Distribution of corals on the Silurian Podolian Shelf

Volodymyr GRYTSENKO

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Abstract: Silurian formations, though widespread on the western flanks of the Ukrainian Shield, are exposed only in the central Dniester River region; in other areas they are studied by borehole material and geophysical methods. Fossils and lithologic features point to the shelf nature of the Podolian sequence. Volumetrically, corals dominate other fossils in certain intervals, especially in reefs and peri-reefal areas; in other areas they are rare or absent. Reefs occur as surface exposures of the Bagovitsa, Konivka, Tsviklivtsy, Rykhta and Troubchin facies. Silurian reefs were also discovered in boreholes in the Volynian, Ternopil and Moldova territories. A facies model for the Silurian Podolian Pericontinental Basin is based on correlations and sequence subdivisions. The migration of shoreline and facies belts was depending on relative sea level changes and regional or local tectonics.

Key words: reefs, coral distribution, facies models, Podolian, Silurian

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Geological faculty Kyiv National University, 90, Vasylkivska str., 03022 Kyiv, Ukraine, e-mail: favosites@mail.univ.kiev.ua, favosites@voliacable.com

1. INTRODUCTION

The Silurian Podolian sequence has played a significant role in interpreting regional and European Silurian stratigraphy over the past century. Nevertheless, attention to this unique "geologic monument" has declined in recent years. In 1985 the Novodniestrovsk hydroelectric power station was built near Bernashovka village. As a result of this construction, many exposures, including stratotypes, will be concealed in the future by rising water levels, and others will be or are already covered by landslides or overburden (Fig. 1).

Palaeontologists, mostly from the Institute of Geological Sciences of Ukraine National Academy of Sciences, have synthesized a geologic history of the Ukraine. They compiled an Atlas of Palaeogeographical maps (see also TSEGELNYUK et al., 1993). Analysis of the Silurian sections is linked to expansion of geological large-scale mapping and prospecting in the Ukraine, at scales of 1:50.000 and 1:200.000.

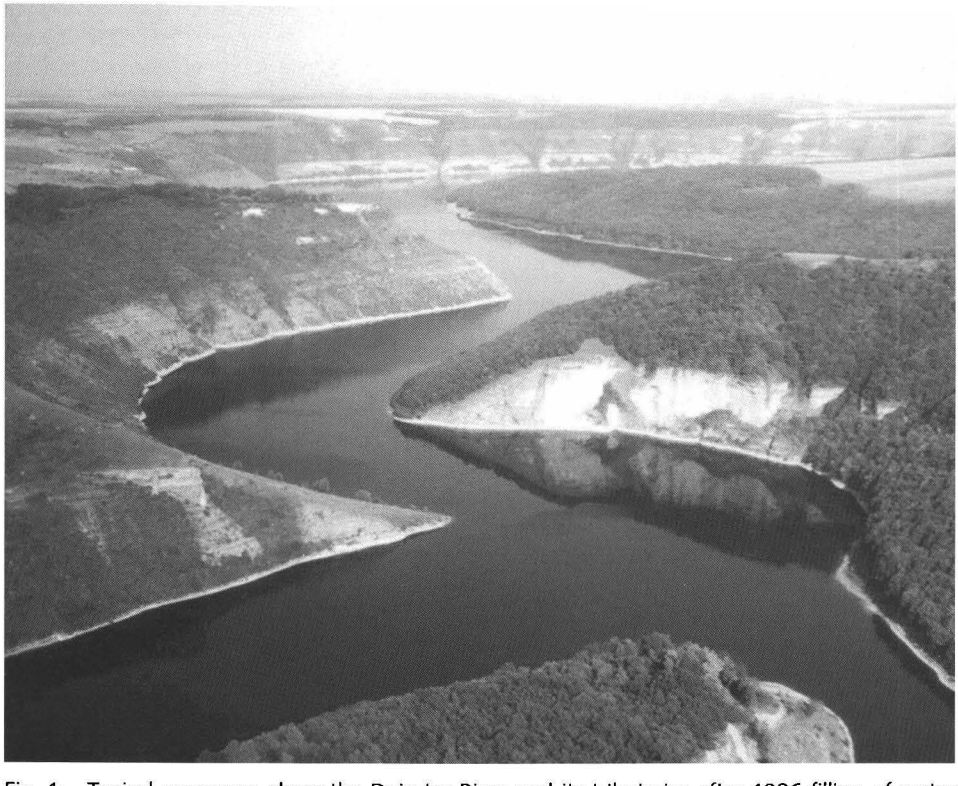

Fig. 1: Typical exposures along the Dniester River and its tributaries after 1986 filling of water storage.

2. STUDY AREA

The Ukrainian Geological Survey organized detailed 1:50.000 investigations of the territory of northwest Khmelnitskiy and the Volynian area. Before its immersion by water, the territory of the Dniester Hydroelectric Storage Station was studied at the same scale (Figs. 2, 7).

3. MATERIAL AND METHODS

Almost all known outcrops and hundreds of boreholes have been investigated and correlated. Careful analysis has shown the facies distribution of coral species and genera. Correlations were confirmed with bentonites and the biostratigraphy of thousands of corals and stromatoporoids. In addition, more than tenthousand thin sections, profiles of boreholes and descriptions of outcrops were elaborated.

4. RESULTS

The Podolian Silurian shelf includes: I – a shallow facies belt with corals; II – reefs in the Sursha, Muksha and Ustia Subsuites of the Yarouga, Malynivtsy and Roukshin Series. We add, III – a facies model of the Podolian Silurian shelf, and, IV – a dynamic facies reconstruction.

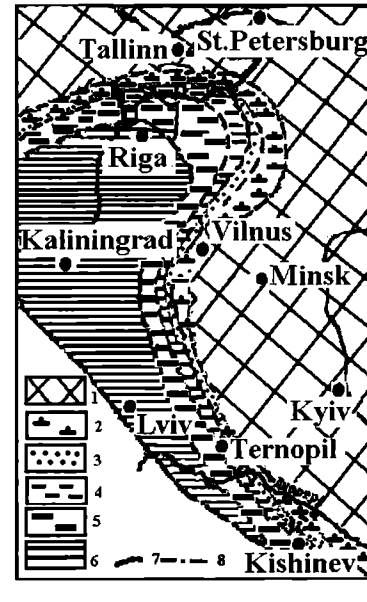

Fig. 2: Paleogeographical reconstruction of the western part the East European platform during the maximum of the Ludlovian transgression.
Legend: 1 – lagoon, 2 – bar, 3 – open shelf, 4 – slope, 5 – open deep sea, 6 – land; 7 – suspected boundaries of facies zones, 8 – Tornquist line.

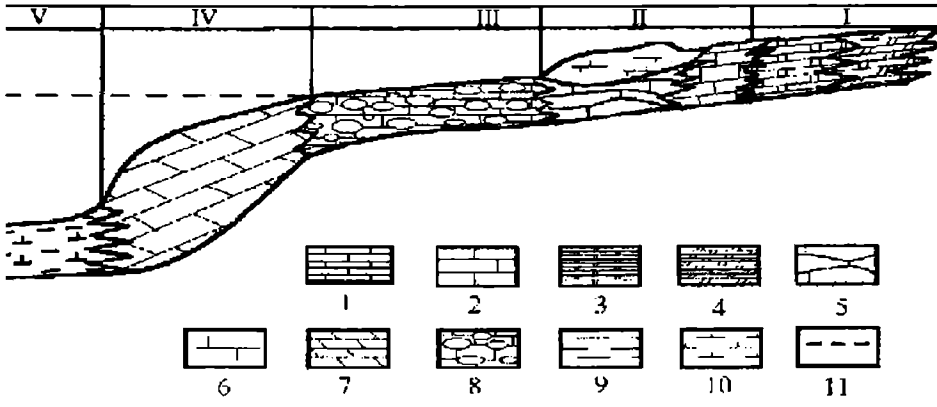

Fig. 3: Facies model of the Podolian Silurian reference section
Legend: Zones – I –V (I – Lagoon, II –Bar, III – Shallow Shelf, IV – Deep Shelf, V – Deep Sea)
Rocks 1–10: 1 – thin bedded limestones, 2 – detrital limestones, 3 – thin bedded dolomites, 4 – dolomitic-marls (domarit), 5 – nodular detrital limestones, 6 – massive limestones of bioherms, 7 – nodular argillaceous-detrital limestones, 8 – marls, 9 – argillites, 10 – calcareous argillites; 11 – wave base.

4.1. The shallow facies belt and its corals

All corals are closely connected to their benthic environment. This applies to modern corals (Zlatarsky & Nereida, 1980), as well as fossil corals (Tesakov, 1974). Four shelf facies zones were established on the basis of field observations of the Silurian sequence of the central Dniester River region. The deepest water clays were discovered in outcrops at the base of the Resteve Suite, discovered in boreholes in the western part of the territory and represent open marine conditions (Figs. 2–4).

A Lagoonal Zone (I) is characterized by thin-bedded dolomites, limestones and domarites (dolomite-marls). Corals are rare in this zone. Occasionally occur branched Tryplasmida and sometimes spherical tabulate corals, discovered only near the boundary to the shoal bar zone. Sometimes separate lenticular and flattened stromatoporoids are found there. This zone is characterized by stromatolites, eurypterids and rare high conical or wheel-like gastropods, and ichnofossils. Desiccation features are common. In the Podolian Sequence lagoonal deposits dominate in the Ustia and Shutnivtsy Subsuite, and Isakivtsy and Prygorodok Suites. Significant parts of the Varnitsa and Troubchin Suites consist of lagoonal sediments.

A Shallow Shoal Zone (II) contains reworked limestones marked by detrital, coarse-grained, cross-bedded, oncolitic facies and transitional facies between those (Nestor & Einasto, 1977). Many corals are abundant in granular flaggy limestones with small amounts of terrigenous material. These are flat and branching, lenticular and conical forms of colonial rugosans, tabulate corals (including heliolitids), and stromatoporoids. Species typical of the shoaling zone of the Mouksha Subsuite are *Calamopora* cf. *collatatus* (Klaamann), *Thecia saaremica* Klaamann, *Acervularia ananas* Linnaeus, and *La-*

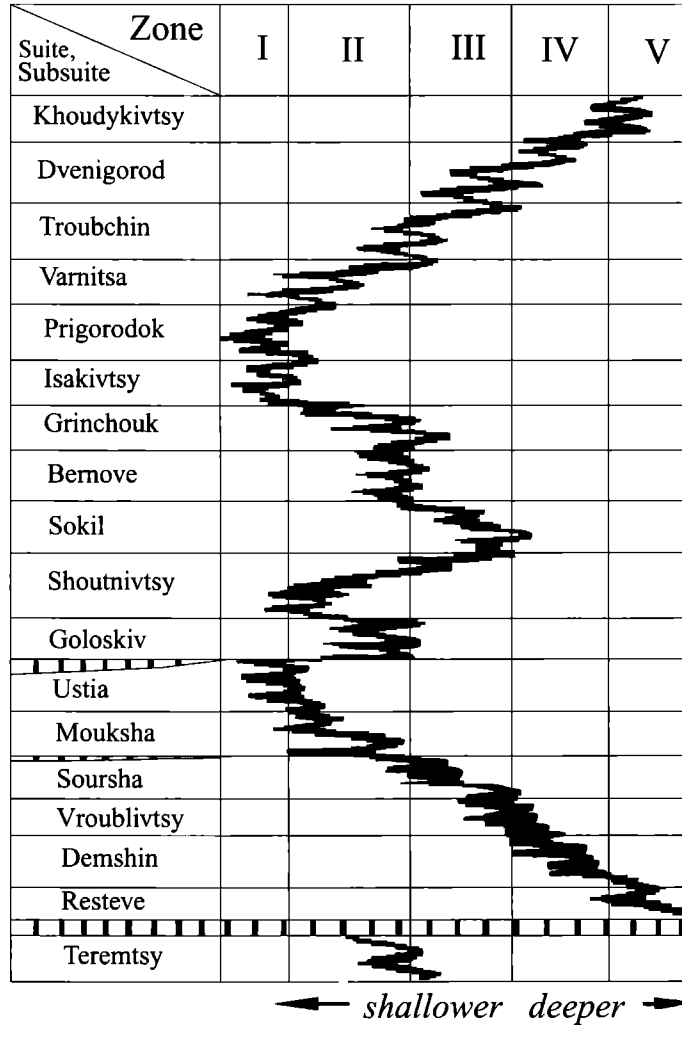

Fig. 4:
Dynamic of facies in the Podolian reference section.

bechia conferta LONSDALE. The last three species are considered characteristic for biohermal conditions. Such corals as *Mesofavosites alveolitoides konovskiensis* TESAKOV, *Kodonophyllum truncatum* (LINNAEUS), *Laceripora cribrosa* EICHWALD and *Acervularia konovskiensis* KADLETZ are especially characteristic for the Konivka Suite of the Middle Ludlow (*leintwardinensis* zone).

The shoal deposits of the late Ludlow (*caudatus-balticus* zone) Grinchouk Suite are located at the top of the succession, where corals include *Rhizophyllum gothlandicus* ROEMER, *Weissermelia lindstroemi* (SMITH & TREMBERGS), *Cystihalysites* sp., and *Syringoheliolites contrarius* BONDARENKO. Heliolitids, stromatoporoids and small bioherms are common.

The bar sediments of the Pridoli Varnitsa and the Troubchin Suites (*ultimus-vetus* zone) are characterized by lamellose coralla of *Riphaeolites prostratus* TESAKOV, massive hemispherical colonies of *Endophyllum commodus* SYTOVA, various branching tabulates and rugosans, and simple trochoid corallites of rugosans such as *Holmophyllum holmi* WEDEKIND.

An Open Shelf Belt (Shallow Shelf – zone III) is represented mainly by clay, detrital-argillaceous and argillaceous nodular limestones, and less commonly by detrital marls (NESTOR & EINASTO, 1977; KALJO, 1970). A large part of the Podolian Silurian Sequence can be assigned to a shallow shelf facies. Shallow open shelf conditions appeared periodically among sediments of the Furmanivka Suite (the Resteve and the Demshin subsuites – *murchisoni* zone). The bulk of the Ternava Suite (the Vrublivtsy subsuite – *lundgreni* zone – and the Sursha subsuite – *nilssoni* zone), the Sokil (*kozlowskii – unicornus* zone) and Grinchuk subsuites (except its upper part), the separate intervals of the Troubchin Suites, and almost all of the Dzvenygorod (or Zvenygorod) Suite, were deposited in conditions of this open shelf facies zone (Figs. 2, 3).

Corals are rare in this zone: these are usually slightly attached or nonattached solitary rugosans. Large lenticular tabulate coralla and coenostea of stromatoporoids are much less common. *Thecia podolica* SOKOLOV marks this facies in the Ternava Suite. *Phaulactis cyathophylloides* RYDER and *Parallelostroma grinchukense* BOLSHAKOVA occur in the Sokil and Grinchuk Suites; *Pachypseudoplasmopora karaespensis* (KOVALEVSKY) and *Holocanthia socialis* (BULVANKER) are characteristic of the Dzvenygorod Suite (*transgrediens* graptolite zone).

The outermost facies is the Distal Shelf Zone (IV). This zone separates facies of the deep sea from those of the shelf and we identified it as transitional zone. The distal shelf (or distal ramp) is characterized by deposition of thicker sediments, approximately twice the thickness as accumulated in adjacent proximal facies. The main sediments are marls, shales, clays, and calcareous clays. Corals are extremely rare. The Distal Shelf Zone includes most of the Resteve Subsuite and marl interbeds of the Demshin Subsuite, containing small corallites of *Syringaxon siluriensis* MCCOY.

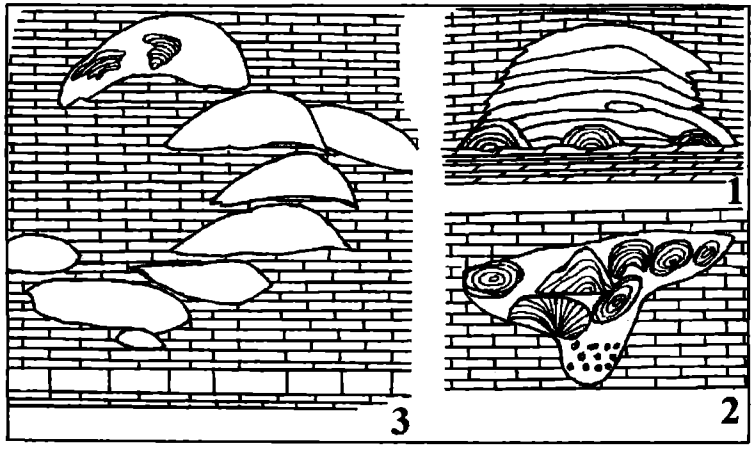

Fig. 5:
Different types of the Podolian Silurian bioherms:
1 – dome-like bioherms,
2 – cone-like bioherms,
3 – biohermal complex.

The fifth facies is the "Deep Sea Zone" (or depression zone), approximating a distal slope or basinal facies. This features graptolitic shales, argillites and marls. Corals are absent, even solitary rugosans. Some interbeds of the Resteve Subsuite, contain graptolite rhabdosomes. This facies occurs in the western part of the basin, known from deep boreholes Chernivtsy-1, Guscha-4015, Pidgaitsy-2, Zavadivka-6, borehole 4109, and others (TSEGELNYUK et al., 1983).

4.2. Reefs

Corals are most diverse and variable in the Shallow Shoal Facies. Reef complexes formed under presumably favourable conditions of temperature (between 28° and 35° C), light, carbonate saturation, salinity, pH, available carbonate substrate, low detrital sediment accumulation, and water depths. Modern reef styles encompass fringing reefs, patch reefs, barrier reefs, and atolls. Fossil reefs have sometimes been divided into a complex and confusing terminology of reef complexes, bioherms and biostromes, and other geological bodies (Figs. 5, 6). Large barrier reefs are produced under ideal conditions of large, available accommodation space (sea level highstands, wide shelves), optimal temperature, light (water depth), carbonate saturation, salinity and low sediment input. Isolated patch reefs are formed when conditions are slightly less suitable for growth,

Fig. 6:
A big bioherm in the Konivka Suite on the right bank of Dniester River. It shows changes of communities and lithological succession.

e.g. rapid sediment supply rates, deeper waters, fluctuating salinities, and low carbonate saturation. Biostromes, or coral carpets and meadows as known in the Holocene, we understand as banks of corals, sponges or bryozoans that appear to be generated under conditions at the limit for proper reef growth.

The Podolian shelf reef complexes were built up primarily in the zone that separated lagoonal onshore from open marine facies. The reef cores were surrounded by detrital slope or flank deposits. In the cores of Podolian reefs there are generally massive, almost non-laminated limestones, composed of frame-building benthic skeletal invertebrates, microbial carbonates and calcareous red and green algae. The gaps in the framework are filled with carbonate muds, calcite sparry cement and calcarenites, i.e., calcite and detrital sand-sized grains. Quieter hydrodynamic and raised salinity conditions in the lagoon led to the formation of dolomite and gypsum.

4.2.1. Reefs of the Fourmanivka Suite (murchisoni graptolite zone)

In the Vroublivtsy subsuite, reefs are very small and rare. There are overgrowing colonies of *Tuvaelites hemisphaericus* TCHERNICHEV sometimes attached to *Favosites gothlandicus* LAMARCK or other tabulate corals. Small bioherms are found in the upper Sursha Subsuite near Demshin Village on the Dniester River and Ternava River banks. Near Velyka Sloboda and Bagovitsa villages beds of the large early Wenlock brachiopod *Pentamerus gothlandicus* LEBEDEV are exposed. Nowadays most of those outcrops are submerged by reservoir water. Early exposures discovered reefs constructed by the tabulate coral *Halysites*. We believe that new reef outcrops will be created by wave erosion from the scarps to the reservoir.

4.2.2. Reefs of the Bagovitsa Suite (Ludlow; nilssoni and leintwardinensis zone)

Within the Volynian and Podolian regions, reefs occur in the Muksha Subsuite of the Bagovitsa Suite, and other "shallow water" parts of the section of Early Ludlow age (SYTOVA, 1966). A detailed analysis of the reefs, despite the rather small outcrops, indicates reef clusters or sets. Reef cores outcrop on the left bank of Muksha River in Velyka Sloboda village, now partially drowned. The core shows the cerioid rugosans *Acervularia ananas* LINNAEUS, prostrate tabulate corals with thick walls, tabulae and septa, such as *Thecia saaremica* KLAAMANN, and thin branching coralla like *Taxopora xenia* SOKOLOV. In several reefs the stromatoporoid *Labechia conferta* LONSDALE dominates. Gaps between skeletons of frame-building organisms are filled with pure massive, coarse-grained or fine-grained, light grey limestones without distinct bedding. The core facies at the mouths of the Muksha and Bagovitsa rivers outcrops in a west – northwest direction (along more than 2 km). In that exposure bedded, coarse-grained limestones were discovered which dip away from the bioherms, defining a reef front slope. In an outcrop on the right bank of the Muksha River, near the broken down water mill, it was possible to see clays or marls with large coenostea (diameter 20–30 cm) of *Labechia conferta* LONSDALE and colonies of the cerioid rugosan *Acervularia ananas*. In the lower part of the Bagovitsa Suite a large reef (height up to 10 m, diameter 20 m) was formerly exposed, but presently only the top is observable. Other reef bodies crop out

along the right bank of the Dniester River up to the railway bridge and in the valleys of the Muksha and Bagovichka rivers for some kilometers (visible by boat).

The widespread shallow lagoonal facies of the Ustia reef complex start with basal dolomitic marls (domarites) with desiccation fractures. Within the domarites there are beds of limestone with thin branching and lenticular coralla of *Favosites*, reptant colonies of tryplasmatids and solitary rugosans, and *Cystihalysites*. Some brown limestones with partially weathered fossils are petroliferous. Reefs correlative with lagoonal facies are intersected by boreholes several tens of kilometers to the west.

4.2.3. Reefs of the Malynivtsy Series (upper part of leintwardinensis to caudatus-balticus zone)

Reefs of the Konivka Suite (Figs. 2, 5, 6) occur as rather small undifferentiated mounds (SYTOVA, 1966). Probably, these mounds did not form a barrier chain and were isolated bodies. The bioherms of the Tsviklivtsy and Rykhta Suites are also small, isolated bodies, which did not play a significant role.

4.2.4. Reefs of the Rukshin Series (ultimus-vetus zone to transgrediens zone)

YELTYSHEVA et al. (1971) described bioherms in the Rashkiv Suite as tabular buildups. We found cross-sectional exposures of an uncovered reef of Troubchin age (*ultimus-vetus* zone) at the same stratigraphic level in the Zbruch River valley near Milivtsy village. The Troubchin Reef extends more than 120 m and its core is about 6 m thick. The main reef constructors are stromatoporoids, colonial rugosans, heliolitids and other tabulates and large single rugosans. The core of this reef consists of massive blue-grey dolomite with prominent cavities, corals and others frame-builders. Underneath the massive core is a bed of grey, cross bedded calcarenite about 3 m thick, including 2 m of wavy limestones.

4.3. The Silurian shelf sea facies model of Podolia

Field studies indicate that cnidarians dominate other fossils in certain intervals of the sequence, though in others they are rare or absent. Corals and stromatoporoids are abundant in the bioherms and biostromes. SYTOVA (1966) first paid attention to reefs in the Podolian Sequence investigating coral bioherms in the Malynivtsy Suite (see also YELTYSHEVA et al., 1978). From our observations reefs were distributed only in shallow settings, in the Muksha, Konivka, Grinchuk and Troubchin formations on the banks of the Dniester River and its tributaries. Coral buildups were also found in boreholes in the Volynian, Khmelnitskiy, and the Ternopil areas.

Faunal assemblages and lithological studies point to the shelf nature of the formations of the Podolian Silurian Sequence. Paleogeographic reconstructions of the western part of Eastern Europe show that the Podolian Silurian Sea was closely connected to the Paleobaltic Basin, both in pericontinental positions (Figs. 2, 7).

The facies model of the Paleobaltic Basin (KALJO et al., 1970, 1977) includes five facies zones and associated macrofacies: 1 – lagoonal-littoral (thin bedded dolomite), 2

– shallow-water (coarse grained limestones), 3 – open shelf (marls with nodules and clayey limestones), 4 – transitional zone (marls-calcareous shales) and 5 – deep-water. The macrofacies are specified in parentheses and consist of a set of facies features. So, for example, coarse grained limestone macrofacies of the shallow-water zone includes facies such as: "bahamites", detrital skeletal banks or shoals, bioherms and hardgrounds

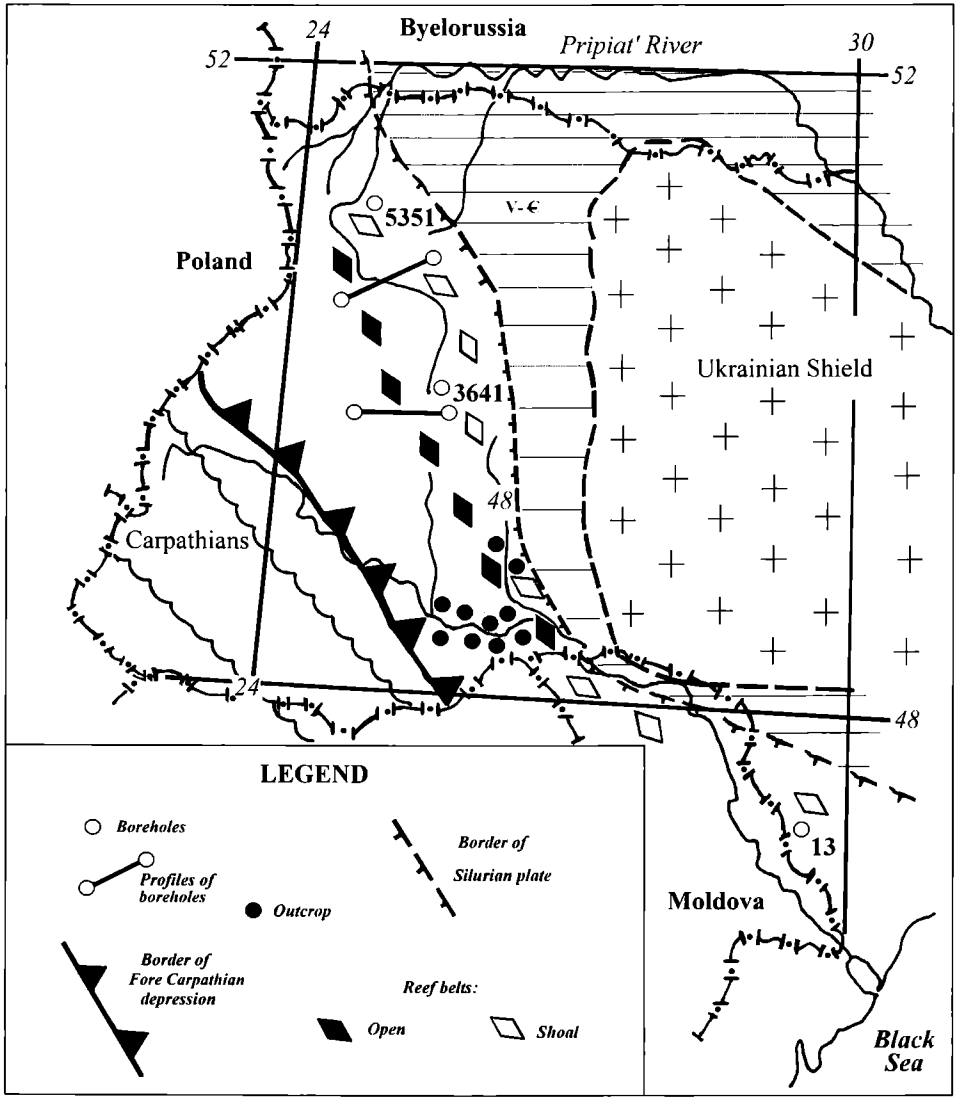

Fig. 7: Tectonic reconstruction of the western part of the Ukraine.

(Nestor & Einasto, 1977). For facies definition of stratigraphic units we used a simpler facies model for the Silurian Podolian Pericontinental Basin (Fig. 3).

The shoreline and facies belts were moved as a result of relative sealevel change. The cumulative picture looks rather complicated, but for separate sections and strata we constructed more or less simple schemes. Our attempt to reconstruct the Podolian Silurian sequence is as follows (Fig. 3): the deposits of the Lagoonal Belt (zone I) contain trails and fossils of gastropods, bivalves, eurypterids, large ostracodes, worms (scolecodonts), stromatolites and stromatoporoids. The Shoal and Sandbar Belt (zone II) deposits are characterized by abundant stromatoporoids, tabulates and rugosans with branching and encrusting colonies, solitary rooted rugosans, brachiopods with thick shells, bryozoans and crinoids. The Shallow Shelf Belt (zone III) was favorable for the growth of stromatoporoids, tabulate and rugose corals with massive colonies, various bryozoans, and brachiopods.

In the Distal Shelf Deposit Belt (zone IV) trilobites, brachiopods, small ostracodes, gastropods and branching colonies of tabulates and rugosans occur. This zone is often called the slope or transitional zone. In the Deep Sea Zone (zone V) predominantly nektic organisms (hyolithids) and plankton (graptolites, "acritarchs" and chitinozoans) occur. Benthic organisms (brachiopods, trilobites) are rare.

4.4. Facies dynamics

On the basis of the above mentioned facies interpretation of the Podolian sequence, the facies dynamics (or history of development) are represented as indicated below. In Teremtsy time (*crenulata* graptolite zone, Telychian, late Llandoverian) there was a short transgression followed by a regression. The top of the Teremtsy Suite is marked by interruption of deposition and partial erosion (and red color of the rocks) before sediments of the next cycle were deposited (Fig. 4).

The next cycle started during maximal transgression during Yarouga time (1.8 m and 2 m above the basement of the series *Momoclimacis priodon* and *Cyrtograptus murchisoni* occur), and is represented mostly by deeper facies in the lower part of the section. The transgression was followed by regression and shallowing. The Resteve, Demshin and Vrublivtsy Subsuites mark lowstands. In Sursha time (which correlates with Early Ludlow – *nilssoni* graptolite zone) shallowing is indicated by increasing detrital material and development of brachiopod shell-beds. Facies shows a change from slightly clayey detrital and coarse–nodular limestones to thick platy limestones. Continued regression resulted in deposition of shallow-water sediments with bioherms (Muksha Subsuite). In Ustia time (Early Ludlow – mostly *leintwardinensis* graptolite zone) the regression reached its maximum and the shelf was closed off by reefs, which was mirrored in extremely shallow-water deposits and the accumulation of restricted lagoonal sediments. The top of the Ustia horizon shows paleokarst.

The beginning of a new transgression is marked by formation of Shoal and Sandbar facies in Goloskiv time. In Shutnivtsy time (end of *leintwardinensis* graptolite zone) the development of local lagoonal conditions occurred (Perepelitska member). The Sokil Subsuite mirrors a maximum transgression in Malynivtsy time (middle Ludlow – *kozlowskii – unicornus* graptolite zone), which was replaced by regression in the Bernove,

shallowing (next episode of middle Ludlow age) was not significant. At the beginning of the Grinchou episode (late Ludlow – *caudatus-balticus* graptolite zone), the depositional environment suffered deepening and then underwent a step-by-step retreat. By the end of Isakivtsy time (end of Ludlow) a new relative sealevel lowstand set in, identified by cross-bedded and tidally sigmoidal granular limestones, which were altered by secondary dolomitisation. This time interval is marked by interruption in the top part section of the subsuite (TSEGELNYUK, 1974).

The Pridolian (Skalian = Rukshin) transgression began with deposition of the Prygorodok shallow lagoonal dolomitic marls. In Varnitsa time (early Pridoli – *ultimus-vetus* graptolite zone) shallow-water and lagoonal sediments were alternately interbedded. The Troubchin Suite (middle to late Pridoli) was generated in shallow, open shelf conditions, and the Dzvenygorod Suite (late Pridoli – *transgrediens* graptolite zone) in the upper part shows evidence of deeper marine conditions (Figs. 3, 4). Thus, three stages of transgressive – regressive cycles were present in the Podolian Silurian sequence. The Teremtsy transgression in late Llandoverian time is mirrored in the section only by a single bed 45 cm in thickness. In Moldovan boreholes, the Llandovery is represented by an almost complete sequence from Rhuddanian to Telychian age in moderately deep facies with graptolitic shales (of *crenulata* graptolite zone). Such trends are also reflected in shelly faunas (YELTYSHEVA et al., 1971).

5. DISCUSSION

In the area of Lutzk Troubchin, a reef complex of Ludlow and Pridoli age was intersected by the Lockachy boreholes at a depth of 1700 m (borehole Lockachy-6). The limestones in these boreholes are light, brown-grey and light-grey. Carities within the light grey secondary dolomites suggested to be of reefal origin. Similar bodies in the Kirbla and Tukhu reefs of Estonia are dolomitized, and most of the fossils are represented only as cavities (ALOE & EINASTO, 1970).

The Volynian and Podolian Silurian reefs are similar to those of Gotland (HADDING, 1950; MÕTUS, 1999; CALNER et al., 2000). It is suspected that the Podolian, Volynian and Gotland reef belts were linked through Byelorussia, Lithuania, Latvia and Estonia (Figs. 2, 5).

Our observations do not confirm the conclusion of SYTOVA (1966) concerning the similarity between reefal and nonreefal corals. We consider that corals in bioherms differ from associations in bedded limestones. In bioherms and their flanks this may be explained by wave action. In some instances the essential roles were played by crinoids, with large unbroken stalks and attached rhizoids (e.g. *Crotalocrinites* sp. with diameters up to 2.5 cm). Brachiopods and bivalves were not important in the construction of Podolian reefs, with the exceptions of *Kirkidium knighti* and *Pentamerus oblongus*, which sometimes formed buildups similar to oyster banks.

The Pidgaitsy and Lockachy borehole cores in the Ternopil and Volynian areas provided more than 1000 coralla and corallites, revealing biohermal sections and shallow deposition (GRITSENKO et al., 1999). Reefs are found in almost all shallow settings of the Volynian, Podolian and Moldavian Middle and Late Silurian, with the exception of the Prygorodok Suite, which shows extremely shallow formations deposited during condi-

tions of variable salinity. The reefs discovered in the Lockachy and Pidgaitsy boreholes are apparently located at the edge of the shelf and may have formed a barrier (MARKOWSKIY & KOTYK, 1975). Reefs which crop out on slopes along the Dniester River were fringing, patch or nearshore types.

6. CONCLUSIONS

Silurian deposits of the Volynian and Podolian regions are rich in corals, stromatoporoids and calcareous algae which locally built reefs in Wenlock, Ludlow and Pridoli times. The reefs grew only in shallower areas of the basin. In the Podolian shelf setting, reefs are best exposed in the outcrops of the Konivka, Tsviklivtsy, and Rykhta (Malynivtsy series – Ludlow) and Trubchin suites (Rukshin series – Pridoli). On the western flanks of the Ukrainian Shield nine levels of reefs are exposed along the Dniester, Zbruch, Smotrich, Muksha and Bagovichka rivers. In more "seaward" sections reefs are accessed by boreholes in the Ternopil and Volynian areas of Ukraine, with bioherms up to 40 m in thickness.

Some recrystallization and dolomitisation is present. Dolomitisation led to increased porosity and permeability. Porosity and cavities are widespread in the Bagovitsa horizon, holding mineral waters ("Zbruchanskaia" and "Tovtry").

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