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EWA TOMCZYKOWA and HENRYK TOMCZYK

STRATIGRAPHY OF THE POLISH SILURIAN AND LOWER DEVONIAN AND DEVELOPMENT OF THE PROTO-TETHYS

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The biostratigraphic value of graptolites of Polish Silurian is discussed. This group makes possible a detailed zonation of deposits ranging in age from the Llandovery to the Ludlow the *leintwardinensis* Zone. Younger Silurian deposits of Poland divided into Siedlce and Podlasie Series and subsequently graptolite biozones, represent reference section for Upper Silurian of other regions.
Shelly fauna of the Polish Silurian, sometimes accompanied by graptolites, indicates isolation of shelves of the Gondwanian and Fennosarmatian continents. An attempt is made to reconstruct the history of the Proto-Tethys Ocean separating the continents and its relation to the Proto-Atlantic.
Key words: Stratigraphy, paleogeography, graptolites, Silurian, Lower Devonian, Proto-Tethys, Poland.

Ewa Tomczykowa and Henryk Tomczyk, Instytut Geologiczny, ul. Rakowiecka 4, 00-975 Warszawa, Poland. *Received: June 1978.*

INTRODUCTION

The discovery of the clay lithofacies predominating in the Polish Lowlands markedly contributed to the knowledge of graptolite succession in the Silurian of Poland. The lithofacies is connected with the deep part of the Fennosarmatian shelf i.e. the marginal part of the Epigothic East-European Platform (fig. 1). In Poland, it was recorded in over 200 deep drillings made in the Peribaltic, Podlasie and Lublin depressions. The Lublin depression is closely connected with northern part of the Swiętokrzyskie Mts (Holy Cross Mts) in the south-west and the Podolia region in the south-east. In all the borehole sections studied by the authors, claystones occur in the interval from the Llandovery to the Gedinnian, attaining 800 to 3500 m in thickness. The core material gathered in the years 1957—1977 made it possible to trace the stratigraphic ranges of graptolite species, genera and even families. The data concerning the ranges and variation of graptolite species are sufficient to identify biozones or, sometimes, even their parts.

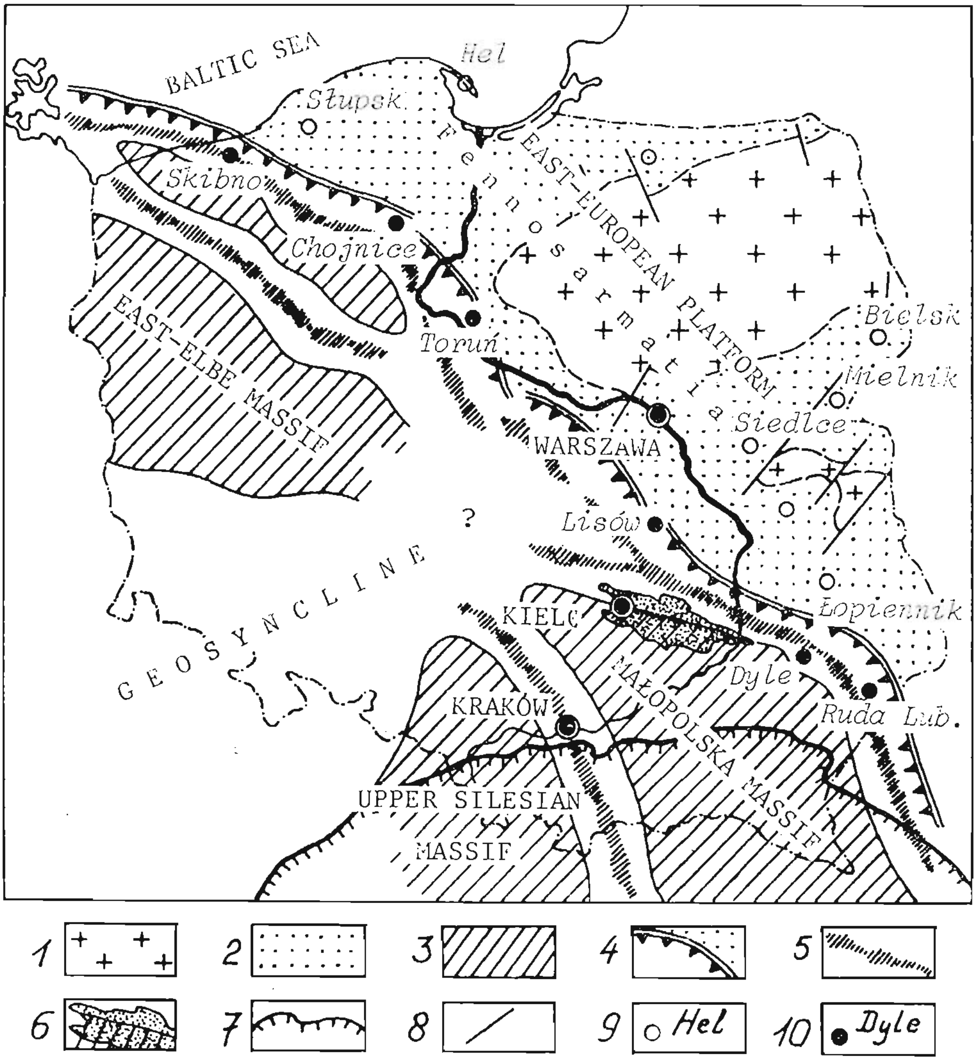

Fig. 1. Tectonic-regional subdivision of Poland with the reference to the Caledonian epoch: *1* bedrock of the East European Platform, without Paleozoic sedimentary cover in Mazury-Byelorussian anteclize; *2* Lower Paleozoic (Cambrian, Ordovician and Silurian) preserved in the area of the East European Platform: the Peribaltic syneclize on the north and the Podlasie and Lublin depressions on the south-east; *3* present-day arrangement of pre-Caledonian, mainly Baikalian (Assynthian-Cadomian) massifs and blocks: Szczecinek block (massif) marked NE of the East Elbe massif after Pożaryski (1978); *4* margin of old, epi-Gothian East European Platform according to geological, geophysical and deep borehole data; *5* inferred deep facture zones; *6* the Paleozoic of the Holy Cross Mts divided into southern Kielce region belonging to the Małopolska Massif and northern Łysogóry region situated in labile zone of the Platform slope; *7* Carpathian overthrust; *8* major faults; *9* main boreholes in the East European Platform; *10* main boreholes in marginal and slope parts of epi-Gothian East European Platform.

The elaboration of the stratigraphic subdivision of the Polish Silurian down to biozones proceeded gradually starting from the works of Czarnocki (1936), Kozłowski (1929), Samsonowicz (1934) and others. Along with further works, especially those connected with first deep drillings in the East-European Platform, graptolite index species were differentiated in the Peribaltic, Podlasie and Lublin depression (Tomczyk 1960, 1962, 1970; Teller 1964; Urbanek 1966, 1970). Unification of graptolite zonal schemes for the whole Platform made it possible to introduce regional stratigraphic units such as the Pasłęk, Mielnik, Siedlce and Podlasie Beds (Tomczyk 1962). At the same time, the Bardo and Prągowiec Beds or their narrower regional equivalents were proposed for the area of the Świętokrzyskie Mts (Tomczyk 1962).

Graptolite zones of the Silurian of the Platform, the Świętokrzyskie and Sudeten Mts may be also easily correlated with those of the Wales and Barrandian in the case of the Llandovery, Wenlock and Ludlow, up to the top of the *Saetograptus leintwardinensis* Zone. Some minor differences are connected with interpretation of the Wenlock/Ludlow boundary and the correlation of the Sheinwoodian, Homerian, Eltonian, Bringewoodian and Leintwardinian stages with the Polish regional Bielskian and Mielnikian stages (Tomczykowa and Tomczyk 1969).

The graptolite facies disappear in Great Britain in the *leintwardinensis* Zone but not in deep parts of the Polish sedimentary basin. In the latter area, it can be observed in the slope of the Fennosarmatian shelf where the Siedlce and Podlasie deposits were formed with graptolites representing continous evolutionary series (fig. 2). The opposite, southern shelf of the Proto-Tethys was characterized by different sedimentary conditions and shelly fauna (Tomczykowa 1975*b*). The Upper Silurian of the Carnic Alps and Barrandian primarily comprises carbonate deposits with some intercalations of graptolite-bearing claystones. The claystones represent only some parts of the continuous sequence of clay deposits of the Siedlce and Podlasie Series. The Siedlce Series contains a very rich and highly differentiated graptolite assemblage and the Podlasie Series — a very poor assemblage, limited to *Mono-*, *Pristio-* and *Linograptus* with simple morphology, indicative of the fact that the group was approaching extinction. Only some relic monograptid persisted in deeper parts of the sedimentary basin till the end of the Early Devonian.

STRATIGRAPHY

Llandovery. — There are no greater differences between the interpretation of the Ordovician/Silurian boundary or the Llandovery zonal scheme used in Poland and the graptolite zonation of the classic area in England (Cocks et al. 1971; Tomczyk and Tomczykowa 1976). The Lower/

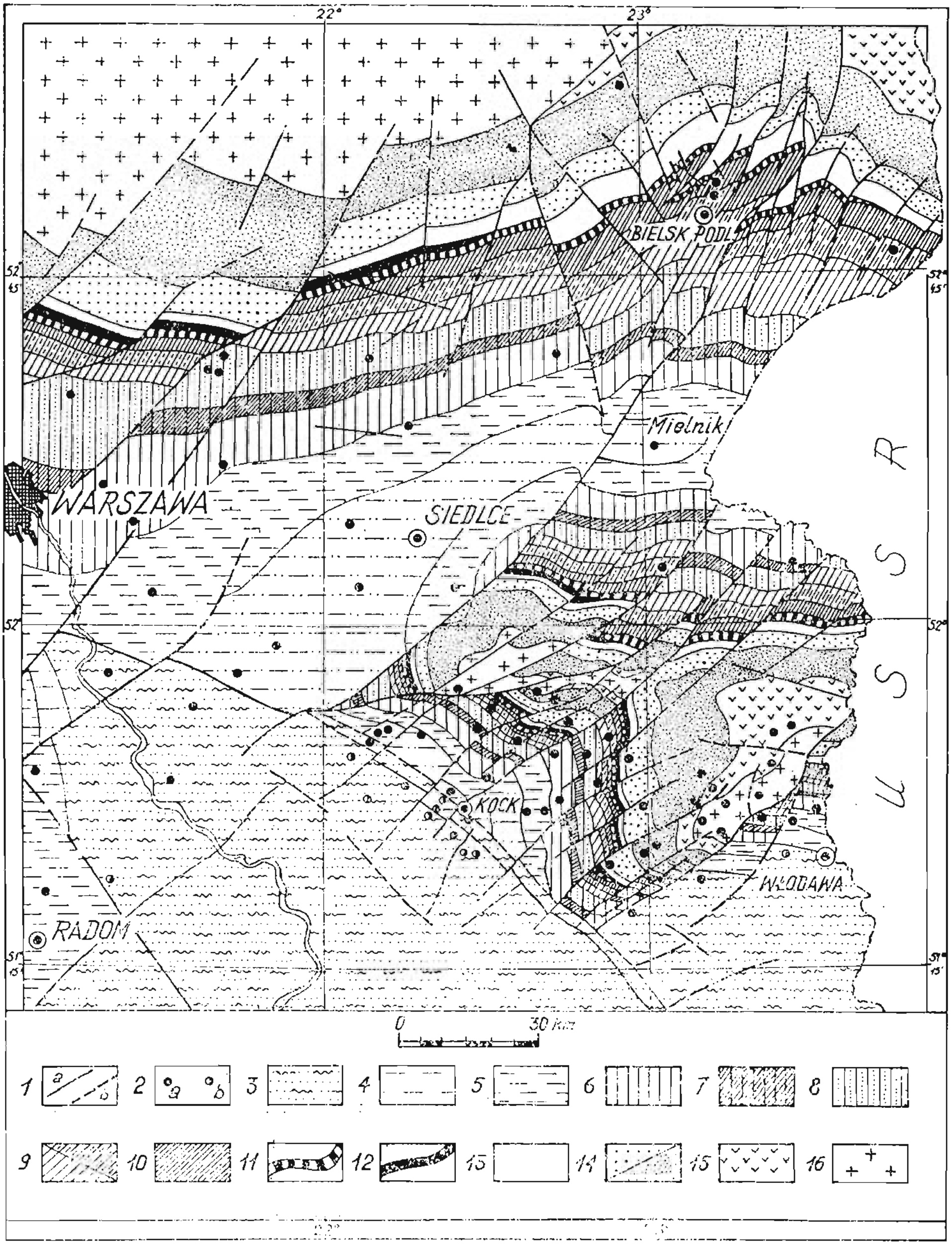

Fig. 2. Geological map of Emsian subcrops in eastern Poland (after unpublished map of H. Tomczyk, 1977): *1a* faults, *1b* inferred faults, *2a* boreholes entering Silurian or older rocks, *2b* boreholes ending in Devonian rocks younger than Emsian, *3* Lower Devonian (Gedinnian and Siegenian), mainly marine, *4* Upper Podlasie, *5* Lower Podlasie, *6* Upper Siedlce, *7* Middle Siedlce, *8* Lower Siedlce, *9* Mielnikian, *10* Upper Bielskian, *11* Lower Bielskian, *12* Llandovery, *13* Ordovician (Ashgill Arenig; including Tremadoc in the Bielsk Podlaski area only), *14* Lower and Middle Cambrian, *15* Upper Eocambrian — Vendian, *16* crystalline basement of the East European Platform.

Upper Llandovery boundary hitherto used in Poland (Tomczyk 1970) is consistent with that between the British Idwian and Fronian stages coinciding with the *convolutus* Zone (table 1). Some small changes recorded at the top of the Llandovery in Poland but not in England, may be explained by Bohemian influences. This is emphasized by the development of the *spiralis* and *grandis* Zones above the *crenulata* Zone.

Wenlock. — In Poland, sedimentation was continuous at the turn of the Llandovery and Wenlock. The boundary between the *grandis* and *insectus* Zones, is well correlative with the stratotype sections from England, despite the replacement of the *centrifugus* Zone by the *insectus* Zone. Wenlock deposits comprising the *insectus* — *testis* graptolite zones were defined as the Bielskian stage (Tomczykowa and Tomczyk 1979) and divided into the lower and upper substages which differ in range from the British Sheinwoodian and Homerian stages. The Wenlock is associated with the flourishing of Cyrtograptidae whose specific diversity was of particular importance for graptolite zonation. The increase in the number of cladia in the *Cyrtograptus ramosus* — *C. multiramis* — *C. radians* evolutionary series may be an example here. It is also possible to trace the reduction in the number of cladia from four in *C. lundgreni* to one or none in *C. serbicus*. The reduction is closely connected with the extinction of Cyrtograptidae and, therefore, with the Wenlock/Ludlow boundary. The top of the Bielskian stage is marked by the extinction of *Testograptus testis*, unlike Wales where the *testis* Zone is not differentiated. In Poland, similarly to Czechoslovakia, *T. testis* appears in the upper part of the range of *C. lundgreni*. The zone with this index species is best developed in the Peribaltic syneclize, where the range of *Testograptus* ex gr. *testis* associated with a rich assemblage of other graptolites comprises deposits about 3000 m thick. The top of the *testis* Zone is marked by the extinction of Cyrtograptidae and *Monograptus flemingi* and *Monoclimacis flumendosae*, typical of the Wenlock, and by the appearance of still scarce representatives of the genus *Gothograptus*. The latter predominate above the *testis* Zone as *G. nassa* partial-range Zone, representing the basal part of the Mielnikian stage, corresponding to the Ludlow Series according to Tomczyk (1956, 1970). The biostratigraphy of the Wenlock and Ludlow and the problem of the boundary of these stages is discussed in detail elsewhere (Tomczykowa and Tomczyk 1979).

Ludlow. — The Mielnikian stage (Tomczykowa and Tomczyk 1979) comprises the *nassa* — *leintwardinensis* Zones. It is further divided into the lower and upper substages, the boundary between which is the top of the *Neodiversograptus nilssoni* range Zone (table 1, fig. 2). It should be noted that the Homerian/Eltonian and, at the same time, the Wenlock/Ludlow boundary is at present drawn at the base of the *N. nilssoni* Zone in England (Cocks *et al.* 1971; Bassett *et al.* 1975). The deposits of the interval from the *G. nassa* to *N. nilssoni* Zones, also referred to as

Table 1

System	Series	Stages and Substages		Graptolite zones or other index fauna	Phases
DEVONIAN /Lower/	EMS	OLD - RED			
	SIEGEN	*Ciepielovian	Upper	Bivalves, brachiopods, tentaculitids etc.	Erian
			Lower	**P.angusticostatus **T.novus ↑ **A.rouaulti - **P.forbesi	
	GEDINNE	*Bostovian	Upper	**D.vialai **D.bostoviensis ↑	
			Lower	**Podolites rugulosus ↑ **A.elsana - **A.tiro	
SILURIAN	PODLASIE	Stages yet not erected	Upper	M.angustidens P.transgrediens ↑ M.bouceki - M.perneri	
			Lower	P.samsonowiczi ↑ M.ultimus	Ardenian
	SIEDLCE		Upper	↑ Formosograptus	
			Middle	M.tomczyki - M.haupti	
			Lower	N.kozlowskii ↑ B.bohemicus - C.aversus	Cracow
	LUDLOW	*Mielnikian	Upper	S.leintwardinensis ↑ L.progenitor	
			Lower	N.nilssoni ↑ G.nassa	?
	WENLOCK	*Bielskian	Upper	T.testis C.lundgreni ↑ C.rigidus	
			Lower	M.flexilis ↑ C.murchisoni C.insectus	
	LLANDOVERY	Upper	Telychian	S.grandis - M.crenulata ↑ M.crispus	
			Fronian	S.turriculatus M.sedgwicki	
		Lower	Idwian	D.convolutus C.gregarius	
			Rhuddanian	P.revolutus - C.cyphus ↑ A.ascensus - G.persculptus	Taconian
ORDOVICIAN /Upper/	ASHGILL			**B.platynota - M.mucronata ↑ **S.clavifrons - **T.granulata	
	CARADOC			C.styloideus D.clingani ↑ Nemagraptus gracilis	

* - Regional stages ** - Trilobite zones

nassa/dubius interregnum, are very well developed in Poland, attaining 15 to 400 m in thickness. Graptolites are usually common here. A special attention should be paid to Retiolitidae, highly differentiated even at the generic level (*Gothograptus, Plectograptus, Holoretiolites, Spinograptus*). Monograptids are less characteristic but their morphological structure is closer to the Ludlow species than to the Wenlock.

Retiolitidae gradually disappear in the upper, Mielnikian stage, being represented by the genera *Plectograptus* and *Holoretiolites* only. Here predominate Ludlow monograptids with typical lineages of *Lobograptus* and *Cucullograptus* as well as characteristic Saetograptinae (see Urbanek 1966). The upper Mielnikian stage corresponds to the upper Eltonian, Bringewoodian and Leintwardinian stages of England. The stages are very restricted, almost to single graptolite zones. It should be noted here that graptolites, on which the zonation of stratotype of older British Silurian is based (Elles and Wood 1900—1914; Cocks *et al.* 1971), disappeared in England in the Leintwardinian stage.

Siedlce. — In Poland, the Upper Silurian may be subdivided into graptolite zones (table 1; fig. 2); this suggested introduction of new stratigraphic units, the Siedlce and Podlasie (Tomczyk 1962, 1970), recently regarded as series (Tomczyk *et al.* 1977). Above the *leintwardinensis* Zone, there may be traced characteristic development of graptolite genera *Bohemograptus, Neolobograptus* and *Neocucullograptus* (Urbanek 1970), not known from the English Whitcliffian stage and still insufficiently known from the Kopanina Formation of Barrandian. These trends in evolution of graptolites, closely connected with the earlier ones of the Ludlow (Urbanek 1966, 1970), comprises 7 graptolite zones of the lower stage of the Siedlce series (Tomczyk 1970). The series previously differentiated as the Lower Siedlce Beds (Tomczyk 1962), contains deposits of clay-siltstone lithofacies best developed in the marginal part of the East-European-Platform and attaining 100 to 1200 m in thickness (fig. 2). In the Świętokrzyskie Mts, the siltstone-greywacke formation (Niewachlów Fm.) with disappearing graptolites is developed from the *scanicus*, and especially *leintwardinensis* Zones upwards, and is fairly thick (Czarnocki 1936; Tomczyk 1956, 1962). In the Sudeten, deposits younger than the *scanicus* Zone are represented by the Lower Żdanów Beds without graptolites (Malinowska 1955).

The disappearance of graptolite-bearing clay facies to the advantage of carbonate or other facies above the *S. leintwardinensis* Zone is widely known in England. In Thuringia, Frankenwald and Sardinia the Lower Graptolite Shales are succeeded by the Ockerkalk, whereas carbonate deposits prevail in Morocco and Barrandian. Up to the present, no equivalents of Polish sections with continuous clay sedimentation and a full evolutionary series of graptolites *Bohemograptus, Neolobograptus* and *Neocucullograptus* are known from other parts of Europe. We are familiar only with some fragmentary sections of graptolite zones, e.g. *B. bohemicus* or *N. inexspectatus* from the top of the Kopanina Fm. in Barrandian and from the Upper Silurian in Yugoslavia (Bouček 1932; Mihajlović 1974).

The middle stage of the Siedlce series still comprises claystones and siltstones up to 200 m thick. Graptolites occurring here are represented by not very characteristic monograptids such as *Monoclimacis tomczyki*, *M. haupti*, *Pristiograptus dubius frequens*, *P. longus*, *P. fragmentalis*, as well as *Linograptus*. This part of the section features the lack of representatives of *Bohemograptus* and *Formosograptus*, typical of the lower and upper Siedlce stages, respectively (table 1; fig. 2).

The upper Siedlce stage comprises still poorly known deposits 100 to 800 m thick. Graptolites predominating here are highly characteristic and diversified (Tomczyk 1962, 1970). They mainly belong to the genus *Formosograptus*, the evolution of which is, unfortunately, still unsufficiently known. The genus includes *F. formosus*, *F. paraformosus*, *F. balticus*, *F. kallimorphus*, *F. lebanensis*, *F. convexus*, *F. purkynei*, and other species. This group is concurrent with still numerous representatives of the genera *Monograptus*, *Pristiograptus* and *Linograptus*, the graptolite fauna being so strongly differentiated for the last time. The species of the genus *Formosograptus*, are markedly differentiated in structure of rhabdosome from very thin forms to thick, and in shape — from coiled to incurved and arcuate and finally almost straight in medial and distal parts. The differentiation in structure of thecae is equally high as they range from simple and tubular through incurved and hook-like to fully separated, almost of the *Rastrites* — type. The sicula is also highly variable. All these changes occur in a definite stratigraphic sequence. They reflect evolution of this group and may be treated as progressive features highly important for stratigraphy. The evolutionary changes in the *Formosograptus* group indicate that rocks bearing these graptolites may be in future subdivided into several new biozones insted of one as it is the case in Barrandian. It should be noted that the concurrence of *Monoclimacis ultimus*, treated by some authors as an auxiliary species characterizing that biozone, indicates the upper part of the *Formosograptus formosus* range Zone only. The lower parts of the *formosus* range Zone yields other monograptids, which have not been described up to now (Tomczyk 1960, 1962).

The extinction of some graptolite groups proceeded mainly through disappearance of characteristic progressive forms and not more conservative species. This can be easily observed above the *Testograptus testis*, *Saetograptus leintwardinensis* or *B. bohemicus* Zones, especially in the case of the extinction of *Formosograptus*. Widely distributed *M. ultimus* is long-ranging, being found above the *F. formosus* Zone and used as an independent index species for a partial range zone (table 1). Similar is the case of conservative *Monoclimacis haupti*, occurring above the range of *Bohemograptus* and used together with *M. tomczyki*, *Pristiograptus dubius*, *P. frequens*, *P. longus* and others to define a partial range Zone and, at the same time, the assemblage zone (Tomczyk 1970).

The position of deposits bearing *Formosograptus* in the Upper Silurian of Poland is so important from both biostratigraphic and regional viewpoints that it appears desirable to differentiate the *Formosograptus* deposits as a separate stage, the upper stage of the Siedlce series (table 1; fig. 2).

Podlasie. — The boundary between the Siedlce and Podlasie Series is associated with the end of the evolutionary line of *Formosograptus* (Tomczyk 1960, 1962). Only rare monograptids (*M. ultimus*) and *Linograptus* are still present in the lowermost Podlasie and the graptolite assemblage seems to disappear. At the turn of the Siedlce and Podlasie, clay junction beds up to 400 m thick originated in the Peribaltic syneclize. Graptolites are very rare in these beds, being represented by single specimens of *Linograptus posthumus and Monoclimacis ultimus* and no graptolites were hitherto found above the *M. ultimus* Zone. The rocks overlying the *M. ultimus* Zone are clay-marly, about 600 m thick and rich in shelly fauna. They were subdivided into 5 ostracod-trilobite zones (Tomczykowa and Witwicka 1974).

Graptolite assemblage of the Podlasie age (fig. 2) was found in the Podlasie and Lublin depressions only (Tomczyk 1962, 1970; Teller 1964). The lower Podlasie deposits overlying the *ultimus* Zone are there divided into the *bugensius*, *chelmiensis* and *samsonowiczi* biozones (table 1; fig. 2). Graptolites occurring in these areas are poorly differentiated in morphology and the specific identifications are questioned by some authors (Jaeger 1977; Rickards *et al.* 1977). One or two graptolite species at the most were recorded in each zone and the zones are often separated by barren deposits.

The Upper Podlasie has a somewhat better faunistic record and it is divided into the *bouceki-perneri*, *admirabilis*, *perbrevis*, *transgrediens* and *angustidens* Zones) (table 1; fig. 2). The majority of these zones are also known from other areas, especially the Barrandian where they were identified much earlier (Bouček 1931, 1960; Přibyl 1941). It should be noted that the zones are separated by an interzone without any graptolites in the Upper Podlasie section. An interzone 50 to 150 m thick, with pelecypods typical of the Upper Podlasie, was traced between the *transgrediens* and *angustidens* biozones in both the Podlasie and eastern Lublin depressions (Tomczyk 1970, 1975, 1976). Some lithofacies changes and somewhat greater differentiation of fauna are first recorded in the upper part of the *angustidens* biozone yielding the trilobite *Acastella elsana*, indicative of the proximity of the Gedinnian (table 1).

Gedinnian. — In Poland, the basal Devonian deposits occurring in sedimentary continuity with the Silurian may be traced in the Lublin depression (fig. 2) and northern part of the Świętokrzyskie Mts (Tomczykowa 1962, Tomczykowa and Tomczyk 1970). The deposits overlying the *angustidens* biozone mainly contain shelly fauna whereas graptolites are very scarce here. The biostratigraphy of these deposits is based on trilobites of the subfamilies Acastavinae, Acastinae and Homalonotinae (Tomczykowa 1975*a*) as well as the pandemic species *Podolites rugulosus* (Alth). In the Bostów Beds of the Gedinnian parastratotype section from Bostów (Tomczykowa and Tomczyk 1962, 1970; Tomczyk *et al.* 1977), E. Tomczykowa found first specimen of *Cyphaspis rugulosus* Alth, 1874, originally described from Borszczów in Podolia. She assumed that this species is a senior synonym of *Cyphoproetus rugosus* Bouček, 1934, typical of the Lochkov Beds which were assigned to the Upper Silurian till 1963. This finding markedly changed the views on the age of both the Lochkov and Borszczów Beds which began to be considered as Lower Devonian.

The Bostów IG-1 borehole, and deep drillings made subsequently in the marginal part of the East-European Platform, especially in the Radom—Lublin depression, confirmed the presence of a thick series of marine deposits with very rich shelly fauna overlying the *M. angustidens* Zone in sedimentary continuity. The deposits, assigned to the Bostów and Ciepielów, stages, correspond to the Gedinnian and presumably Lower Siegenian (table 1).

CORRELATION

The value of graptolite fauna for biostratigraphy has been widely known for many years. The use of that fauna in correlating higher stratigraphic units is, however, not always satisfactory which results in contradictory interpretation of stage or series boundaries. It should be remembered that only some profiles of the European Silurian are fully developed in clay lithofacies displaying development of graptolite fauna. Profiles developed in other facies often display only single graptolite biozones or their parts. On the other hand correlation of graptolite-bearing deposits with biofacies containing shelly fauna is not always accurate. The best example is here the Wenlock/Ludlow boundary, recently revised with reference to lithostratigraphic premises (Wenlock Limestone) (see Cocks *et al.* 1971, Basset *et al.* 1975, Rickards *et al.* 1977) and not, as in the past to graptolites (Elles and Wood 1900—1914). In Poland, the Wenlock and Ludlow are developed in both clay lithofacies with graptolites and carbonate lithofacies with predominating shelly fauna, and the Wenlock/Ludlow boundary is defined by due to the

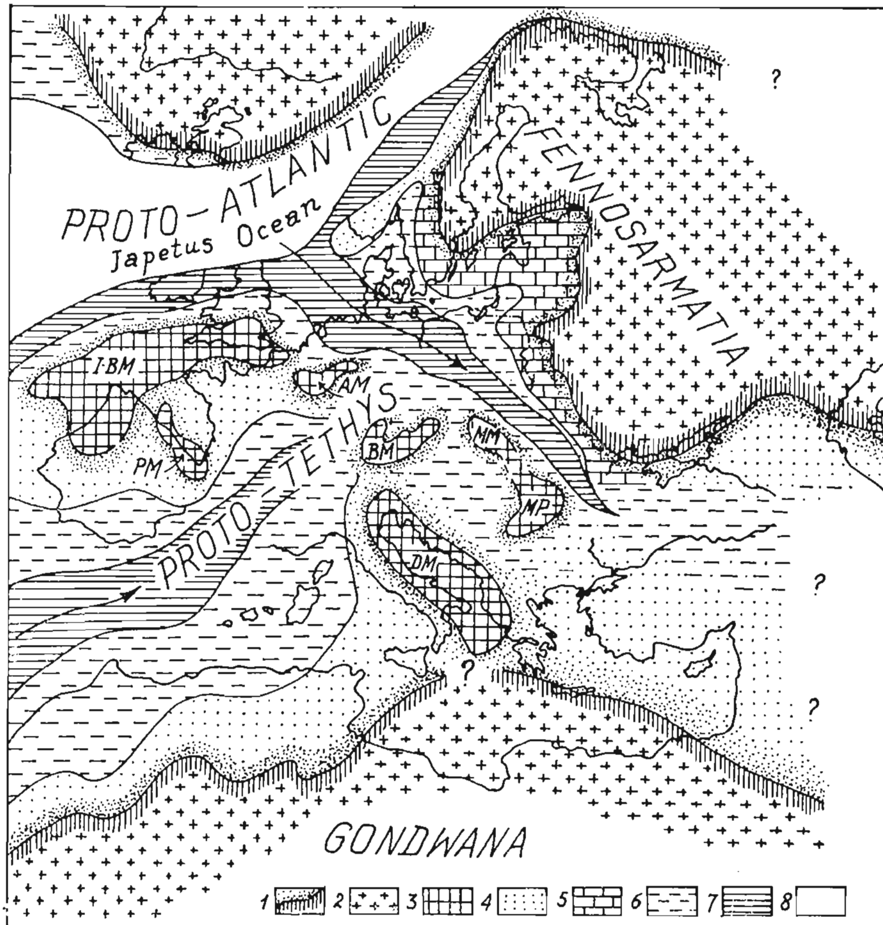

Fig. 3. The relation of shelves of Fennosarmatia and Gondwana to the Iapetus Ocean and its Welsh-Polish miogeosynclinal branch in the Early Caradocian: *1* macro-continent margins; *2* land areas of old continents; *3* inner massifs or microcontinents: PM — (?) Pyrenees massif, I-BM, Iberian-Biskay massif, AM — Ardennes massif, BM — Bohemian massif, DM — Dinaric massif, MP — Moesian plate (massif), MM — Małopolska massif; *4* mainly terrigenous shelf deposits; *5* mainly carbonate shelf deposits; *6* clay deposits of graptolite sea or deeper continental slope; *7* miogeosynclinal areas of siltstone-clay deposition and in places with graptolites; *8* Caledonian geosyncline of Proto-Atlantic Iapetus Ocean.

presence of *Testograptus testis* (see Tomczykowa and Tomczyk 1979). The boundary between Bielskian and Mielnikian stages coincides with the end of *T. testis* range, which may only refine the Wenlock/Ludlow boundary as defined by Elles and Wood (1900—1914).

The majority of members of the IUGS Subcommission on the Silurian System essentially accept the subdivision of Llandovery, Wenlock and Ludlow stages and there are only some minor differences in bio- and chronostratigraphy of these stages. The currently used subdivision is based on the English stratotype sections (Elles and Wood 1900—1914;

Cocks *et al.* 1971). However, graptolite plankton disappears from England at the end of the Lower Ludlow *sensu anglico*, i.e. at the end of the *leintwardinensis* Zone which may be explained by closing of the Proto-Atlantic geosyncline (McKerrow and Ziegler 1972; Tomczykowa and Tomczyk 1978). Sedimentation of graptolite-bearing deposits was still continuing in the Proto-Tethys. That is why the stratotypes of Upper Silurian deposits younger than Ludlow are situated at the slope of the East-European Platform. The Kopanina and Pridoli stratigraphic units from the Barrandian area, as suggested by Czechoslovakian geologists, are not based on graptolite biostratigraphy. It appears desirable to revise the upper boundary of the Ludlow. The most suitable definition seems to be that coinciding with the end of the *leintwardinensis* Zone (Tomczyk *et al.* 1977). Higher up, there should be used the stratigraphic units equivalent of Polish Siedlce and Podlasie series.

A more detailed comparison shows that the Welsh and Barrandian sections are highly diverse from the *leintwardinensis* Zone upwards. The differences may be explained by sedimentary discontinuities in the section of clay lithofacies with graptolites. The trilobite biozones of the Kopanina Fm. in Barrandian (Horny 1960) cannot be correlated with shelly fauna of the Whitcliffian of England (Lawson 1960; Holland *et al.* 1963) nor with that of the Lower Skała Beds of Podolia (Kozłowski 1929) as these faunal assemblages are entirely different. Correlation of these formations is one of the most difficult problems recognized over a wider area, e.g. the *N. inexpectatus* Zone differentiated in Barrandian, Yugoslavia and Poland, or the *Bohemograptus* range known to extend higher than that of *leintwardinensis* one (Tomczyk 1962; Urbanek 1970) are insufficient for correlating stages or series. These scanty graptolite records are insufficient for unequivocal statement whether or not the Siedlce series deposits correspond to the Whitcliffian stage or the upper part of the Kopanina Fm., the stratigraphy of which is not based on graptolites. Similarly, it is an open question whether or not Ockerkalk of Thuringia, and the Isakovtsy dolomites of Podolia represent time equivalents of the Siedlce series.

The rocks developed in clay lithofacies with graptolites on Polish part of the slope of the East-European Platform also contain some deposits of neritic facies (Tomczykowa 1975b; Tomczykowa and Witwicka 1974). Besides the correlations, this fauna also enables analysis of connections within the neritic zone. It should be noted here that the similarity between shelly fauna assemblages of the Whitcliffian of England and the Skała Beds of Podolia is much greater than in the case of that of the Kopanina Fm. of the Barrandian. The differences seem to be due to both the distance between the sections and, which is presumably more important, to the fact that they were connected with shelves of different continents or microcontinents (Tomczykowa and Tomczyk 1978).

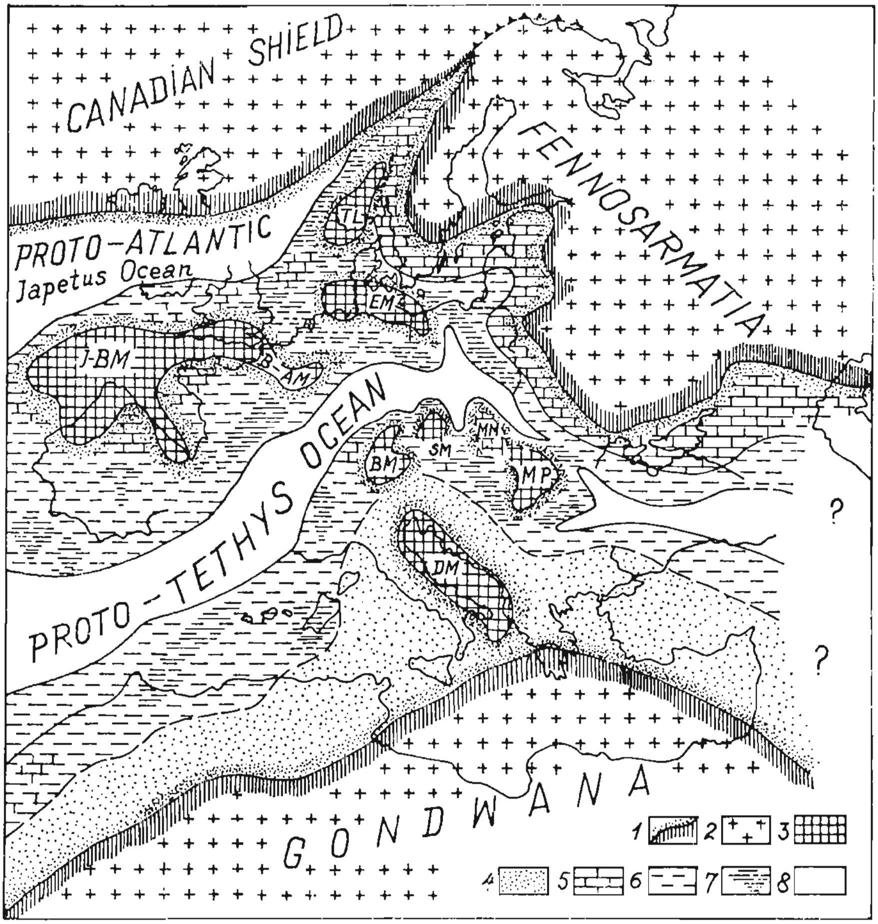

Fig. 4. Development of the Prototethys Ocean in the Late Wenlock. Explanations 1—6 as given in fig. 2, B-AM — Brabant-Ardennes massif, EM — East-Elbe massif; 7 inferred deeper parts of graptolite sea (or facies); 8 areas of Protoatlantic and Prototethys geosynclines.

The benthic fauna of the uppermost Silurian and lowermost Devonian of Poland evidences similar ecological conditions prevailing in the northern neritic zone stretching along the slope of Fennosarmatia (Tomczykowa 1975*b*). The faunal assemblage from that shelf was entirely different from that of the Barrandian. The differences are especially distinct from the base of the Ludlow upwards and later, from the top of the *leintwardinensis* Zone to the end of the Lower Devonian. This is evidenced by trilobites and the shelly fauna as a whole. Fossils known from both regions include scarce graptolites and pelecypods of the genera *Lunulacardium*, *Leiopteria*, *Pterochaenia* and others, indicative of free migration of some types of plankton. The separation of shelves of the Proto-Tethys was suggested by Tomczykowa (1975*b*) in order to explain

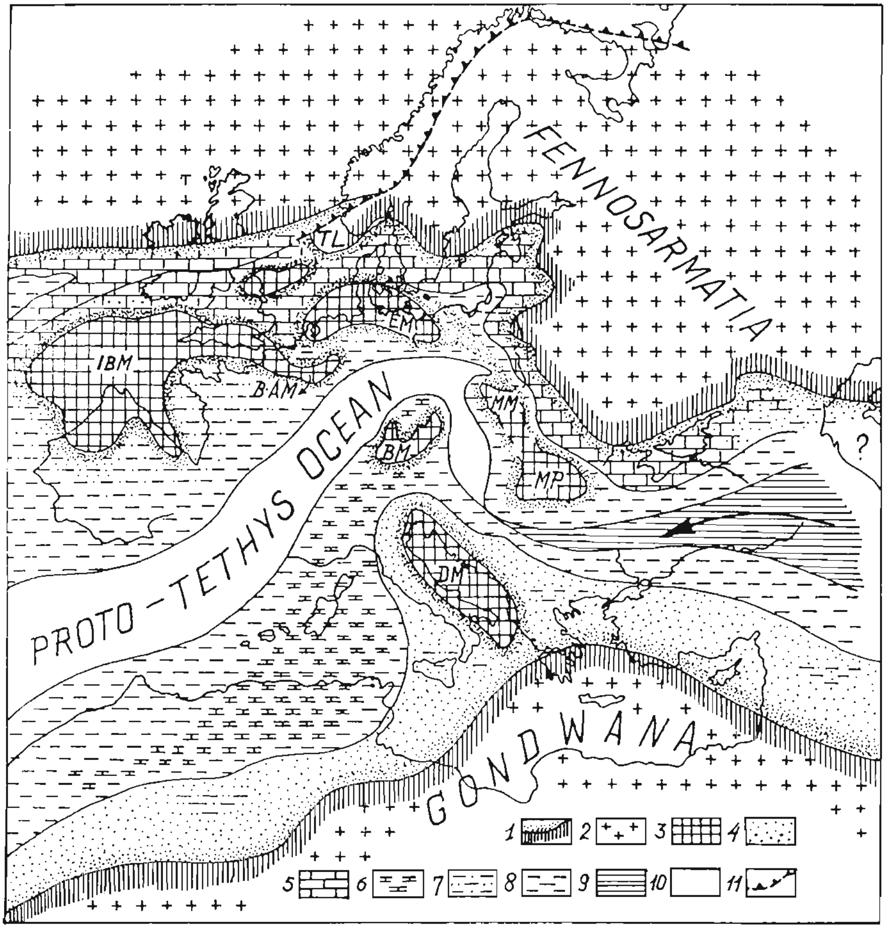

Fig. 5. Map showing development of the Prototethyan Ocean after the Cracow phase (i.e. in the *leintwardinensis* times). Explanations *1—6* as given in fig. 2; B-AM — Brabant-Ardennes massif, EM — East-Elbe massif; *6* ochreous limestones or their local equivalents, *Orthoceras* limestones in areas of predominance of graptolite facies; *7* clay-siltstone graptolite-bearing deposits of continental slopes; *8* clay deposits of graptolite sea or deeper continental slope; *9* miogeosynclinal area; *10* extent of Early Caledonian Prototethyan geosyncline; *11* extent of Scottish-Norwegian Caledonides.

the differences in the faunas of the Gedinnian and Lochkovian At present we may state that there is evidence of separation of these shelves also throughout the Silurian.

PALEOGEOGRAPHIC CONCLUSIONS

The Paleozoic Central-European geosyncline, i.e. the Proto-Tethys ocean, was gradually forming between the Fennosarmatian continent (East-European Platform) and the Gondwana landmass presumably from the Early Cambrian. Between the two landmasses there existed several

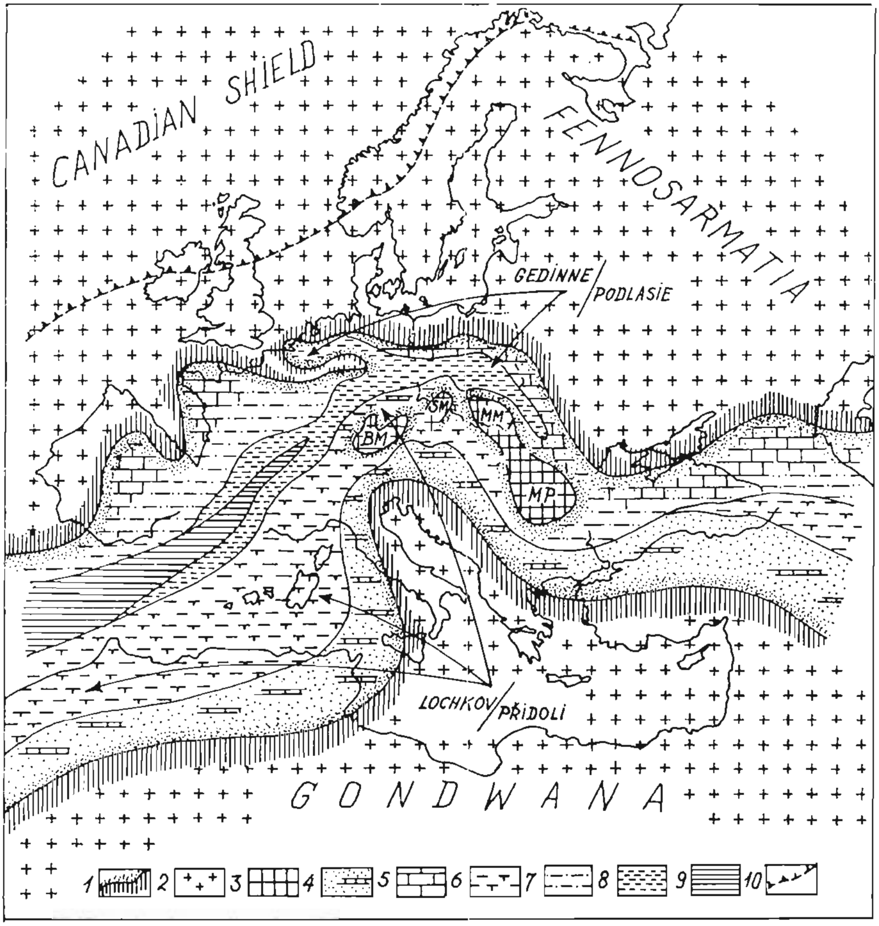

Fig. 6. Map of shelves of Fennosarmatia and Gondwana at the turn of the Silurian and Devonian (decline of the Prototethys): *1* macrocontinent margines; *2* land areas of old continents and post-Caledonian platforms; *3* inner massifs of microcontinents, MM — Małopolska massif, BM — Bohemian massif, SM — Upper Silesian massif, MP — Moesian Plate; *4* shelf deposits mainly terrigenous; *5* shelf deposits, mainly carbonate and sandy; *6* — clay deposits of declining graptolite sea; *7* clay-sandy deposits of shallow-neritic zone; *8* clay-siltstone and locally calcareous deposits of neritic zone; *9* miogeosynclinal zone in the end phase to the Prototethys.

microcontinents (sialic blocks), breaking-off or colliding with them at particular phases of Caledonian movements. The microcontinents were breaking off in various epochs and acted as either alimentary areas for rapidly subsiding areas or buffers during the subduction and collision (Tomczykowa and Tomczyk 1978).

At the beginning of the Ordovician, the Proto-Tethys was separated from the much older Proto-Atlantic by a landmass stretching west of Normandy, Brittany, the Iberian Peninsula and northern Morocco, being presumably connected by the Welsh-Polish miogeosynclinal branch. In the Middle Ordovician, that miogeosyncline was stretching from the Wales

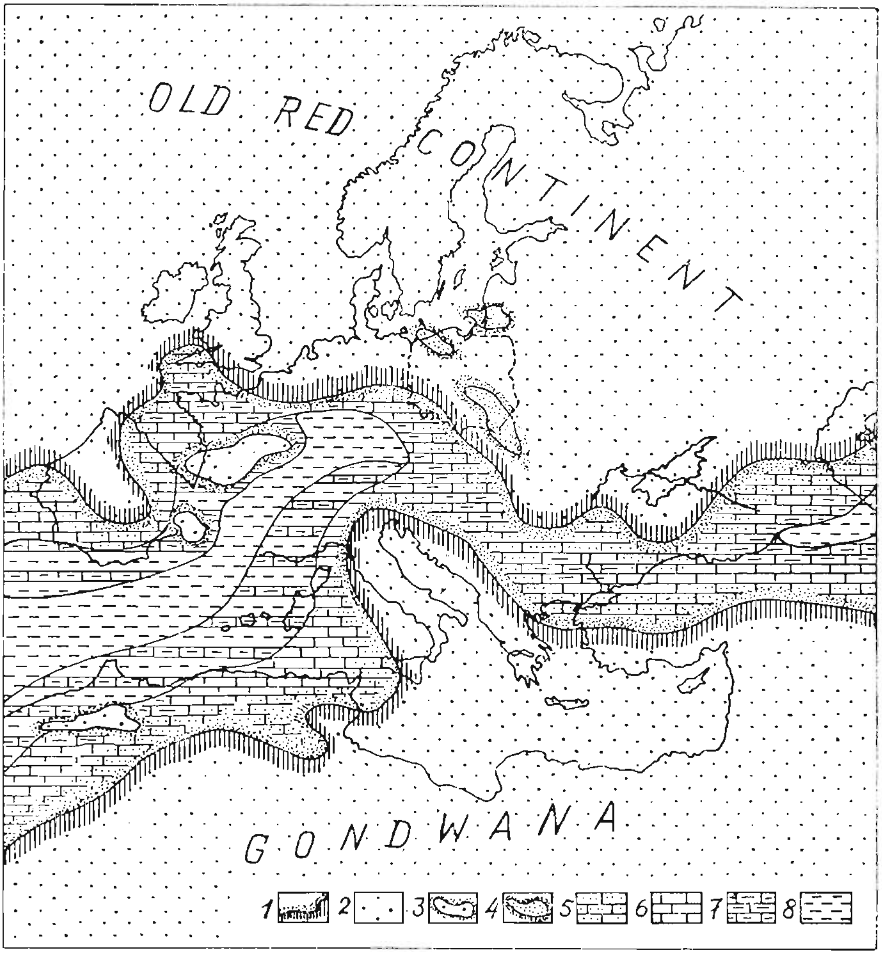

Fig. 7. Map of shelves of Fennosarmatia and Gondwana at the Early Emsian time: *1* macrocontinent margines; *2* Old Red megacontinents; *3* inner massifs or microcontinents; *4* areas with lagoon deposits; *5* shelf deposits, mainly sandy; *6* shelf deposits mainly carbonate; *7* clay-marly deposits of shallow-neritic zone; *8* clay-siltstone deposits of neritic zone, locally miogeosynclinal type.

through Scania and Rügen Island to Poland, where it is evidenced by borehole sections from Skibno, Chojnice, Toruń, Lisów and Dyle (fig. 1).

Climatic changes and Taconian movements from the end of the Ordovician resulted in reconstruction of both the Proto-Atlantic and Proto-Tethys (McKerrow and Ziegler 1972). The Proto-Atlantic geosyncline was displaying a marked trend to closing in the Iapetus Ocean stage, and its western margin became much stronger when the Telemark and East-Elbe massifs joined Fennosarmatian continent (fig. 3). The Taconian phases corresponding to these events are responsible for folding of Ordovician and possibly lowermost Silurian deposits in the area Rügen—Chojnice—Toruń (Tomczyk and Tomczykowa 1976, 1979).

The Proto-Tethys Ocean was fairly wide in the Silurian. Alternating phases of quiescence and unrest, related to phases of predominance of sea-floor spreading and rifting, may correspond to Caledonian phases and time intervals between them (Tomczyk 1964). In the Wenlock, especially at the turn of the Wenlock and Ludlow, there were marked (fig. 4) some phases of unrest, accentuated by an increased rate of subsidence and lithofacies changes (Tomczykowa and Tomczyk 1979).

An essential reconstruction of both Oceans took place at the end of the Ludlow (fig. 5). It was certainly related to the final phase of closing the Iapetus Ocean and lithofacies changes in the Proto-Tethys, traceable almost throughout Europe (Tomczykowa 1975*b*; Tomczykowa and Tomczyk 1978).

Narrowing and shallowing of the Proto-Tethys geosyncline could have taken place at the turn of the Siedlce and Podlasie. The sea was gradually retreating from the East-European Platform, at first from Estonia, on the north-east, Lithuania and Gotland, and latter from Peribaltic syneclize (Tomczykowa and Witwicka 1974).

At the beginning of the Gedinnian, the Proto-Tethys shelf zone shifted to central Poland. From that area it was extending westwards to Rhineand, the Ardennes, Brittany and Spain, and eastwards to Podolia. Deep zones still existed in the Sudeten Mts, Thuringia, Frankenwald, Sardinia and, to a certain extent, Barrandian (fig. 6).

The last phase of subduction, connected with complete shallowing of the Proto-Tethys, took place presumably in the Siegenian and before the Emsian, coinciding with the maximum development of the Old Red in Europe (fig. 7).

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