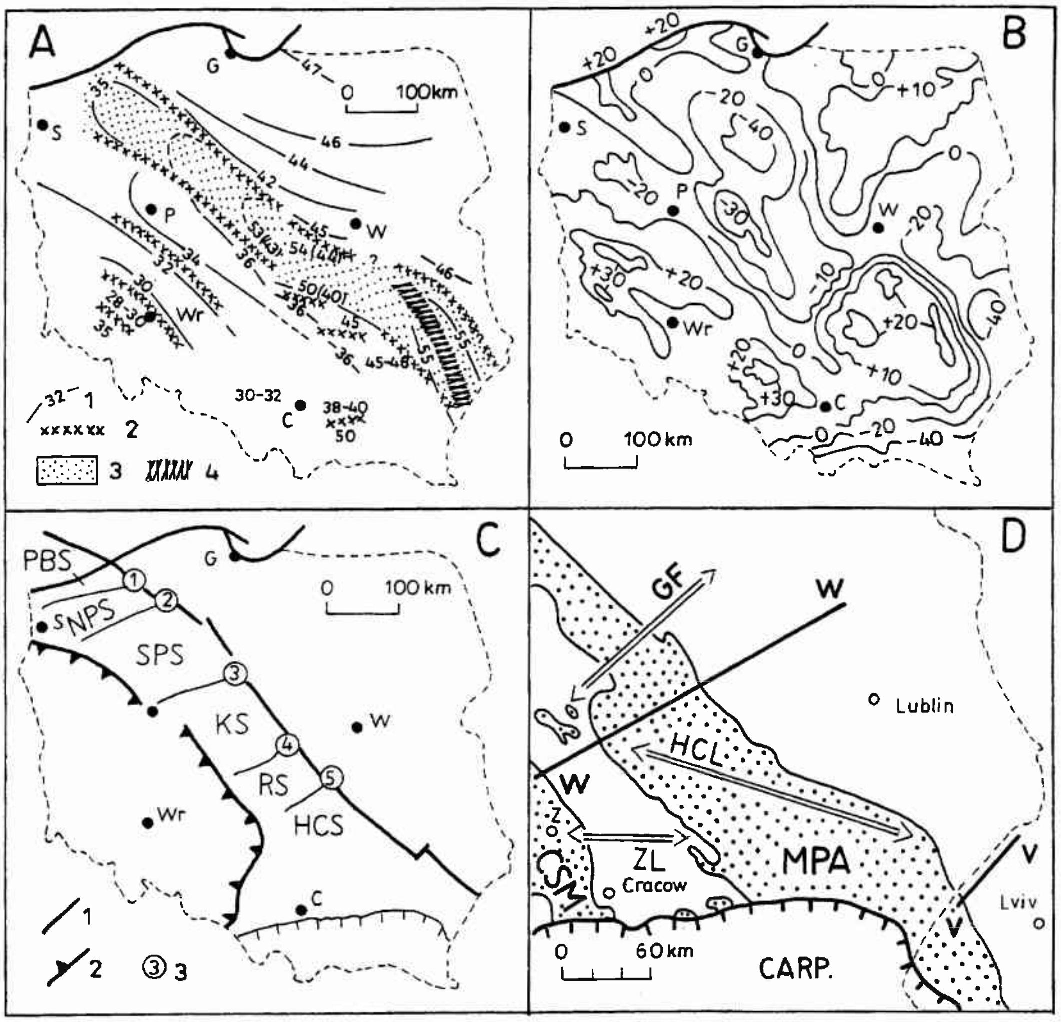

FIG. 4.— **A**, crustal configuration in Poland (after GUTERCH & GRAD, 1996). **1**, depth of the Moho discontinuity in km; **2**, boundaries of crustal blocks; **3**, Teisseyre-Tornquist Zone; **4**, anomalous zone in crustal structure. **B**, gravimetric map of Poland, Bouger anomalies (after SOKOŁOWSKI, 1990, strongly simplified). **C**, segmentation of northern and central parts of the Mid-Polish Furrow (after DADLEZ, 1997b). PBS, NPS, SPS, KS, RS, HCS, Peribaltic, North Pomeranian, South Pomeranian, Kutno, Rawa and Holy Cross Mountains segments. **1**, Szczecin-Miastko Fault; **2**, Choszczno-Szczecin Fault; **3**, Poznań-Toruń Fault; **4**, Sieradz-Łowicz Fault; **5**, Grójec Fault. **D**, segmentation of southeastern part of the Polish Basin. GF, Grójec Fault; HCL, Holy Cross Lineament; ZL, Zawiercie Lineament. Z, Zawiercie. w-w, v-v, location of sections in Figs 5A-C.

*FIG. 4.— **A**, configuration crustale en Pologne (d'après GUTERCH & GRAD, 1996). **1**, profondeur de la discontinuité du Moho en km ; **2**, limites des blocs crustaux ; **3**, zone de Teisseyre-Tornquist ; **4**, zone d'anomalie dans la structure crustale. **B**, carte gravimétrique de la Pologne, anomalies de Bouger (d'après SOKOŁOWSKI, 1990, très simplifiée). **C**, segmentation des parties nord et centrale du sillon Médio-Polonais (d'après DADLEZ, 1997b). PBS, NPS, SPS, KS, RS, HCS, segments Péribaltique, Nord Poméranien, Sud Poméranien, Kutno, Rawa et Montagnes de Sainte Croix. **1**, faille de Szczecin-Miastko ; **2**, faille de Choszczno-Szczecin ; **3**, faille de Poznan-Toruń ; **4**, faille de Sieradz-Łowicz ; **5**, faille de Grójec. **D**, segmentation de la partie sud-est du bassin polonais. GF, faille de Grójec ; HCL, linéament de Sainte Croix ; ZL, linéament de Zawiercie ; Z, Zawiercie. w-w, v-v, localisation des coupes sur les figures 5A-C.*

similar tectonic event affecting the entire Variscan Orogen and its foreland (ZIEGLER, 1990). In Poland (Fig. 2C), main features developing during this deformation are the Lublin Graben (LG) and the Radom-Kraśnik Uplift (RK). The Lublin Graben extends into the western Ukraine, contains Westphalian and older sediments, and is characterized by a complex structure, including narrow horsts. The Radom-Krasnik Uplift consists of numerous subparallel slices of mainly Devonian sediments. Structural analyses indicate that the post-Variscan Permo-Carboniferous deformation was mainly transpressional in south-eastern Poland, whereas in northernmost Poland, in Pomerania, a transition to transtentional structures is observed (ŻELICHOWSKI, 1972, 1983; POŻARYSKI & TOMCZYK, 1993; ANTONOWICZ *et al.*, 1994).

BASIN SEGMENTATION AND GEOMETRY

As evident from the geometry of the Mid-Polish Anticlinorium, the rifted basin out of which it developed was segmented by a multidirectional fault system into compartments that clearly differed in their evolution. The strike of the individual faults, and the timing of their activity, varies considerably, suggesting multidirectional extension during the evolution of the Polish Rift Basin.

The segmentation of the basin in northern and central Poland has been discussed by MAREK & ZNOSKO (1972) and DADLEZ (1997a, b). One of the possible subdivisions of the Mid-Polish Furrow into segments, separated by fault zones, is reproduced herein (Fig. 4C). In the following the segmentation of the southeastern parts of the rifted basin by the cross-cutting Holy Cross, Zawiercie and Grójec lineaments (Fig. 4D) is further discussed.

The Holy Cross Lineament (HCL) strikes WNW-ESE, and subparallels the Caledonian and Variscan structures of the Holy Cross Mountains; it represents a deep-seated crustal discontinuity that probably dates back to the Early Palaeozoic. To the north of the HCL a thicker and more complete Permo-Mesozoic succession accumulated than to the south of it (KUTEK, 1994; HAKENBERG & ŚWIDROWSKA, 1997). During the evolution of the Polish Rift, the HCL acted as a transfer fault, separating the north-western part of the basin, that commenced to subside during the late Early Permian, from its southeastern part that started to subside significantly in the latest Early to Middle Jurassic (KUTEK, 1994). The HCL was reactivated during the latest Cretaceous-Palaeocene Basin inversion, as indicated by the geometry of the Mid-Polish Anticlinorium and the occurrence of a set of anticlines in the Łódź and Miechów depressions (Figs 1, 4D).

In the peri-Carpathian area, located south of the HCL, there is good evidence for Middle Jurassic to Early Cretaceous rifting activity (e.g., KUTEK *et al.*, 1989; KUTEK, 1994; KUTEK & MARCINOWSKI, 1996b). This part of the Polish Rift is subdivided by the E-W striking Zawiercie Lineament (ZL; Fig. 4D). In the Cracow-Silesian Monocline, a thicker and more complete Jurassic-Middle Cretaceous succession is observed than to the south of it (KUTEK, 1996). Moreover, the strike of the Cracow-Silesian Monocline changes across the ZL from N-S in the south to NW-SE to the north. A corresponding change in the strike of the eastern margin of the Mid-Polish Anticlinorium is observed in the eastward projection of the ZL (Figs 1, 4D). In the south-eastern part of the Miechów Depression, a set of anticlines developed only south of the Zawiercie Lineament.

The Grójec Fault (GF), located north of the Holy Cross Mountains, crosses the Mid-Polish Anticlinorium in a SW-NE direction. Across this fault, the width of this anticlinorium changes dramatically (Figs 1 and 4D). Moreover, there is stratigraphic evidence that the GF was tectonically active during Late Palaeozoic to Jurassic times (ŻELICHOWSKI, 1983; HAKENBERG & SWIDROWSKA, 1997). The GF is associated with a distinct gravity gradient (Figs 4B, D; KRÓLIKOWSKI & PETECKI, 1995; WYBRANIEC, 1995).

Regional base-Zechstein structural maps (DADLEZ, 1980), and a series of cross-sections (KARNKOWSKI, 1980), based on borehole and seismic evidence, show that the northern and central parts of the Mid-Polish Anticlinorium are superimposed on an up to 7 km deep through that shallows south-eastwards towards the Holy Cross Mountains, where pre-Permian strata are exposed at the surface. Cross sections through the Polish Anticlinorium, restored to their pre-inversion configuration (POŻARYSKI & BROCHWICZ-LEWIŃSKI, 1978, 1979), enhance the image of the asymmetric geometry of the Polish Rift that was characterized by a system of master faults defining its northeastern margin whereas the southwestern margin is more diffuse (Fig. 5A, B). In this context it must be realized that many of these faults were reactivated during the Laramide phase of foreland compression, which caused the transpressional inversion of the Polish Rift. The asymmetry, with greater thickness contrasts across the northeastern rift border than across its opposite flank, can clearly be recognized in the western Ukraine (SANDLER, 1969; GARETSKY, 1985; KUTEK, 1994), in

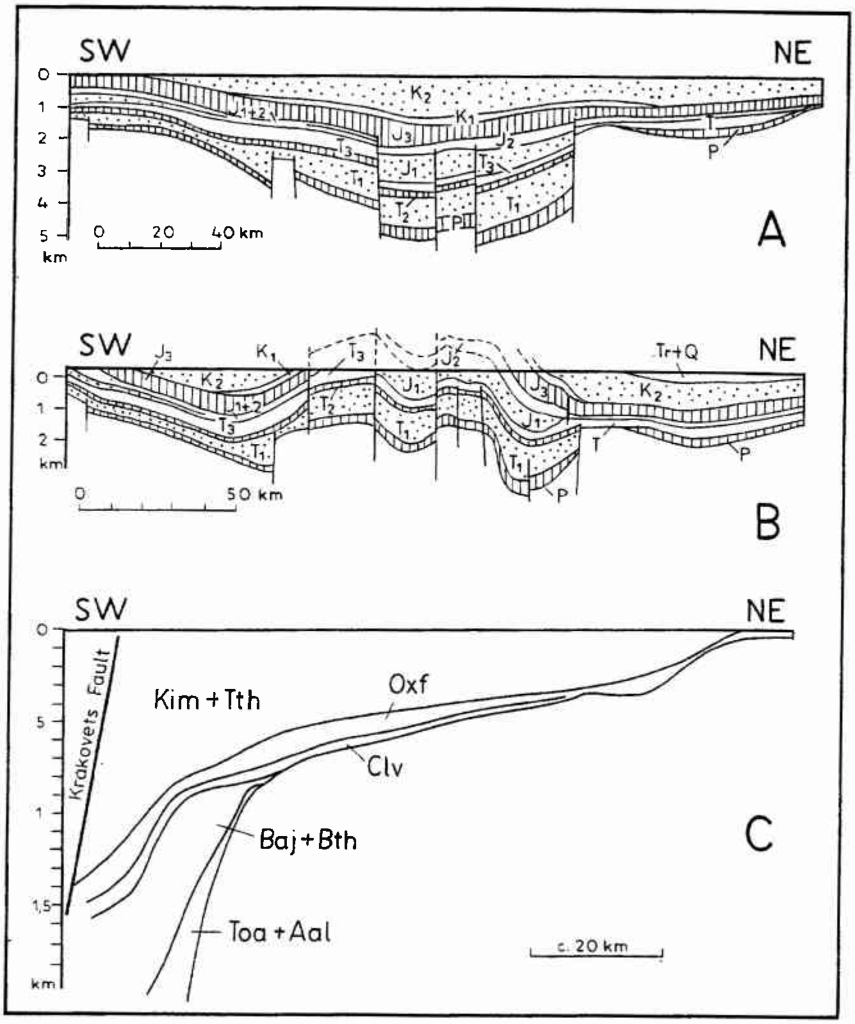

FIG. 5.— Sections across the northern part of the Holy Cross Mountains (after POŻARYSKI & BROCHWICZ-LEWIŃSKI, 1978, 1979). **A**, section restored at the end of the Cretaceous; **B**, section across the present-day structure. **C**, section across Jurassic deposits preserved on the eastern side of the Mid-Polish Anticlinorium in western Ukraine (after VISHNIAKOF *in* GARETSKY, 1985, simplified). Toa+Aal, Toarcian and Aalenian; Baj+Bth, Bajocian and Bathonian; Clv, Callovian; Oxf, Oxfordian; Kim+Tth, Kimmeridgian and Tithonian. For location of sections see figure 4D.

*FIG. 5.— Coupes à travers la partie nord des Montagnes de Sainte Croix (d'après POŻARYSKI & BROCHWICZ-LEWIŃSKI, 1978, 1979). **A**, coupe restaurée à la fin du Crétacé ; **B**, coupe à travers la structure actuelle. **C**, coupe à travers les dépôts du Jurassique préservés à la l'extrémité est de l'Anticlinorium Médio-Polonais en Ukraine (d'après VISHNIAKOF* in *GARETSKY, 1985, simplifié). Toa+Aal, Toarcien et Aalénien ; Baj+Bth, Bajocien et Bathonien ; Clv, Callovien ; Oxf, Oxfordien ; Kim+Tth, Kimmeridgien et Tithonien. Pour la localisation des coupes voir la figure 4D.*

the region of the Holy Cross Mountains and the Miechów Depression (POŻARYSKI & BROCHWICZ-LEWIŃSKI, 1978, 1979; KUTEK, 1994; HAKENBERG & ŚWIDROWSKA, 1997), and also in Pomerania (KARNKOWSKI, 1980; DADLEZ, 1997a). However, the polarity of asymmetry differs in some part of central Poland (DADLEZ, 1997a).

On the southwestern flanks of the Polish Rift, southwest hading extensional faults of Mesozoic age predominate in the Miechów Depression, in the Cracow-Silesian Monocline, and even in Upper Silesia (Fig. 6A; DOKTOROWICZ-HREBNICKI, 1960; KUTEK, 1994).

Broad intrabasinal highs developed on the western flank of the Polish Permo-Mesozoic Basin during several phases of its evolution (DADLEZ, 1989): the Wolsztyn Swell during the Permian

(Figs 7A, B), the Szczecin-Kalisz Swell during the Buntsandstein time, and the Wielkopolska Swell during the Rhaetian and Early to Middle Jurassic (Figs 8A-D).

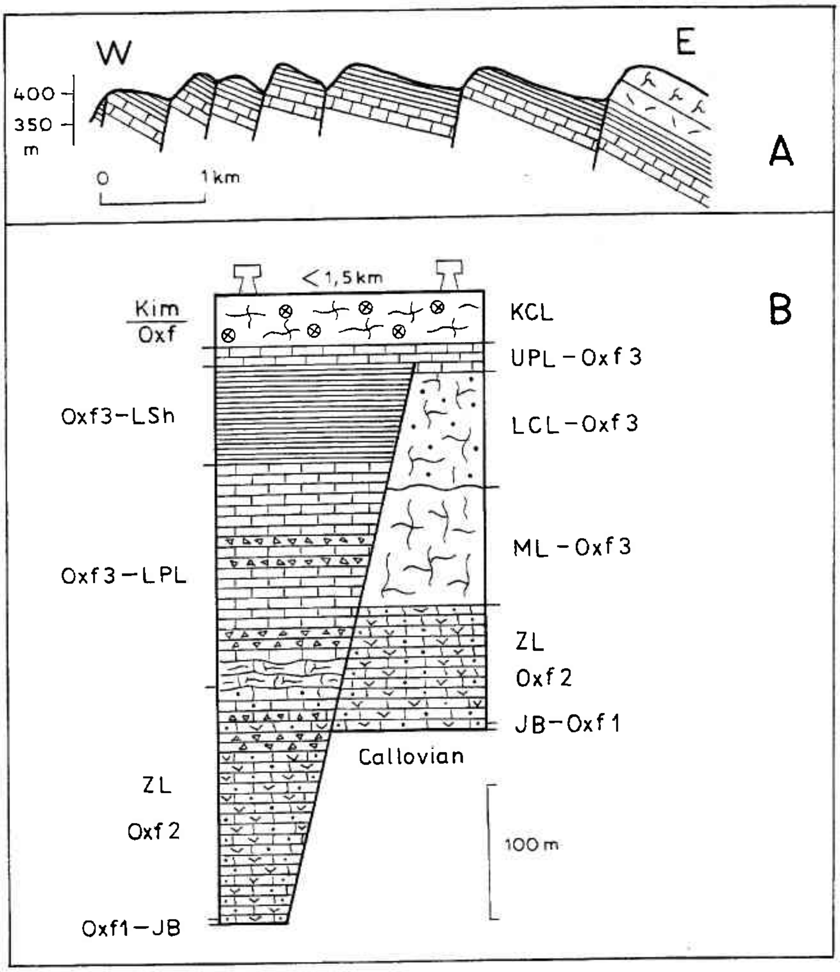

FIG. 6.— Examples of extensional tectonics in the Cracow-Silesian Monocline. **A,** a set of tilted blocks, composed of upper Oxfordian lithostratigraphic units, east of Zawiercie (after BEDNAREK, 1974). **B,** the Kobyłczyce Fault, syndepositionally active during the late Oxfordian; northern part of CSM (section based on unpublished material). Biohermal chalky (LCL) and massive (ML) limestones are developed only in the footwall, but redeposited material occurs in turbidites, debris flows and slumps within layered spongy (ZL) and micritic (LPL) limestones in the hanging wall. Shallow-water limestones with corals (KCL), straddling the Oxfordian-Kimmeridgian boundary, are a post-fault deposit.

*FIG. 6.— Exemples de tectonique extensive dans le monoclinal de Cracovie-Silésie. **A,** une série de blocs basculés, composés d'unités lithostratigraphiques de l'Oxfordien supérieur, à l'est de Zawiercie (d'après BEDNAREK, 1974). **B,** faille de Kobyłczyce, active durant le dépôt de l'Oxfordien supérieur ; partie nord de CSM (coupe basée sur du matériel non publié). Des calcaires crayeux biothermaux (LCL) et massifs (ML) sont développés uniquement dans la série chevauchée, mais du matériel remanié est présent dans des turbidites, des debris flows et des slumps avec les calcaires spongolites bien stratifiés (ZL) et micritiques (LPL) dans la série chevauchante. Les calcaires d'eau peu profonde avec des coraux (KCL), à cheval sur la limite Oxfordien-Kimméridgien sont des dépôts post faille.*

SEDIMENTARY BASIN FILL

The Permian and Triassic sedimentary sequences of the Polish Permo-Mesozoic Basin display close similarity with those developed further West in the Central European Basin (Fig. 10). Accordingly, the Rotliegend is followed by the Zechstein, Buntsandstein, Muschelkalk and Keuper.

Even several minor lithostratigraphic units established in Germany, such as the lower, middle and upper Muschelkalk, or the Schilfsandstein within the Keuper, can be recognized in Poland.

The Polish Lower Jurassic, on the contrary, displays several distinctive features. It is largely composed of non-marine sediments, to the degree that only a few ammonites have been found in the Liassic of Poland beyond the Carpathians. The Liassic lithologies comprise chiefly shales and sandstones, with some gravel in the lowest members. The high-quality petroleum source rocks developed in the Toarcian (Liassic epsilon) of northwest Germany do not extend into Poland.

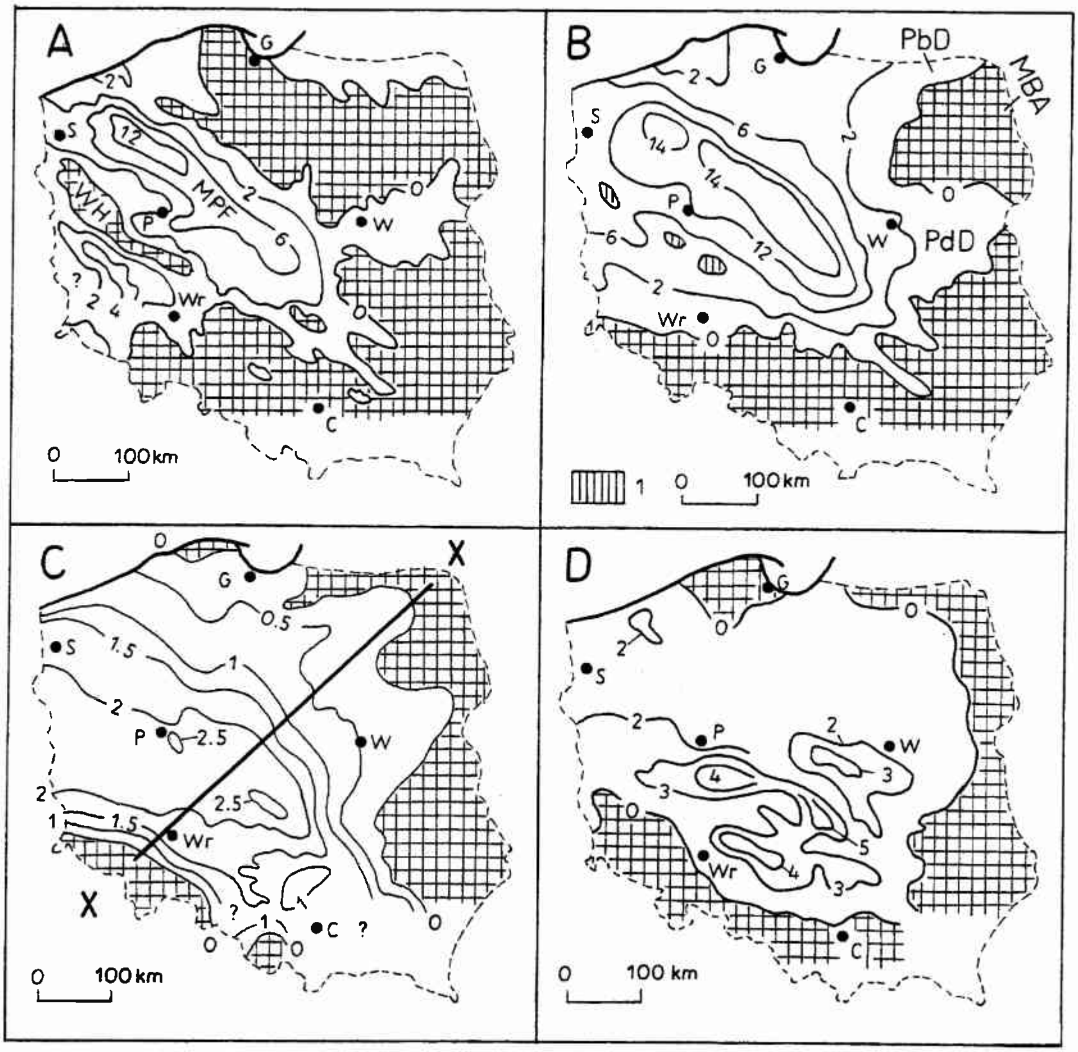

FIG. 7.— **A,** palaeotectonic map (primary extent and thickness of sediments indicated) of the upper Rotliegend (after POKORSKI, 1988, simplified). MPF, Mid-Polish Furrow; WH, Wolsztyn High. **B,** palaeotectonic map of the Zechstein (after WAGNER, 1988; simplified). 1, elevations within the Wolsztyn High. **C,** palaeotectonic map of the lower and middle Muschelkalk (after GAJEWSKA *in* MAREK & PAJCHLOWA, 1997, simplified); x-x, location for section in figure 8E. **D,** palaeotectonic map of the Norian (after DECZKOWSKI & FRANCZYK, 1988a, b, simplified). Isopachs in hectometres in all maps.

*FIG. 7.— **A**, carte paléotectonique (extension primaire et épaisseur des sédiments indiquées) du Rotliegend supérieur (d'après POKORSKI, 1988, simplifié). MPF, Sillon Médio-Polonais ; WH, antéclise de Wolsztyn. **B**, carte paléotectonqiue du Zeichstein (d'après WAGNER, 1988, simplifiée). 1, surélévations à l'intérieur de la hauteur de Wolszyn. **C**, carte paléotectonique du Muschelkalk inférieur et moyen (d'après GAJEWSKA* in *MAREK & PAJCHLOWA, 1997, simplifié) ; x-x, localisation de la coupe sur la figure 8E. **D**, carte paléotectonique au Norien (d'après DECZKOWSKI & FRANCZYK, 1988a, b, simplifié). Isopaques en hectomètres pour toutes les cartes.*

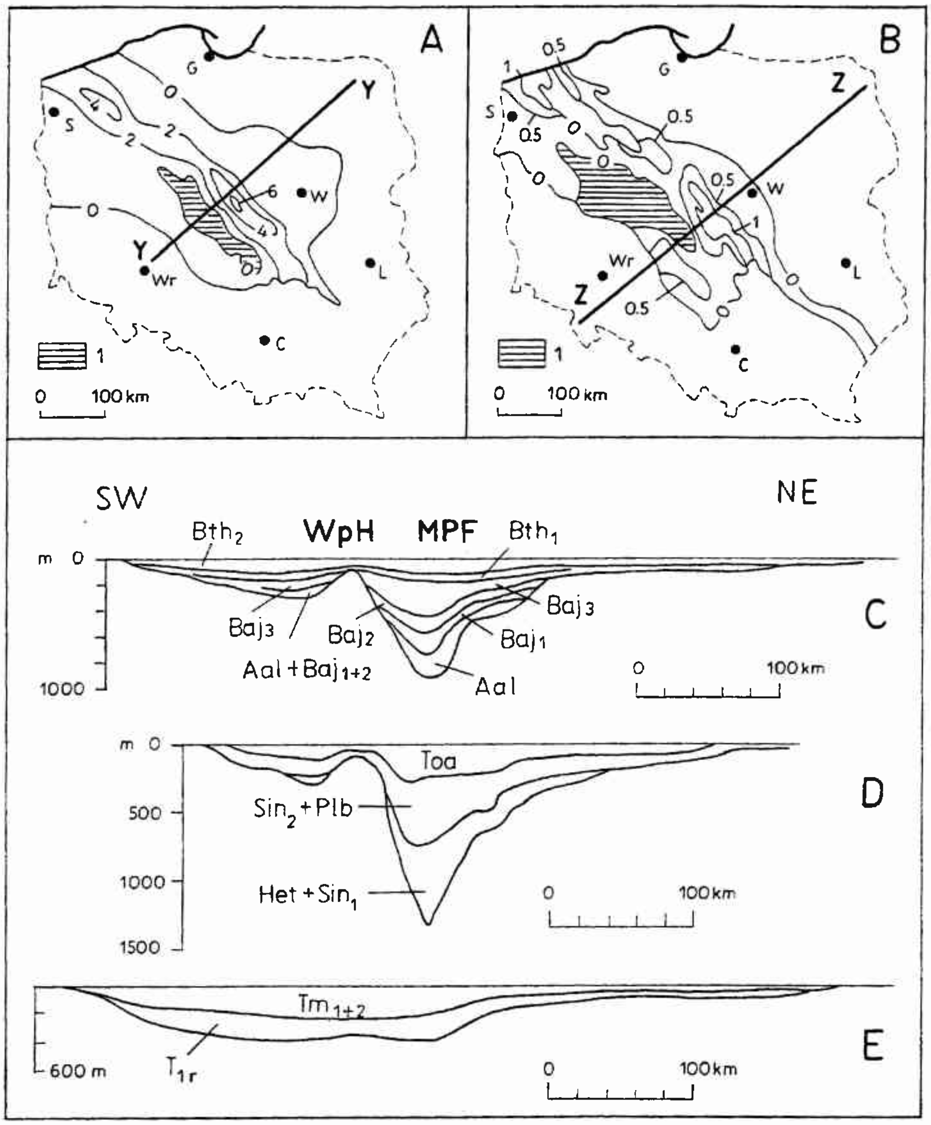

FIG. 8.— **A**, thickness of (preserved) Hettangian and lower Sinemurian deposits (after DECZKOWSKI & FRANCZYK, 1988b, simplified), isopachs in hectometres. **1**, Wielkopolska High; y-y, location for section in figure 8D. **B**, thickness of (preserved) lower Bajocian deposits (after DAYCZAK-CALIKOWSKA & MORYC, 1988, simplified); isopachs in hectometres. **1**, Wielkpolska High; z-z, location for section in figure 8C. **C**, restored section across Mid-Jurassic deposits (after DAYCZAK-CALIKOWSKA *in* MAREK & PAJCHLOWA, 1997); location in figure 8B. WpH, Wielkopolska High; MPF, Mid-Polish Furrow; Aal, Aalenian; $Baj_{1,2,3}$, lower, middle and upper parts of Bajocian; $Bth_{1,2}$, lower and middle Bathonian. **D**, restored section across Lower Jurassic deposits (after DECZKOWSKI *in* MAREK & PAJCHLOWA, 1997); location in figure 8A. Het+Sin_1, Hettangian and lower Sinemurian; Sin_2+Plb, upper Sinemurian and Pliensbachian; Toa, Toarcian. **E**, restored section across deposits of the Röt and lower and middle Muschelkalk (after GAJEWSKA *in* MAREK & PAJCHLOWA, 1997); location in figure 7C. T_{1r}, Röt; T_{m1+2}, lower and middle Muschelkalk.

*FIG. 8.— **A**, épaisseur des sediments (préservés) de l'Hettangien et du Sinémurien inférieur (d'après DECZKOWSKI & FRANCZYK, 1988b, simplifié), isopaques en hectomètres. **1**, hauteur de Wielkopolska ; z-z, localisation de la coupe voir la figure 8D. **B**, épaisseur des dépôts (préservés) du Bajocien inférieur (d'après DAYCZAK-CALIKOWSKA & MORYC, 1988, simplifié) ; isopaques en hectomètres. **1**, antéclise de Wielkopolska ; z-z, localisation de la coupe voir la figure 8C. **C**, coupe restaurée à travers les dépôts du Jurassique moyen (d'après DAYCZAK-CALIKOWSKA* in *MAREK & PAJCHLOWA, 1997), localisation sur la figure 8B. WpH, Hauteur de Wielkopolska ; MPF, Sillon Médio-polonais ; Aal, Aalénien ; $Baj_{1,2,3}$, parties inférieure, moyenne et supérieure du Bajocien ; $Bth_{1,2}$, Bathonien inférieur et moyen. **D**, coupe restaurée à travers les dépôts du Jurassique inférieur (d'après DECZKOWSKI* in *MAREK & PAJCHLOWA, 1997) ; localisation sur la figure 8A. Het+Sin_1, Hettangien et Sinémurien inférieur ; Sin_2+Plb, Sinémurien supérieur et Pliensbachien ; Toa, Toarcien. **E**, coupe restaurée à travers les dépôts du Röt et du Muschelkalk inférieur et moyen (d'après GAJEWSKA* in *MAREK & PAJCHLOWA, 1997) ; localisation sur la figure 7C. T_{1r}, Rotliegend ; T_{m1+2}, Muschelkalk inférieur et moyen.*

The Middle Jurassic is chiefly composed of marine sandstones and shales, with some mixed siliciclastic/carbonate lithologies in the Callovian.

Carbonates prevail in the Upper Jurassic. This is a consequence of the strong downwarping of the Meta-Carpathian Arch (Fig. 9A), that transformed most of Poland into a shelf of the Tethys. Accordingly, the sponge megafacies strongly developed in the Oxfordian (up to 800 m thick) of southern and central Poland (KUTEK, 1994) has its counterpart not in the Oxfordian of northwest Germany, but in the Upper Jurassic of the Franconian and Swabian platforms (ZIEGLER, 1990). Moreover, striking similarities, down to horizon level, are displayed by the ammonite assemblages of South Germany and Poland (MATYJA & WIERZBOWSKI, 1995). The Pałuki Formation of central

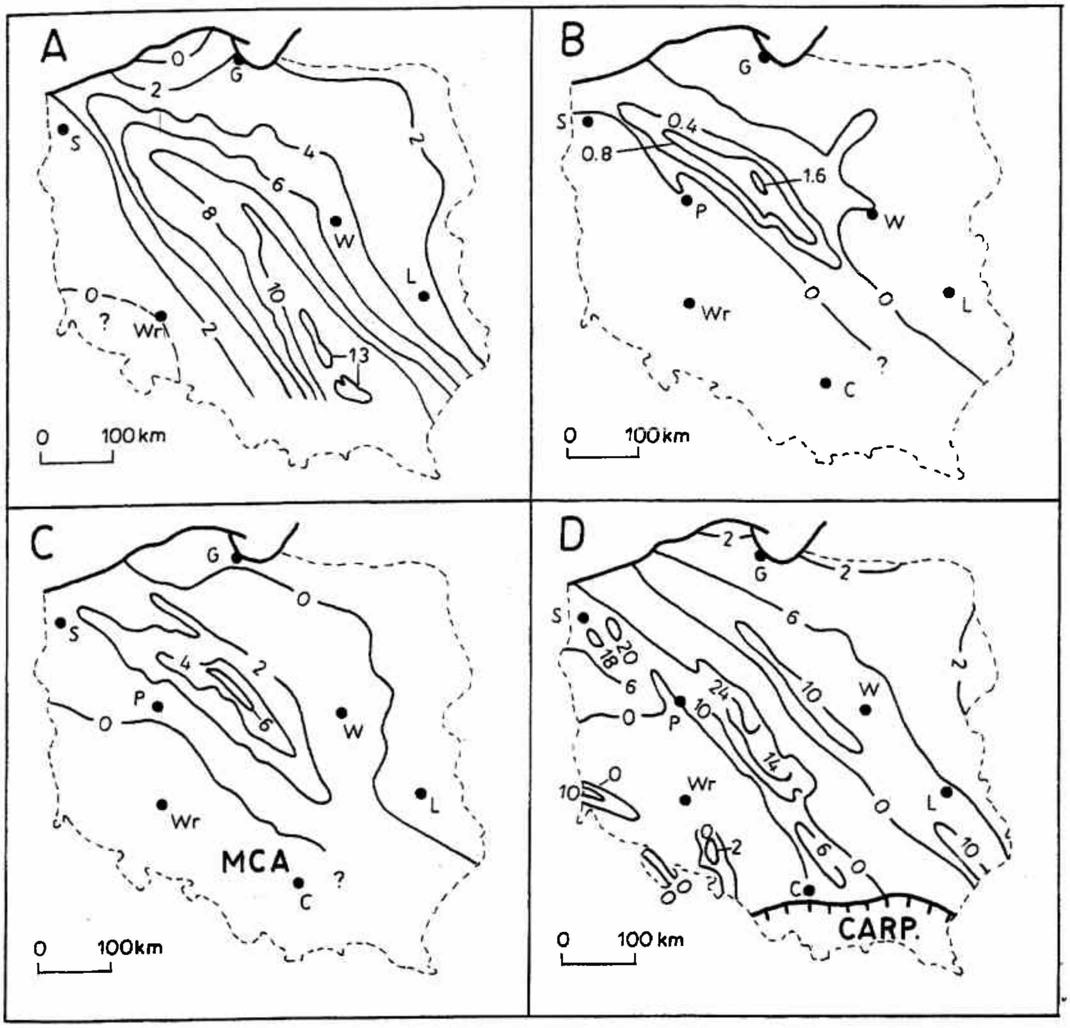

FIG. 9.— **A,** palaeotectonic map of the Upper Jurassic (after NIEMCZYCKA & BROCHWICZ-LEWIŃSKI, 1988; simplified). **B**, palaeotectonic map of the lower Valanginian (after MAREK, MORYC & RACZYŃSKA *in* MAREK, 1988, simplified). **C,** palaeotectonic map of the Lower Cretaceous, at the end of the middle Albian (after MAREK & FELDMAN-OLSZEWSKA *in* MAREK & PAJCHLOWA, 1997, simplified). **D,** thickness of (preserved) Upper Cretaceous deposits (chiefly after JASKOWIAK & KRASSOWSKA *in* ZNOSKO, 1968; JASKOWIAK-SCHOENEICHOWA & KRASSOWSKA, 1988, strongly simplified). Isopachs in hectometres in all maps.

*FIG. 9.— **A**, carte paléotectonique du Jurassique supérieur (d'après NIEMCZYCKA & BROCHWICZ-LEWIŃSKI, 1988, simplifié). **B**, carte paléotectonique du Valanginien inférieur (d'après MAREK, MORYC & RACZYŃSKA* in *MAREK, 1988, simplifié). **C**, carte paléotectonique du Crétacé inférieur, à la fin de l'Albien moyen (d'après MAREK & FELDMAN-OLSZEWSKA* in *MAREK & PAJCHLOWA, 1997, simplifié). **D**, épaisseur des dépôts (préservés) du Crétacé inférieur (principalement d'après JASKOWIAK & KRASSOWSKA* in *ZNOSKO, 1968 ; JASKOWIAK-SCHOENEICHOWA & KRASSOWSKA, 1988, très simplifié). Isopaques en hectomètres pour toutes les cartes.*

Poland, ranging from the late Kimmeridgian into the middle Volgian, consisting of calcareous shales with limestone intercalations, and very rich in ammonites (KUTEK & ZEISS, 1997), is somewhat reminiscent of the British Kimmeridge Clay, but does not shares its high petroleum source rock potential. Purbeck-type sediments, straddling the Jurassic-Cretaceous boundary, are developed in central Poland, testifying to a renewed uplift of the Meta-Carpathian Arch (KUTEK *et al.*, 1989).

The Lower Cretaceous of the Polish Basin displays a tripartite subdivision. The Neocomian (Berriasian to Hauterivian) interval is represented by marine sandstones and shales, with some carbonates in southeastern regions. Ammonites of Tethyan origin testify to marine connection along the Polish Rift with the Carpathian domain (KUTEK *et al.*,1989). The Barremian, Aptian and lower Albian are represented by sandstones and shales, non-marine in part. Siliciclastic lithologies prevail in the clearly marine deposits of the middle and upper Albian.

The bulk of the Upper Cretaceous sediments is composed of several varieties of the chalk megafacies. Siliciclastic deposits occur in some peripheral areas of the sedimentary basin, especially in northern and southwestern Poland (in the North Sudetic and Intrasudetic depressions).

The Permo-Mesozoic successions display variable sedimentation rates (Fig. 10; DADLEZ 1989, 1997b; HAKENBERG & ŚWIDROWSKA, 1997). In particular, strongly contrasting thicknesses are revealed by several continuous sections, for which high-resolution stratigraphy is available, as for instance, in the southwestern margin of the Holy Cross Mountains.

The marine sediments of the Polish Permo-Mesozoic Basin were mostly deposited in shallow-water environments. A somewhat greater water-depth, of the order of a few hundred meters, can be suggested for some sediments of the Zechstein, Oxfordian and Upper Cretaceous. In the area of the Cracow-Silesian Monocline, an Oxfordian fault-controlled submarine relief, amounting to 150-200 m (MATYJA & WIERZBOWSKI, 1996), gave rise to large submarine slumps, debris flows and proximal turbidites (Fig. 6B).

For further information on the Permian and Mesozoic stratigraphy of the Polish Basin the reader is referred to papers published in the volume 32 (1) of the *Kwartalnik Geologiczny*, and in MAREK & PAJCHLOVA (1997), which include a large number of palaeotectonic and palaeogeographic maps. However, some of the interpretations presented in these maps are disputable, particularly those concerning areas where no stratigraphic record is preserved due to erosion.

MAGMATISM

Early Rotliegend volcanics occur nearly exclusively in western Poland (Fig. 2D), where they attain thicknesses of the order of a few hundred meters (POKORSKI *in* MAREK & PAJCHLOWA, 1997); their occurrences overlap the area of the Mid-Polish Anticlinorium, and of the Mid-Polish Furrow, only in a part of north-western Poland (Figs 1, 2D, 5-7). On the other hand, numerous Variscan plutons occur in Lower Silesia, yielding Carboniferous and Early Permian radiometric ages (KRYZA, 1995). Volcanic activity ceased prior to the late Rotliegend onset of subsidence of the Mid-Polish Furrow. However, in this context, it must be noted that the thermal anomaly introduced during the Permo-Carboniferous tectono-magmatic event played a significant role in the subsidence of the Southern Permian Basin of Central Europe, of which also the Polish Basin formed part (VAN WEES *et al.*, 2000).

In the Holy Cross Mountains, pre-Permian magmatic activity is very poorly expressed by minor occurrences of lamprophyre and diabase. In the neighbouring Lublin region, similar diabases are demonstrably of earliest Carboniferous (Bretonian) age (ŻELICHOWSKI, 1972).

During the Late Permian and Mesozoic evolution of the Polish Rift, there is no evidence for any magmatic activity.

MULTISTAGE BASIN EVOLUTION

Quantitative subsidence analyses (DADLEZ *et al.*, 1995) revealed two stages of extension affecting the evolution of the Polish Rift Basin, one in the Permian and Early Triassic, the other in the Late Jurassic. The estimated beta stretching factors range from quite small values to 1.74 for the Permo-Triassic period of extension, and suggest strongest Late Jurassic extension in the southern part of the basin. These interpretations are in good agreement with geological evidence. However, a greater number of phases of extension is indicated or suggested by geological data.

There is good geological evidence for rifting in late Rotliegend, Zechstein and Buntsandstein (pre-Röt) times (POŻARYSKI & BROCHWICZ-LEWIŃSKI, 1978, 1979; KARNKOWSKI, 1980; POKORSKI; 1988; WAGNER, 1988; SZYPERKO-TELLER & MORYC, 1988; ANTONOWICZ *et al.*, 1994; HAKENBERG & ŚWIDROWSKA, 1997). The Mid-Polish Furrow was then clearly outlined as an axis of subsidence (Fig. 7A, B); there is also ample evidence for syndepositional faulting, especially along the north-eastern border of the rift graben (Fig. 5A, B). Interestingly, the Wolsztyn Swell developed west of the Mid-Polish Furrow in the Permian (Fig. 7A, B), possibly as a roll-over structure. In Buntsandstein time, the Szczecin-Kalisz Swell came into evidence in a similar tectonic position.

In marked contrast, the thickness patterns of Röt, Muschelkalk and lower Keuper deposits (Figs 7C, D, 8E) delineate a downwarped basin, with depocenters located west of the Mid-Polish Furrow (GAJEWSKA, 1988a and in MAREK & PAJCHLOWA, 1997). The geometry of these deposits is suggestive of a sag-basin stage of evolution of an asymmetrical rift basin.

Geological evidence for extension is again available for the Rhaetian, Early Jurassic, and early Middle Jurassic (SANDLER, 1969; DADLEZ & FRANCZYK, 1976; POŻARYSKI & BROCHWICZ-LEWIŃSKI, 1978, 1979; KARNKOWSKI, 1980; GARETSKY, 1985; DECZKOWSKI & FRANCZYK, 1988a, b; DAYCZAK-CALIKOWSKA & MORYC, 1988; KUTEK, 1994; HAKENBERG & ŚWIDROWSKA, 1997). This evidence includes the development of a distinct northeastern rift border (Fig. 5A-C), and a differential thickness pattern clearly depicting the Mid-Polish Furrow as an axis of subsidence (Fig. 8A-D). Characteristically, the Wielkopolska High came into evidence during the Rhaetian, and continued to develop until the late Bajocian (Fig. 8A-D). The widespread but fairly thin Bathonian deposits, as shown in the figure 8C, suggest a change of tectonic regime.

Late Jurassic extension, most strongly expressed in southern Poland near the Carpathians, is attested by quantitative subsidence analyses (DADLEZ *et al.*, 1995), and the thickness pattern of Upper Jurassic deposits (Fig. 9A). Spectacular examples of syndepositional faulting are provided by Oxfordian deposits of the Cracow-Silesian Monocline (Fig. 6B). In the Oxfordian, strongest subsidence occurred at some distance to the west of the rift border (KUTEK, 1994; HAKENBERG & ŚWIDROWSKA, 1997); this is a feature consistent with the numerical model of simple-shear extension, developed by ISSLER *et al.* (1989).

However, several discrete tectonic events can be recognized during the Late Jurassic evolution of the Polish rifted basin. Extension in the late Oxfordian (Bimammatum and Planula Zones) is indicated by a strongly differentiated facies and thickness pattern, and by syndepositional faulting. A sag-basin stage of tectonic evolution is indicated, in turn, by the much more homogenous facies and thickness pattern of the lower Kimmeridgian sediments (Platynota and Hypselocyclum Zones) preserved along the margins of the Holy Cross Mountains and in the Nida Depression and the Cracow-Silesian Monocline (KUTEK, 1968, 1994; MATYJA, 1977; GUTOWSKI, 1998). An extensional phase in Kimmeridgian to Tithonian time is indicated by the Upper Jurassic deposits preserved east of the Mid-Polish Anticlinorium in the western Ukraine (Fig. 5C; SANDLER, 1969; GARETSKY, 1985; KUTEK, 1994). A still greater number of alternating Late Jurassic extension and post-extension phases is suggested by sequence stratigraphy (KUTEK, 1994).

Several data (e.g., KUTEK *et al.*, 1984; MATYJA & WIERZBOWSKI, 1995) indicate that the region in southwestern Poland, now devoid of Jurassic deposits (Fig. 1), was a site of marine sedimentation during the Oxfordian and early Kimmeridgian. As Cenomanian deposits overlie pre-Jurassic rocks in parts of this region, the Oxfordian and lower Kimmeridgian sediments must have been removed by erosion in latest Jurassic and Early Cretaceous times. Uplift of that region in latest Kimmeridgian and Volgian/Tithonian time is suggested by biogeographical data (KUTEK & ZEISS, 1997). Uplift during the Albian is indicated by the occurrence of coarse-grained Albian sediments in the Łódź Depression (RACZYŃSKA, 1979).

Despite the moderate thicknesses of the Lower Cretaceous deposits preserved in Poland beyond the Carpathians (Fig. 9C), extension in Neocomian (Berriasian to Hauterivian) time is indicated by the development of the Mid-Polish Furrow as an axis of subsidence (Fig. 9B), and several examples of syndepositional faulting (POŻARYSKI, 1970; MAREK, 1983, 1988; KUTEK & MARCINOWSKI, 1996a).

During the middle Albian, the Meta-Carpathian Arch was transected by a narrow marine strait, trending NW-SE along the north-eastern border of the Polish Rift. Through this sea-way, subboreal ammonites migrated from the Central European Basin into the Carpathian domain (KUTEK & MARCINOWSKI, 1996b). This strait remained open and widened during the late Albian, encompassing a part of the area of the Miechów Depression. In this area there is a marked contrast between the NW-SE trending, and suggestive of block-faulting, distribution and thickness pattern of upper Albian deposits, and that of Cenomanian deposits (HAKENBERG, 1986), which widely overstep the Albian ones. The available evidence, though circumstantial in part, indicates that a rifting event occurred in south-eastern Poland in middle to upper Albian time.

Significantly, evidence for rifting during the Permian and Early Triassic is provided by northern and central Poland, whereas most evidence for Middle and Late Jurassic, and Early Cretaceous, extension phases can be found in southern Poland, near the Carpathians. Several tectonic events recognized in the Carpathian foreland appear to be synchronous with events that occurred in the Carpathian domain during the Jurassic and Cretaceous (KUTEK, 1994; KUTEK & MARCINOWSKI, 1996b).

BASIN INVERSION

The Mid-Polish Anticlinorium, as defined by numerous exploration wells, reflection-seismic data and outcrops in the Holy Cross Mountains area, is the most spectacular manifestation of inversion of the Polish Permo-Mesozoic Basin (Fig. 1). Uplift of this anticlinorium was fairly uniform along strike, amounting usually to 2-3 km. Whereas in the northwestern and central parts of this anticlinorium erosion cut down into Lower Cretaceous and Jurassic strata, Palaeozoic and even Precambrian rocks are exposed in its south-eastern parts where Permo-Mesozoic strata were much thinner. Upper Cretaceous sediments are preserved along the flanks of the Mid-Polish Anticlinorium and attain substantial thicknesses in its marginal depressions, exceeding e.g., in the Łódź Depression, 2500 m (Fig. 9D).

The Laramide folds and flexures exposed in the Mesozoic margins of the Holy Cross Mountains display a north-eastern vergency. Structural analyses in the Holy Cross Mountains indicate that the deformation of the Mid-Polish Anticlinorium was of a transpressional nature (JAROSZEWSKI, 1972).

The youngest strata involved in inversion structures of the Mid-Polish Anticlinorium are early Palaeocene in age. The oldest post-inversion strata are dated as middle Eocene. Correspondingly, the main inversion of the Mid-Polish Furrow coincides with the Laramide phase of intraplate compression that affected large areas in the Alpine-Carpathian foreland (ZIEGLER, 1990; ZIEGLER *et al.*, 1995). However, there is still considerable controversy about the timing of the onset of inversion movements in Poland. In this respect, STEPHENSON *et al.* (1993), DADLEZ *et al.* (1995), as well as the authors of several palaeotectonic maps of successive stages of the Upper Cretaceous (JASKOWIAK-SCHOENEICHOWA & KRASSOWKA, 1988, and *in* MAREK & PAJCHLOWA, 1997), suggested that the axial parts of the Mid-Polish Anticlinorium commenced to be uplifted, or individualized as a zone of reduced subsidence, already during the Senonian, or even earlier. On the other hand, the interpretations presented in a similar series of maps recently published by ŚWIDROWSKA & HAKENBERG (1999) preclude any uplift of the anticlinorium prior to the Campanian in Pomerania, and prior to the Maastrichtian in southeastern Poland. Other relevant evidence seems also to be conflicting. In northern and central Poland, some Senonian sediments, where still preserved, increase in thickness in the depressions flanking the anticlinorium and thin towards its axis (MAREK, 1977; DADLEZ, 1987). On the other hand, further south, in the Miechów Depression, Upper Cretaceous sediments, at least up to the Campanian, increase in thickness towards the anticlinorium (KUTEK & GŁAZEK, 1972; HAKENBERG & ŚWIDROWSKA, 1998). In this context it must be noted that no significant intra-Senonian unconformities have been observed along the flanks of the anticlinorium. However, it should be kept in mind that the Late Cretaceous strata were deeply eroded over the culmination of the Mid-Polish Anticlinorium that has a width of about 100 km in its south-eastern parts, narrows to about 50 km in its central parts, and widens to about 75 km in the northwest. Progressive uplift and erosion probably destroyed much of the stratigraphic record of its early development.

Nevertheless, in southern Poland, there is unequivocal evidence for a tectonic event that took place mainly during the Coniacian. Whereas in the Carpathian foreland the Late Cretaceous series is continuous along the southwestern flank of the Mid-Polish Anticlinorium, Santonian sediments rest unconformably on Coniacian, Turonian, Cenomanian, and even Upper Jurassic deposits in the western parts of the Miechów Depression (HELLER & MORYC, 1985). Throughout the eastern margin of the Cracow-Silesian Monocline, a base-Senonian discontinuity is evident, implying that uplift increased to the west. In the Cracow region, local extensional deformations are indicated by tilted fault-blocks and neptunian dykes. Further west, structural and sedimentological data suggest that the Nysa Graben (Fig. 1) developed during the latest Turonian and Coniacian (WOJEWODA, 1997). The timing of these events coincides with the Subhercynian phase of foreland compression in the Carpathian and the eastern Alpine foreland (ZIEGLER 1990; ZIEGLER *et al.*, 1995).

The Cenomanian and Turonian marine sediments of the Opole, North Sudetic and Intrasudetic depressions represent relics of a previously continuous sedimentary cover. There are, however, insufficient data to evaluate to what degree these depressions developed already in pre-Senonian time as depocenters. Due to the nearly total lack of Santonian and the complete absence of Campanian and Maastrichtian strata in southwestern Poland, it is difficult to evaluate to what extent the Subhercynian and Laramide pulses of foreland compression contributed towards the structuration of this area. In this respect it should be noted that upthrusting of the basement blocks forming the Bohemian Massif commenced already during the late Turonian, intensified during the Senonian, and culminated during the Palaeocene (MALKOVSKY, 1987).

The Late Cretaceous and Cainozoic evolution of the Polish Basin can be summarized as follows: 1) Cenomanian and Turonian post-rift subsidence, followed by the Subhercynian tectonic event during the late Turonian and Coniacian; 2) Senonian subsidence, and incipient uplift of the Mid-Polish Anticlinorium (possibly only in late Senonian time); 3) Laramide main uplift of the anticlinorium during the Palaeocene; 4) Late Eocene and Oligocene transgression of thin post-inversion series across the deeply truncated anticlinorium.

CRUSTAL CONFIGURATION AND HEAT FLOW

The crustal structure of Poland, as shown in the figure 4A, is fairly well constrained by a network of refraction-seismic profiles (GUTERCH *et al.*, 1986, 1991, 1994; GUTERCH & GRAD, 1996). Whereas the East-European Craton is characterized by a crustal thickness in the 42-47 km range, the crust of Palaeozoic Platform to the southwest of the Mid-Polish Anticlinorium ranges in thickness between 28 and 35 km. The Moho discontinuity descends to depth of 50 to 55 km in the central and south-eastern parts of the Teisseyre-Tornquist Zone, which coincides fairly well with the Mid-Polish Anticlinorium in northwestern and central Poland, but less so in southeastern Poland (Figs 1, 4A, 11). Only beneath the north-western part of this anticlinorium is the Moho slightly uplifted, as could be expected for a slightly inverted rift.

The present-day crustal configuration has been attributed to: 1) "docking" of Palaeozoic crust against Proterozoic crust during Palaeozoic orogenies; 2) modifications of the crust during Permo-Carboniferous wrenching and the subsequent formation of the Polish Trough; 3) modification of

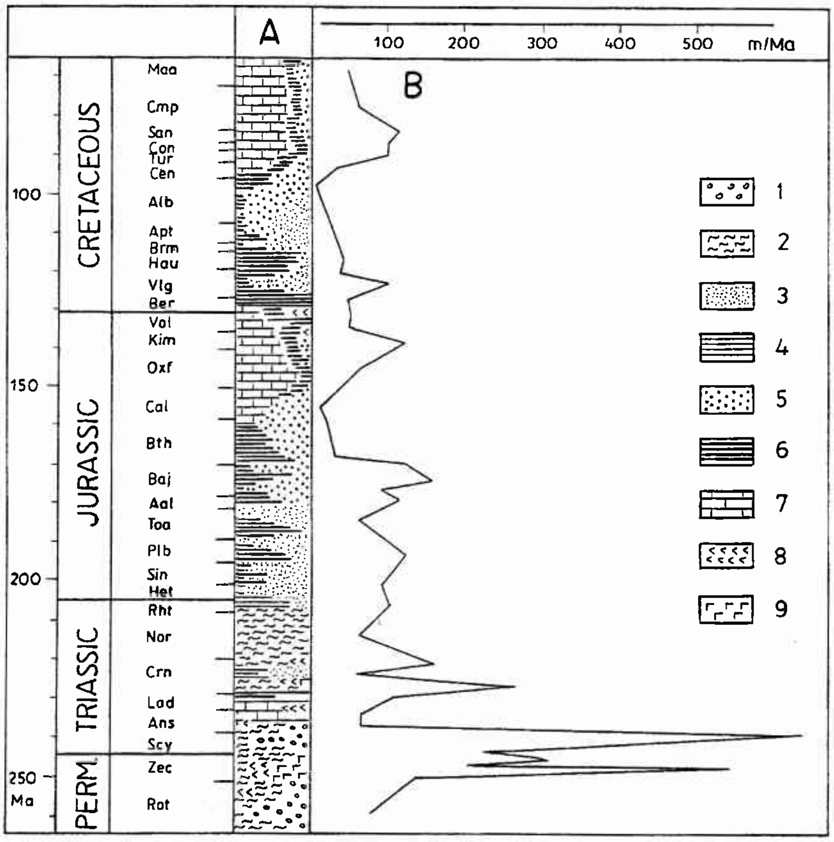

FIG. 10.— Lithologic successions of Permian and Mesozoic epicontinental sediments in Poland (**A**), and maximum sedimentation rates in the Mid-Polish Furrow (**B**), after DADLEZ, 1989. **1**, red-beds (conglomerates and sands); **2**, red-beds (mudstones and shales); **3**, continental and paralic sands; **4**, continental and paralic shales; **5**, marine sands; **6**, marine shales; **7**, marine carbonates; **8**, anhydrites; **9**, rock salts.

*FIG. 10.— Successions lithologiques des sédiments épicontinentaux permiens et mésozoïques en Pologne (**A**) et maximum de taux de sédimentation dans le Sillon Médio-Polonais (**B**), d'après DADLEZ, 1989. **1**, couches rouges (conglomérats et sables) ; **2**, couches rouges (argilites et shales) ; **3**, sables continentaux et paraliques ; **4**, shales continentaux et paraliques ; **5**, sables marins ; **6**, shales marins ; **7**, carbonates marins ; **8**, anhydrites ; **9**, sels.*

the crust during the Late Cretaceous-Early Palaeogene Basin inversion (STEPHENSON *et al.*, 1993; GUTERCH & GRAD, 1996). The following aspects of Poland's crustal structure and evolution are also worth of note.

A laminated structure of the lower crust has been revealed by wide-angle and near-vertical reflection surveys within the relatively thin crust of the Fore-Sudetic region in south-western Poland (GUTERCH *et al.*, 1991), where a thick orogenic crust presumably developed during the formation of the Variscan Fore-Sudetic thrust belt (Figs 2C, 4A, 11). This suggests significant post-Variscan crustal extension in the area forming the south-western flank of the T-T Zone, and of the Mid-Polish Furrow.

In southeastern Poland and the western Ukraine, as displayed by refraction-seismic profiles (Fig. 11), crustal thicknesses in the range of about 50-60 km are observed beneath the Lublin Graben and the Radom-Kraśnik Uplift, which coincide with an area of Permo-Carboniferous transpressional deformation. On the other hand, the crustal thicknesses decrease to 36 km westwards across the Mid-Polish Anticlinorium along the profile VIII, which parallels the Caledonian and middle Carboniferous Variscan structures of the Holy Cross Mountains (Figs 2C, 11). Thus, in south-eastern Poland, the crustal configuration displays good correlation only with the Permo-Carboniferous wrenching event. It is more difficult to evaluate how particular tectonic processes contributed to the present-day crustal configuration in central and northern Poland, where the effects of Permo-Carboniferous tectonics, and of the formation of the Mid-Polish Furrow and the Mid-Polish

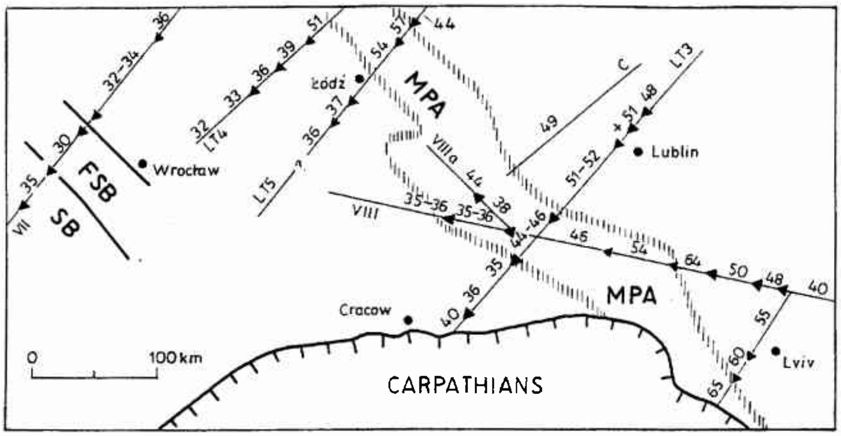

FIG. 11.— Crustal configuration in southern Poland and western Ukraine, as revealed by deep refraction-seismic profiles (after ŻYTKO, 1985, simplified). MPA, Mid-Polish Anticlinorium; FSB, Fore-Sudetic Block; SB, Sudetic Block.

FIG. 11.— Configuration crustale en Pologne méridionale et en Ukraine occidentale, d'après les profils de sismiques réfraction (d'après ŻYTKO, 1985, simplifié). MPA, Anticlinorium Médio-Polonais ; FSB, Bloc avant-Sudète ; SB, bloc Sudète.

contributed to the present-day crustal configuration in central and northern Poland, where the effects of Permo-Carboniferous tectonics, and of the formation of the Mid-Polish Furrow and the Mid-Polish Anticlinorium, where superimposed on the effects of the formation of the Caledonian frontal thrust belt (Figs 1, 2C, 4A). In any case, the available seismic and geologic data appear to indicate that the faulted north-eastern border of the Mid-Polish Furrow was located in a zone where a thick (hence weak) crust existed prior to the late Rotliegend.

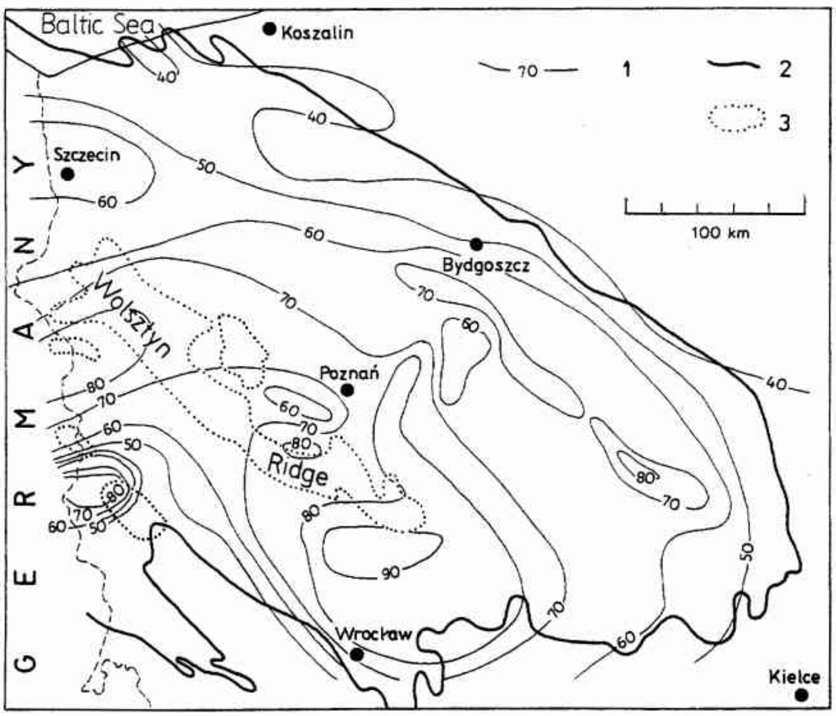

FIG. 12.— Map of Permian to Jurassic heat flow, based on computer modeling (courtesy of P.H. KARNKOWSKI). **1**, limits of the Rotliegend Basin; **2**, heat flow in mWm^{-2}; **3**, outline of Wolsztyn Swell.

FIG. 12.— Une carte du flux thermique du Permien au Jurassique, basée sur une modélisation informatique (document aimablement fourni par P.H. KARNKOWSKI). 1, limites du bassin Rotliegend ; 2, flux thermique en mWm^{-2} ; 3, aperçu de l'antéclise de Wolsztyn.

The heat flow map given in the figure 12 is based on a large amount of unpublished vitrinite reflectance data, collected by the petroleum industry. High values of Permian to Jurassic heat flow are recorded to the west of the Mid-Polish Furrow, and the Mid-Polish Anticlinorium, where fairly low Permian and Mesozoic thermal gradients are also indicated by conodont colour alteration data (BEŁKA, 1990). This evidence, together with the absence of Mesozoic magmatic activity, suggests that the lithosphere/astenosphere boundary was not significantly disturbed beneath the Mid-Polish Furrow during the rifting stages of its tectonic evolution.

MINERAL RESOURCES

In the Polish Lowlands, commercial hydrocarbon accumulations are essentially restricted to Permian Rotliegend sands and Zechstein carbonates. Gas contained in Rotliegend reservoirs covers only part of Poland's requirements. So far, no giant gas fields, comparable to those of the North Sea, have been found in Poland. Zechstein carbonates contain several, generally small oil accumulations. The Mesozoic strata of the Polish Lowland are devoid of commercial oil and gas accumulations, despite the fact that strong subsidence in the Polish Basin induced favourable thermal conditions for the maturation of potential source-rocks. This is mainly due to the paucity of viable source-rocks in the Mesozoic series that have entered the hydrocarbon generation window. Moreover, the poor quality of potential sealing rocks and the rather important basin inversion are also degrading factors. However, some oil and gas accumulations occur in Mesozoic strata in the Carpathian Foredeep. These were, charged with oil generated by source rocks, chiefly Oligocene in age, contained in the Carpathian flysch nappe systems which in themselves host numerous oil fields (BESSEREAU *et al.*, 1996).

Rock salt is a remarkable constituent of the Zechstein successions in a large part of the Polish Permian Basin, in contrast to the much more restricted occurrences of deposits of potassium-magnesium salts.

Of considerable economical value are copper deposits that developed at the base of the Zechstein in Lower Silesia, and lead-zinc deposits housed in carbonate rocks of the Muschelkalk in Upper Silesia and the Cracow-Silesian Monocline. The copper ores, which are connected with the Zechstein Kupferschiefer, contain also other elements (Ag, As, Au, Ni, Pb, Se, Zn). The lead-zinc ores are developed as stratiform deposits; their location is controlled, to some degree, by a network of extensional and strike-slip faults. Sedimentary iron ores of Early and Middle Jurassic age have lost their economical value.

The lithologically diversified Permo-Mesozoic series also contains a large number of raw materials, such as building and road stones, ceramic clays, foundry and glass sands, and limestones, marls and clays for cement and lime industry.

Further information on the mineral resources of Poland can be found in a recent paper of PRZENIOSŁO (1996).

DISCUSSION

The Mid-Polish Anticlinorium developed by latest Cretaceous and Palaeocene inversion of the Mid-Polish Furrow, that formed part of the Polish Permo-Mesozoic Basin. The inverted basin extends from the Baltic Sea over a distance of about 800 km to the southeast where it disappears beneath the Carpathian nappes.

The Mid-Polish Furrow is superimposed on the Caledonian suture between Palaeozoic Europe and the Precambrian East-European Craton, and roughly coincides with the Teisseyre-Tornquist Zone. During the Variscan orogeny the southern parts of this zone were reactivated, with compressional intraplate deformations controlling uplift of the Holy Cross Mountains, and the Malopolska Massif to the south. At the end of the Carboniferous, the domain of the T-T Zone was probably characterized by thickened and rheologically weak crust. During the Permo-Carboniferous tectonic event, the T-T Zone was reactivated by wrench faulting; however, there is no evidence for contemporanous magmatic activity. Correspondingly, it is likely that its crustal configuration was not significantly changed, except for possible transpressional thickening in its southeastern part and possible transtentional thinning in its northwestern part.

Regional isopach maps of late Rotliegend and Zechstein series, as well as quantitative, subsidence curves, indicate that the Mid-Polish Furrow began to subside during late Early and Late Permian times. There is also evidence for several major and minor pulses of extension during the Mesozoic, with the last extensional pulse in the middle and late Albian. This indicates that the evolution of the Polish Permo-Mesozoic Basin was indeed rift-controlled.

This is corroborated by the asymmetric geometry of the Polish Basin, as shown by regional cross-sections that were restored to the their pre-inversion configuration. These indicate that this basin was characterized by a system of major break-away faults along its north-eastern margins whereas its south-western margin is more diffuse and displays the configuration of a gentle hanging-wall roll-over structure. This is suggestive of simple-shear crustal extension (WERNICKE, 1985, 1992; COWARD, 1986). In this context it should be kept in mind that along the T-T Zone the crustal fabric of the Caledonian Orogen was presumably dominated by northeast verging thrust sheets. Their tensional reactivation probably favoured a simple-shear mode of extension during the Permo-Mesozoic rifting phases of the Polish Basin. Such a model also accounts for the absence of a significant uplift of the crust-mantle boundary beneath the Mid-Polish Furrow, as well as for the higher heat flow, and the development of thinner crust with a laminated lower part, in areas flanking the furrow to the southwest.

The magnitude of crustal stretching factors across the Polish Rift Basin is difficult to determine, in particular because there are indications that rifting was not a continuous process but that it was cyclical in nature and interrupted by periods of decreased or minimal extension rates, and thermal subsidence. The fact that Jurassic and Cretaceous sediments have been completely removed by erosion from several parts of southwestern Poland is another unfavourable factor. However the depocentres that developed during the Röt, Muschelkalk and early Keuper, southwest of the Mid-Polish Furrow, can be interpreted as an asymmetrically located thermal sag-basin.

Inversion of the Polish Rift probably commenced during the Senonian and culminated during the Palaeocene. The main inversion phase post-dates the Albian rifting by some 30-40 Ma. The basin inversion was transpressional in nature. The Mid-Polish Anticlinorium, that was formed as a result of this inversion, has a structural relief mostly in the range of 2-3 km. Eocene and younger subsidence across the inverted basin was very minor, reflecting that after its inversion the lithosphere of Poland was essentially in thermal equilibrium with the asthenosphere (ZIEGLER *et al.*, 1995).

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