ASPECTS OF SILURIAN CARBONATE PLATFORM SEDIMENTATION

by D. KALJO, H. NESTOR *and* R. EINASTO

ABSTRACT. Silurian carbonate sedimentation was controlled by climatic, bathymetric, tectonic and biological factors comparable with those in Recent seas. There are two basic types of carbonate deposits: shallow water shelf and deep water pelagic sediments. In the Silurian, the latter type was of very restricted distribution (e.g. Ockerkalk of Thuringia, Sardinia). Shallow water carbonates were widespread because many palaeocontinents were located at lower latitudes and their low relief prevented high clastic influx. Silurian cratonic areas show a great variety of carbonate facies, ascribed to different sedimentary models. Facies patterns differ in the pericratonic (e.g. Baltic, western Urals) and epicratonic (e.g. North America, Siberia) regions. In the Baltic region, carbonate deposition took place mostly on ramp environments, with the high energy shoal belt relatively close to the shore and with only a minor change in gradient at the shelf margin. Three main facies belts – tidal flat/lagoonal, shoal and open shelf – are distinguished within the carbonate platform, followed by argillaceous deeper water shelf margin and basin facies. In the Ural pericratonic sea the shelf was rimmed by a reef barrier, separating the broad shelf from a steep slope. The epicratonic seas of the Siberian and North American platforms were very broad and shallow, with an unusually flat bottom and characterized by platform to bank type carbonate sedimentation.

IN Silurian sequences carbonate rocks are of widespread importance, forming variably complex facies assemblages in many different basins. The facies models discussed in this paper are used extensively in analysing the distribution of patterns, environmental conditions of sedimentation, and relevant composition of the rocks. In addition, detailed knowledge of carbonate sedimentation in Recent seas greatly facilitates an understanding of Silurian facies.

MODERN CARBONATE ENVIRONMENTS

The distribution and facies patterns of carbonate deposits in Recent seas are controlled by climate, water depth, tectonic setting, and the biological characteristics of carbonate-producing organisms (Milliman 1974; Lees 1975; Flügel 1979; Scholle *et al.* 1983*b*).

There are two basic types of carbonate deposits: 1, shallow water, shelf or neritic carbonates; and 2, deep water or pelagic deposits. Pelagic carbonates cover approximately one-third of the modern ocean floor (Flügel 1979) and are represented mainly by *Globigerina* and pteropod oozes. Pelagic lime muds may also occur in back-arc basins, on continental slopes, and on the deeper shelf (Tucker 1974; Scholle *et al.* 1983*a*).

Carbonate sedimentation in shallow water environments is controlled strongly by water temperature and salinity (Lees 1975; Carannate *et al.* 1988). Intense production of shallow water carbonates is confined to lower latitudes, mostly between 30° N and 30° S (Wilson 1975), and attains its maximum in arid, tropical trade wind belts on the east-facing continental shelves and on isolated carbonate platforms where warm and somewhat more saline sea water reaches a relatively high degree of carbonate saturation (Lees 1975; Heckel and Witzke 1979). In addition to intense secretion of carbonates by benthic skeletal organisms, carbonate may precipitate biochemically out of sea water, forming ooids and cementing carbonate grains together into grapestones. In arid climates, evaporation causes physico-chemical precipitation of dolomite in basins of restricted circulation, and diagenetic formation of dolomites on supratidal flats, or sabkhas (Friedman and Sanders 1967). A much greater variety of environments was characterized by dolomite formation in the geological past (Bezborodova 1988).

In cool, normal marine water the only reasonable source for carbonate deposits is the disintegration of

[Special Papers in Palaeontology No. 44 (1991), pp. 205–224]

skeletons of temperature-tolerant groups of organisms, such as foraminifers, different molluscs, echinoderms, bryozoans, etc. (Lees and Buller 1972; Simone and Carannate 1988; Nelson 1988). Very intense land weathering and clastic influx from rivers suppress carbonate sedimentation on marine shelves in the temperate climatic belt (Heckel and Witzke 1979; Doyle and Roberts 1988).

Modern shallow water carbonate sediments accumulate in epicontinental seas (e.g. Persian Gulf), on the shelves and offshore banks of passive continental margins (eastern coast of North America, Coral Sea in Australia), fringing areas of island arcs (e.g. the New Hebrides), young rift basins (Red Sea, Aden Bay, Shark Bay in north-west Australia), and around oceanic coral islands (Pacific) (Konyukhov 1988). In the Silurian period shallow water carbonate deposition probably took place in more or less similar tectonic settings, although there is no definite information on oceanic environments.

This paper concentrates mainly on carbonate sedimentation in Silurian cratonic basins.

DISTRIBUTION OF SILURIAN CARBONATE SEDIMENTS

Silurian shallow water carbonates were far more widespread than those of the Recent because of the location of large continental masses in climatically favourable low palaeolatitudes, combined with a generally low relief on the continents, which thus did not lead to suppression of carbonate deposition by intense clastic influx. A general picture of the distribution of carbonate rocks can be obtained from the global Palaeozoic lithological–palaeogeographical maps compiled by Ronov *et al.* (1984). We have transferred these data onto a world palaeogeographical base map compiled by Scotese (1986), representing the position of the continents in Wenlock time (Text-fig. 1). The situation in North America, Siberia, and Baltoscandia is modified somewhat following Berry and Boucot (1970), Johnson (1987), Tesakov *et al.* (1986), and based on our own data.

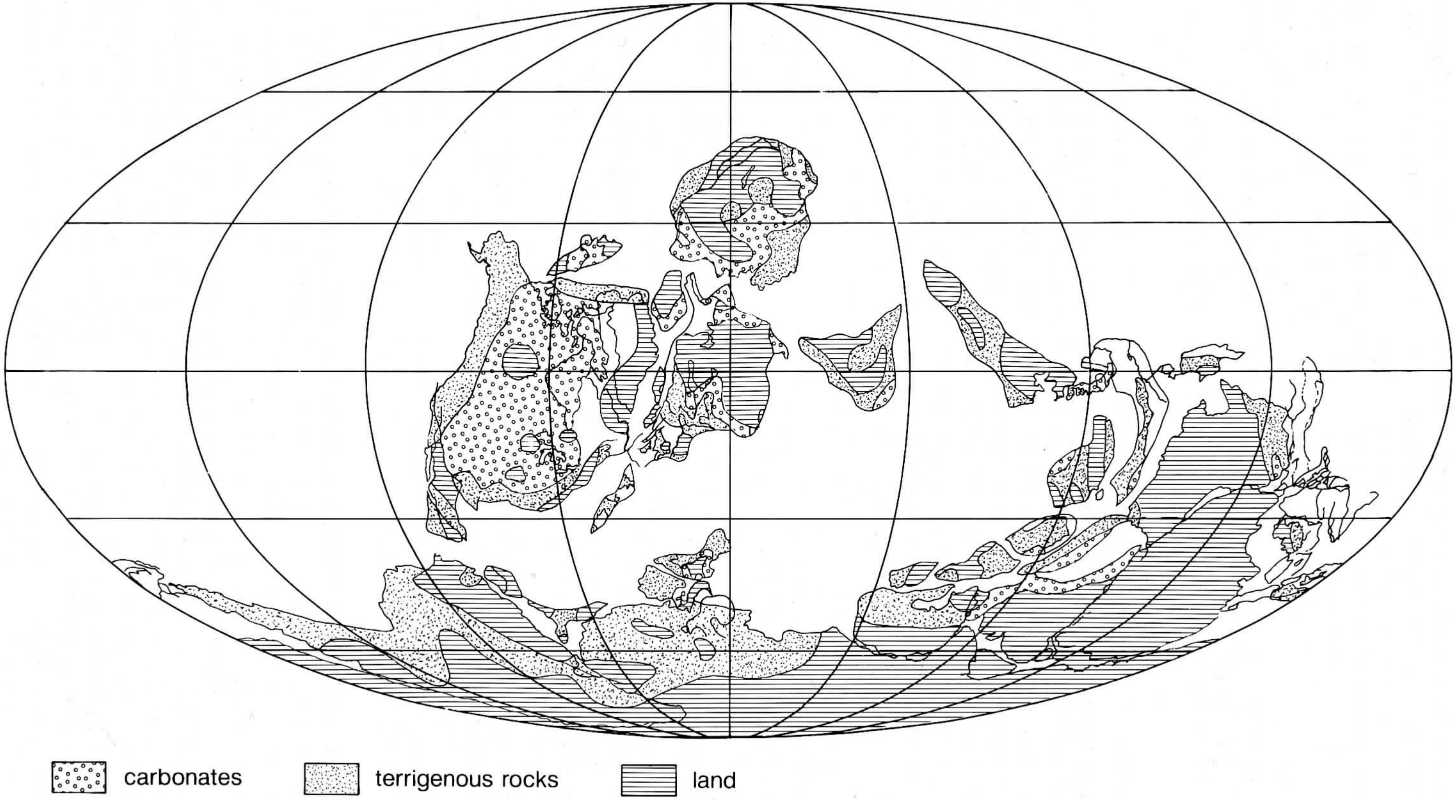
During the early Silurian (Llandovery and Wenlock), carbonate and terrigenous sediments were of almost equal distribution in cratonic areas. The largest regions blanketed with carbonate deposits embraced the typical epicontinental seas of North America and Siberia. On the East European craton, carbonates were distributed along its present-day south-western margin from the Baltic to Podolia, and along the eastern margin adjacent to the Urals. Unlike the North American and Siberian epicontinental seas, those on the East European craton can be considered as pericontinental. Carbonate sediments were also typical of the Kolyma and Bering massifs.

On other cratons, carbonate deposits were of relatively restricted distribution. Around the Gondwanan subcontinents, carbonate-terrigenous mixed sediments have been recorded only from the northern margin of India and from Afghanistan. Carbonate accumulation was episodic on the Yangze Platform of South China.

In geosynclinal belts, shallow water carbonates have been recorded from the orogenic continental margins, flanks of central massifs, and drowned sialic blocks in Tien-Shan, Altai-Sayan, Armorican–Bohemian Massif, Indo-China, Malacca, and Japan. Carbonate sediments including reef limestones are known also from ancient volcanic island arc settings; e.g. in the eastern Urals, the Alexander Archipelago along the western coast of North America, and in the east Australian geosynclinal belt.

In the late Silurian (Ludlow and Přídolí), profound regression of seas took place across all cratons, while there was also a concomitant increase in the area extent and tectonic activity of orogenic areas. The role of carbonate sediments decreased correspondingly. Regression was particularly noticeable on the North American and Siberian cratons, since large parts of these epicontinental seas were transformed into semi-isolated inland evaporite basins (e.g. Michigan, Hudson Bay, Sommerset Island, Tunguska basins). Normal carbonate sedimentation continued only along some cratonic margins. Gradual regression took place also in the Baltic basin, while the Urals margin of the East European craton continued subsiding and in places a typical barrier reef complex was developed. In other regions where carbonate sedimentation had taken place in early Silurian times, similar processes continued also in the late Silurian. There was also an expansion of carbonate facies to the flanks of the Bohemian Massif, to Turkey in the vicinity of the Bosphorus, eastern Iran, and to the Balkhash area of Kazakhstan.

Text-figure 1 shows that the position of the main Silurian areas of carbonate deposition in North



TEXT-FIG. 1. Areas of carbonate and terrigenous types of sedimentation and non-sedimentation (land) in the early Silurian. Continental reconstruction modified slightly after Scotese (1986). Distribution of land areas and main types of deposits after Ronov *et al.* (1984) and modified after Berry and Boucot (1970), Johnson (1987), Tesakov *et al.* (1986), and others.

America, eastern Europe, and Siberia was in good accord with the modern known distributional pattern. These continents were located in the equatorial belt between 35° N and 35° S, together with the Kolyma and Bering massifs. Kazakhstan and north and south China were also located in the optimal climatic belt, but as they were sites of active tectonic movements and produced abundant terrigenous clastics, conditions were less favourable for carbonate deposition on those continents.

Subcontinents and massifs of the Gondwana plate assemblage mostly lay at higher latitudes and beyond the optimum limits for carbonate precipitation. Nevertheless, calcareous deposits in association with terrigenous sediments were formed in late Silurian times on the margins of Hindustan, Tibet, Afghanistan, and the Armorican–Bohemian Massif, and also in Turkey and Iran, which according to Scotese's reconstructions were located at latitudes between 30° and 50° south. These carbonates may have formed in a temperate climatic zone, but this cannot be determined with certainty without further sedimentological analysis.

In the opposite (northern) hemisphere, only the carbonates of north-west Mongolia, Tuva, and Sayano-Altai have an untypically high latitudinal position (between 40° and 50°). Text-figure 1 also shows that, climatically, the western margin of the Urals occupied the most favourable position for reef building, as this continental margin was exposed to equatorial trade currents. The vast North American carbonate platform, in contrast, was sheltered from trade currents by the East Greenland and Appalachian land barriers. The same situation was characteristic of the Baltic-Podolian area, which was located along a west-facing continental margin. As noted further below, circumstances such as these controlled the different types of sedimentation on the various carbonate platforms.

PELAGIC CARBONATES

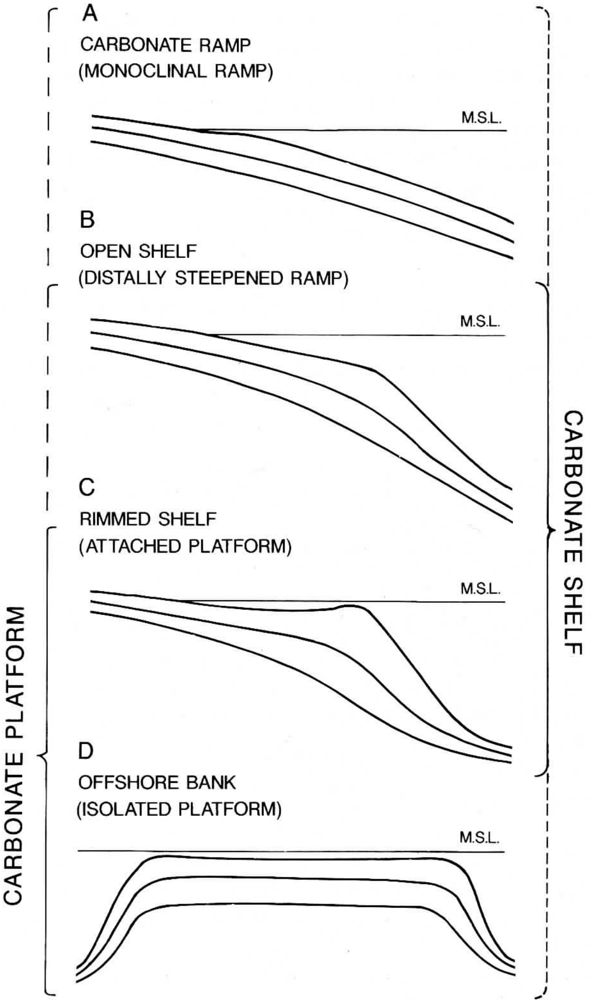
Silurian pelagic carbonate deposits were of very restricted distribution. Apart from the generally poor preservation of oceanic deposits in the geological record due to subduction processes, an essential reason for this was the lack of planktonic micro-organisms with calcareous tests, which appeared only in the Cretaceous Period. Of great significance also was the weak aeration of ancient oceans, particularly in the Precambrian and early Palaeozoic when euxinic conditions prevailed in the deeper water layers as suggested by Degens and Stoffers (1976), Ryan and Cita (1977), Berry and Wilde (1978, 1983) and others. This is borne out by the wide geographical spread of organic-rich black shales in geosynclinal sequences, and the absence of benthic organisms. Calcareous material cannot be deposited under anoxic conditions (Berger and Winterer 1974; Patrunov 1987) and, therefore, the carbonate compensation level was evidently much higher in early Palaeozoic times than at present. By the end of the Precambrian deeper water layers became ventilated and aerated from time to time, probably as a result of the development of deep oceanic currents in glacial periods.

During the first half of the Silurian Period (in the Llandovery and Wenlock), euxinic conditions were evidently prevalent, whereas in deeper basins mostly graptolitic shales were formed. In the late Silurian in several regions (central and northern Europe, north Africa, Urals, etc.) black graptolitic shales were replaced by limestones, resembling Devonian pelagic cephalopod limestones (e.g. Tucker 1974). The best known is the so-called Ockerkalk found in Thuringia and Sardinia (Jaeger 1976), which is a 10–30 m thick limestone formation sandwiched between black graptolitic alum shales in the stratigraphical interval from the *Monograptus chimaera* to *M. transgrediens* biozones. Jaeger (1976) described the Ockerkalk as thick bedded, bluish-grey, compact argillaceous limestone with an irregularly nodular structure and high pyrite and siderite content which on weathering turns into ochre. It contains pelagic crinoids (*Scyphocrinites*), ostracodes, orthoceratids, palaeoconchs, and conodonts, together with benthic forms like small smooth brachiopods, solitary corals, conulariids, blind trilobites and trace fossils. Low species diversity, and the occurrence of pelagic, dwarf and blind forms provide evidence that the Ockerkalk formed in deep water environments.

FACIES MODELS

Stratigraphical sequences of shallow water carbonates and their facies patterns are controlled primarily by the rate of sedimentation, local crustal movements, and eustatic sea-level changes. A limited number of basic facies models, each characterized by different bathymetric profiles, enables general descriptions to be made of carbonate platform sedimentation (e.g. see Ahr 1973; Wilson 1975; Read 1982, 1985; Tucker 1985). Simplified bathymetric curves for each of the basic regional types are shown in Text-figure 2. There is no unanimity in the terminology employed for carbonate deposition, but the main parallel names are given in Text-figure 2, with those used in this paper listed first.

TEXT-FIG. 2. Basic types of depositional settings of shallow marine carbonate sediments showing mean sea level (M.S.L.) and sea-bottom topography of carbonate platforms.



The only uniformitarian carbonate shelf model applied hitherto has been for the interpretation of neritic sedimentation. According to that model (Text-fig. 2*C*), carbonate deposition takes place on a comparatively flat shelf-plateau, with high energy environments at the abrupt shelf margin, and followed by a steep slope to a deep water basin. The shelf margin usually has a coral reef rim or a shoal barrier, separating an inshore, low energy shelf lagoon. Several authors (e.g. Wilson 1975; Tucker 1985) have applied the term carbonate platform to a shelf with an extremely flat surface and steep slopes. This term, however, has often been used also in a wider sense, i.e. as a common name for all types of shallow water carbonate settings.

Ahr (1973) suggested a ramp model for situations with a gently sloping sea floor lacking considerable changes in gradient (Text-fig. 2*A*). In such cases, facies are arranged as distinctive, wide belts, with the high energy zone situated relatively close to the shore. The Trucial coast of the Persian Gulf is an example of a modern carbonate ramp. Between a typical or homoclinal ramp and a well-developed rimmed shelf, several authors have distinguished a distally steepened ramp (Read 1982, 1985) or open shelf (Tucker 1985) in essentially the same sense. The bathymetric curve of such a feature is depicted in Text-fig. 2*B*. Unlike a typical ramp, the latter shows a distinct change in the gradient of the sea floor in the middle of the curve, but unlike a rimmed shelf it lacks the barrier of coral reefs or shoal deposits at the shelf edge.

As a separate category, one can also differentiate an off-shore carbonate bank or isolated platform, represented today for example by the Bahama banks (Text-fig. 2*D*). This region has an extremely flat surface and shallow water. The facies patterns depend not on bottom topography but on the differences in water dynamics and salinity on the windward and leeward sides of the bank, respectively. Wilson (1975) and Tucker (1985) have shown that a carbonate ramp can evolve into an open shelf, and then in turn into a rimmed shelf and finally an offshore bank. The Bahama banks have passed through all these stages of development (Schlager and Ginsburg 1981).

CARBONATE FACIES PATTERNS IN CRATONIC BASINS

Baltic pericratonic sea

Silurian epicratonic and pericratonic seas were characterized by a great variety of carbonate facies, which have been studied extensively in the Baltic area. Facies models for the Baltic Silurian palaeobasin have been described on a number of occasions by the authors of this paper (e.g. Kaljo 1970; Nestor and Einasto 1977, 1982; Einasto 1986).

The gulf-like Baltic basin was a typical cratonic sea situated on the south-western segment of the peneplaned East European platform, and represented an area of interaction between two geosynclinal belts: the British–Scandinavian terranes to the north-west and the central European (Mediterranean) area to the south-west, which in plate tectonic models are regarded as resulting from the closing Iapetus and opening Rheic (Palaeo-Tethys) oceans, respectively (e.g. McKerrow and Ziegler 1972; Tomczyk and Tomczykova 1979; Ziegler 1982). This tectonic framework led to a simultaneously rising north-west margin and subsiding south-west margin of the continent. During the Silurian the positive movements were predominant, and terrigenous influx became progressively intense from the Scandinavian Caledonides into the Baltic basin. The axial zone of the basin coincided with the Baltic 'syneclise' in west Latvia, Lithuania, the Kaliningrad district and north Poland, and represented a comparatively deep intracratonic depression with hemipelagic argillaceous sediments, while the basin margins formed a shallow water carbonate platform. To the south-west the Baltic cratonic sea was bounded by the Toernquist–Teissere lineament (text-fig. 4), which forms the south-west margin of the East European platform. A transition from platform margin to ocean floor across the Toernquist–Teissere lineament is unknown.

In a general facies model for the Baltic Silurian basin (Nestor and Einasto 1977), five facies belts are distinguished, as follows (text-fig. 3): 1, near-shore low energy tidal flat/lagoonal belt with argillaceous dolomitic sediments (laminated and bioturbated argillaceous dolomites and dolomitic micrites with impoverished biota); 2, high energy shoal belt with various sparitic calcarenites (skeletal, oncolithic, oolitic, pelletal grainstones), coquina banks and organic build-ups; 3, storm-agitated to quiet water open shelf with nodular skeletal packstones and wackestones, containing argillaceous intercalations and tempestite interlayers; 4, calm water transitional facies belt (the slope of Nestor and Einasto 1977), situated at the shelf margin and represented by calcareous mudstones, argillaceous micrites and marls; 5, basinal depression with graptolitic mudstones and shales. These facies belts coincide closely with the main facies described for carbonate platforms by Read (1985), apart from some variation in terminology. The first three belts formed the carbonate platform *sensu stricto* with high-energy shoal belt in the middle part.

In the evolution of the Baltic Silurian sea, three stages can be distinguished. Facies patterns for these stages are described with appropriate reference and modification to the facies model (text-fig.

considerable changes in gradient (Text-fig. 2*A*). In such cases, facies are arranged as distinctive, wide belts, with the high energy zone situated relatively close to the shore. The Trucial coast of the Persian Gulf is an example of a modern carbonate ramp. Between a typical or homoclinal ramp and a well-developed rimmed shelf, several authors have distinguished a distally steepened ramp (Read 1982, 1985) or open shelf (Tucker 1985) in essentially the same sense. The bathymetric curve of such a feature is depicted in Text-fig. 2*B*. Unlike a typical ramp, the latter shows a distinct change in the gradient of the sea floor in the middle of the curve, but unlike a rimmed shelf it lacks the barrier of coral reefs or shoal deposits at the shelf edge.

As a separate category, one can also differentiate an off-shore carbonate bank or isolated platform, represented today for example by the Bahama banks (Text-fig. 2*D*). This region has an extremely flat surface and shallow water. The facies patterns depend not on bottom topography but on the differences in water dynamics and salinity on the windward and leeward sides of the bank, respectively. Wilson (1975) and Tucker (1985) have shown that a carbonate ramp can evolve into an open shelf, and then in turn into a rimmed shelf and finally an offshore bank. The Bahama banks have passed through all these stages of development (Schlager and Ginsburg 1981).

CARBONATE FACIES PATTERNS IN CRATONIC BASINS

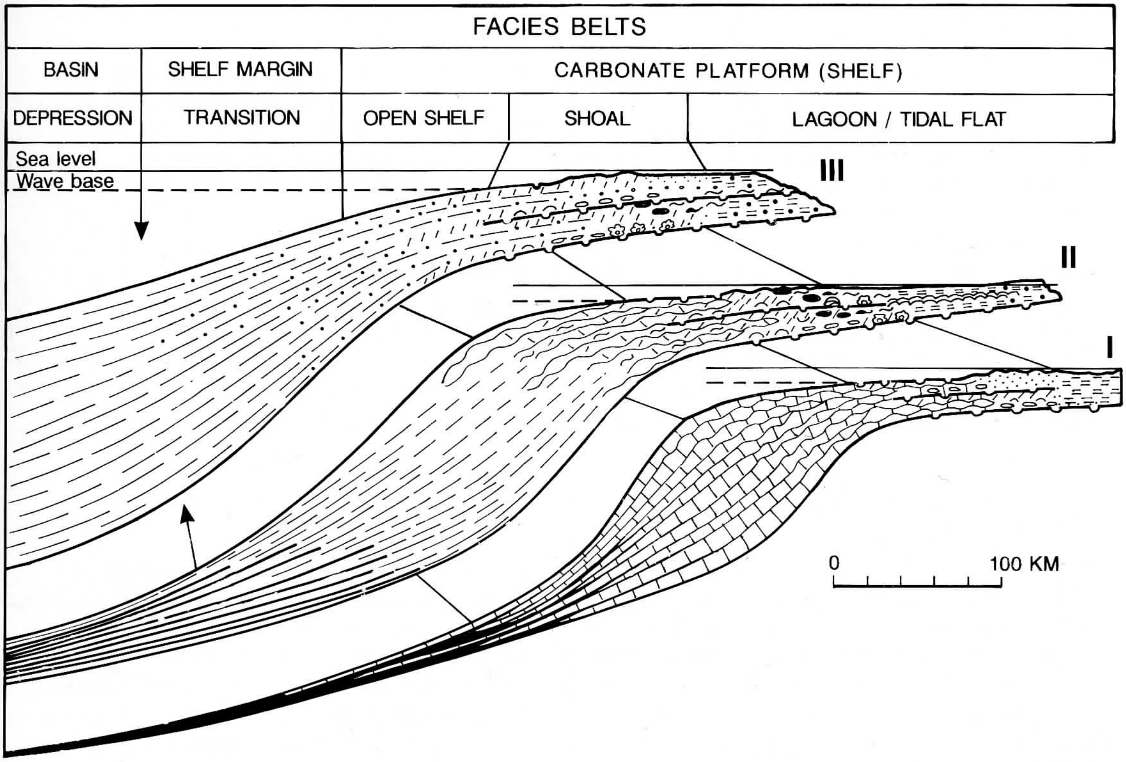
Baltic pericratonic sea

Silurian epicratonic and pericratonic seas were characterized by a great variety of carbonate facies, which have been studied extensively in the Baltic area. Facies models for the Baltic Silurian palaeobasin have been described on a number of occasions by the authors of this paper (e.g. Kaljo 1970; Nestor and Einasto 1977, 1982; Einasto 1986).

The gulf-like Baltic basin was a typical cratonic sea situated on the south-western segment of the peneplaned East European platform, and represented an area of interaction between two geosynclinal belts: the British–Scandinavian terranes to the north-west and the central European (Mediterranean) area to the south-west, which in plate tectonic models are regarded as resulting from the closing Iapetus and opening Rheic (Palaeo-Tethys) oceans, respectively (e.g. McKerrow and Ziegler 1972; Tomczyk and Tomczykova 1979; Ziegler 1982). This tectonic framework led to a simultaneously rising north-west margin and subsiding south-west margin of the continent. During the Silurian the positive movements were predominant, and terrigenous influx became progressively intense from the Scandinavian Caledonides into the Baltic basin. The axial zone of the basin coincided with the Baltic 'syneclise' in west Latvia, Lithuania, the Kaliningrad district and north Poland, and represented a comparatively deep intracratonic depression with hemipelagic argillaceous sediments, while the basin margins formed a shallow water carbonate platform. To the south-west the Baltic cratonic sea was bounded by the Toernquist–Teissere lineament (text-fig. 4), which forms the south-west margin of the East European platform. A transition from platform margin to ocean floor across the Toernquist–Teissere lineament is unknown.

In a general facies model for the Baltic Silurian basin (Nestor and Einasto 1977), five facies belts are distinguished, as follows (text-fig. 3): 1, near-shore low energy tidal flat/lagoonal belt with argillaceous dolomitic sediments (laminated and bioturbated argillaceous dolomites and dolomitic micrites with impoverished biota); 2, high energy shoal belt with various sparitic calcarenites (skeletal, oncolithic, oolitic, pelletal grainstones), coquina banks and organic build-ups; 3, storm-agitated to quiet water open shelf with nodular skeletal packstones and wackestones, containing argillaceous intercalations and tempestite interlayers; 4, calm water transitional facies belt (the slope of Nestor and Einasto 1977), situated at the shelf margin and represented by calcareous mudstones, argillaceous micrites and marls; 5, basinal depression with graptolitic mudstones and shales. These facies belts coincide closely with the main facies described for carbonate platforms by Read (1985), apart from some variation in terminology. The first three belts formed the carbonate platform *sensu stricto* with high-energy shoal belt in the middle part.

In the evolution of the Baltic Silurian sea, three stages can be distinguished. Facies patterns for these stages are described with appropriate reference and modification to the facies model (text-fig.



TEXT-FIG. 3. Facies models of three stages in the development of the Baltic Silurian sea (after Einasto 1986). I, transgressive stage; II, stability stage; III, infilling stage. For legend see Text-figure 5.

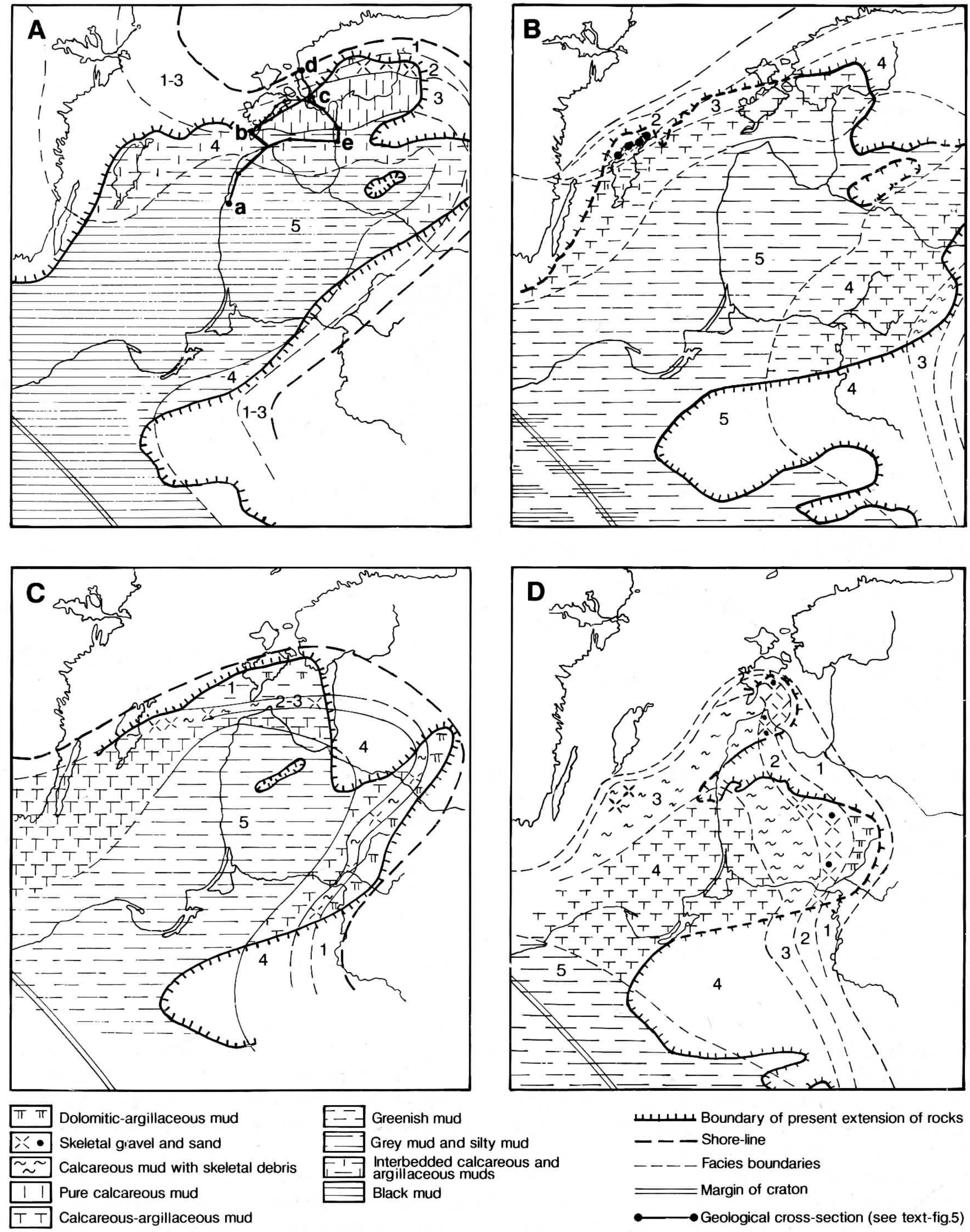
3) and the schematic lithofacies maps (Text-fig. 4). During the first, transgressive stage of evolution (early and mid Llandovery), influx of terrigenous material into the basin was extremely low periodically. Over the whole carbonate platform, as well as on the shelf margin, comparatively pure carbonate muds accumulated (Text-fig. 4*A*). Only in the high energy shoal belt were pelletal and skeletal sand also deposited. In the basinal depression, condensed dark graptolitic shales were formed.

The second stage, which was one of relative stability, lasting up to the late Ludlow, was characterized by moderate influx of fine terrigenous material, deposited partly in the lagoonal and open shelf belt but mostly in the transitional belt, result in lateral filling of the 'starved' basin with sediment lenses and leading to gradual progradation of the carbonate platform margin. Text-figures 4*B* and 4*C* demonstrate different phases in this stable stage of development, showing a well developed facies zonality.

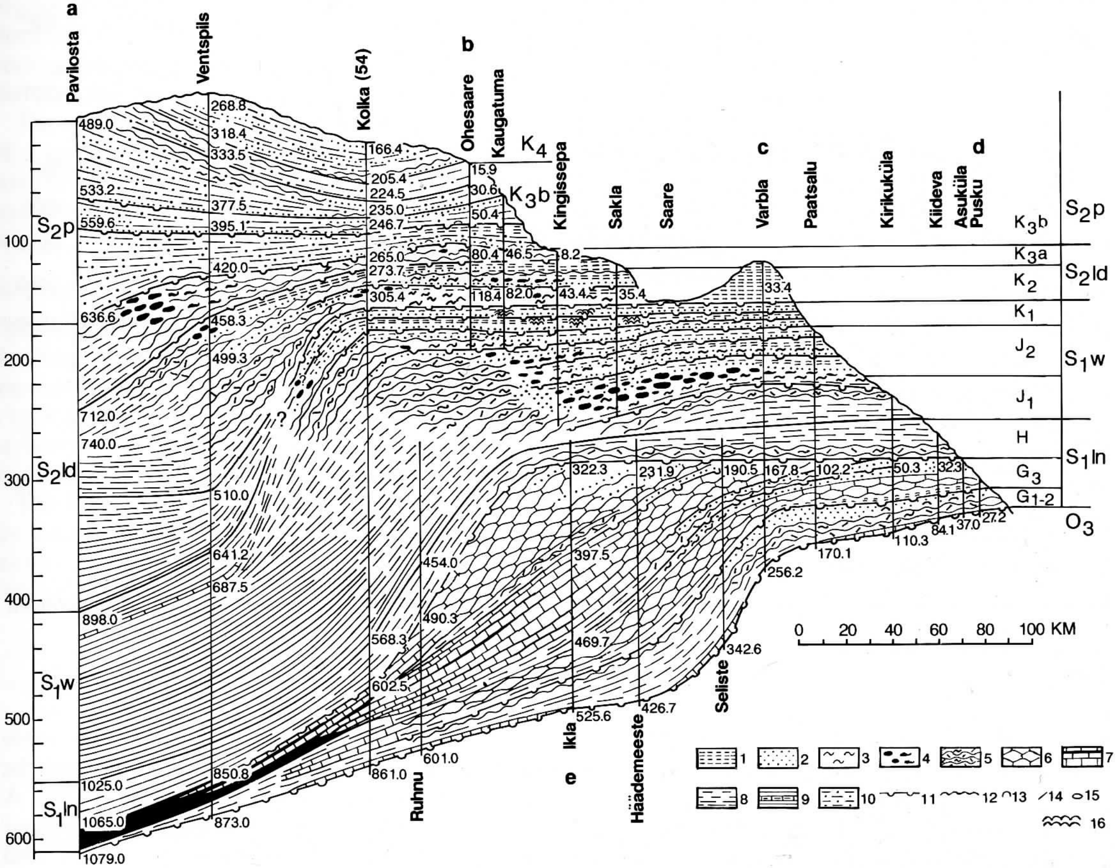
At the beginning of the Wenlock Epoch there was a maximum of transgression of the Baltic Silurian sea, when the deepest water facies with argillaceous deposits covered very large areas (Text-fig. 4*B*). Intense regression then followed, culminating at the end of the Wenlock (Text-fig. 4*C*). Wide areas of the carbonate platform were covered with shallow water lagoonal sediments, but shoal and open shelf belts were very narrow or absent.

The last stage of basin evolution involved infilling in the late Ludlow-Přídolí, initiated by intense influx of terrigenous material which filled the basin depression and also diluted carbonate sedimentation on the open shelf, where skeletal packstones were replaced by skeletal marls. This process caused extensive migration of all facies belts towards the cratonic margin (Text-fig. 4*D*).

A geological cross-section through the northern margin of the Baltic basin (Text-fig. 5) shows



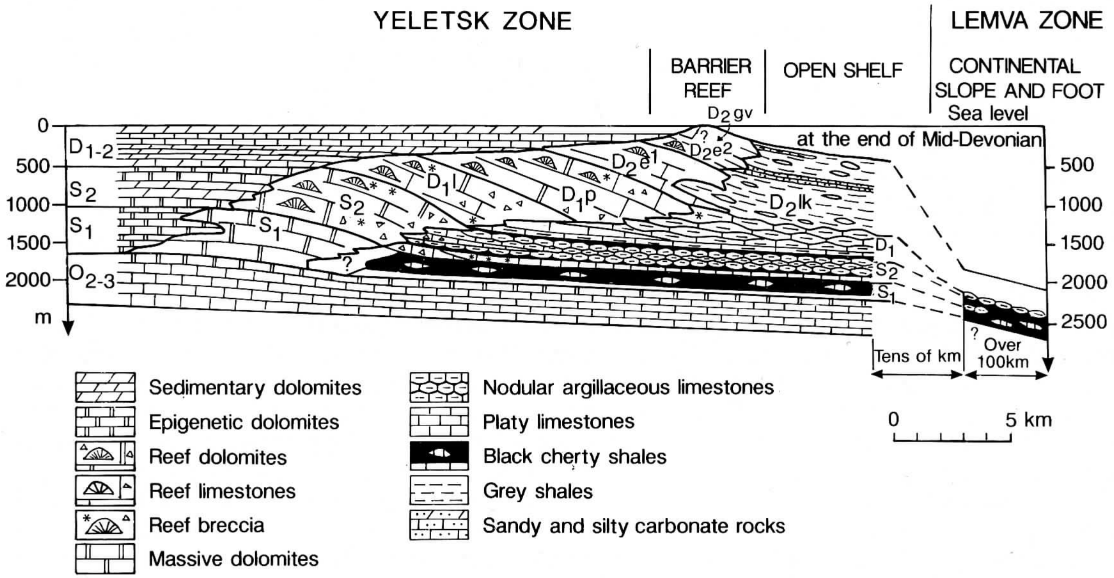
TEXT-FIG. 4. Distribution of sediments and facies belts at selected time levels in the development of the Baltic Silurian sea. *A*, Llandovery, a time slice within the interval represented by the *convolutus* Biozone (**a-b-c-d-e**: location of the geological cross section of Fig. 5); *B*, early Wenlock, representing the *murchisoni* Biozone (after Bassett *et al.* 1989); *C*, late Wenlock, within the *nassa* Biozone; D, Přídolí, a time slice within the *Frostiella groenvalliana* Biozone (after Bassett *et al.* 1989).



TEXT-FIG. 5. Cross-section through Silurian facies of the northern flank of the Baltic sedimentary basin, from the Kurzeme Peninsula in Latvia to western Estonia. Location of the cross-section is shown in text-fig. 4*A*. 1, argillaceous dolomites; 2, sparitic calcarenites; 3, bioturbated calcareous mudstones; 4, organic build-ups with back reef sediments; 5, nodular skeletal packstones and wackestones, 6, nodular calcilutites; 7, intercalating calcilutites and graptolitic mudstones; 8, calcareous mudstones or marls; 9, graptolitic mudstones; 10, silty mudstones; 11, hardgrounds; 12, surface of post-Silurian erosion; 13, brachiopod banks; 14, skeletal particles; 15, conglomerate; 16, stromatolites.
Indices of regional stages: G_{1-2} = Juuru; G_3 = Raikküla; H = Adavere; J_1 = Jaani; J_2 = Jaagarahu; K_1 = Rootsiküla; K_2 = Paadla; K_3a = Kuressaare; K_3b = Kaugatuma; K_4 = Ohesaare.

lenticular outbuilding of carbonate sediments, which resulted in the southerly progradation of the platform margin over a distance of 150–200 km during Silurian times. A noteworthy feature was also the cyclic alternation of facies through the vertical sequence, which is clearly seen in the shallowest (lagoonal and shoal) deposits. Hardgrounds were also typical, some of them being very extensive and spreading across the whole platform.

In general, carbonate sedimentation in the Baltic basin included several features typical of ramp-type deposition, such as the presence of distinct facies belts, and the location of a high energy shoal belt in the middle or near-shore part of the platform region. Commonly, and especially in regressive phases, there were characteristic developments in shelf morphology, such as flattening of the platform surface and the formation of a distinct break in gradient at the platform margin.



TEXT-FIG. 6. Reconstructed cross section through the Silurian–Devonian prograding shelf margin of the western Polar-Urals (after Shishkin 1986).

Polar-Ural pericratonic sea

In the Uralian palaeo-ocean, sea floor spreading began in the Silurian (Korinevsky 1988), and the western slope of the Urals constituted a passive continental margin (e.g. Putshkov 1979). A transition from neritic to bathyal sediments can be demonstrated (Text-fig. 6) on the reconstructed geological cross-section through the Polar Urals compiled by Shishkin (1986, 1987) and characterizing the situation from the Middle Ordovician to the Middle Devonian.

Voinovskiy-Krueger (1947) first distinguished two tectonic zones on the western slope of the Urals – the Yeletsk and Lemva zones. Facies of the Yeletsk zone are regarded as pericratonic shelf sediments, whilst those of the Lemva zone are considered as bathyal continental slope and foot of slope sediments.

The Yeletsk zone, in turn, can be subdivided into three distinct belts. The westernmost, near-shore belt is a shelf lagoon or restricted shelf ranging for 100 km and containing terrigenous-carbonate sediments; this belt is characterized by cyclic sedimentation. Shallowing upward cycles are dominant containing skeletal packstones and grainstones or dolomites, with an impoverished ostracode–gastropod community in their lower part; in the upper levels there are laminated and bioturbated sedimentary dolomites, in places with desiccation cracks. In the early Silurian the shelf was more differentiated, often representing open shelf conditions. In the late Silurian it became increasingly isolated. The total thickness of sediments in this belt is about 1200 m.

In the east the restricted shelf was bounded by a barrier reef belt characterized by thick, massive secondary dolomites, dolomitized boundstones, and reef breccias. Stromatactis structures are present. Algae, problematical hydroids, and less commonly corals and stromatoporoids served as frame builders (Shuiskiy 1983). During the Silurian and early-mid Devonian the reef barrier (with a width of 5 to 10 km) prograded for 10–15 km over the deeper water sediments. Total thickness of the reef complex in the Silurian was about 1500 m. A typical reef barrier was formed in the late Silurian.

To the east of the reef complex there are transitional sections, where lower Silurian facies are represented by black cherty graptolitic shales (thickness 150 m), and the upper Silurian by argillaceous nodular limestones containing conodonts and crinoids, and with grainstone interbeds demonstrating evidence of grading (probably calcareous turbidites). Shishkin has interpreted these rocks as deposits of the open shelf. In fact they more closely resemble the true bathyal deposits of the Lemba Zone, i.e. deposits of the continental slope and foot of slope.

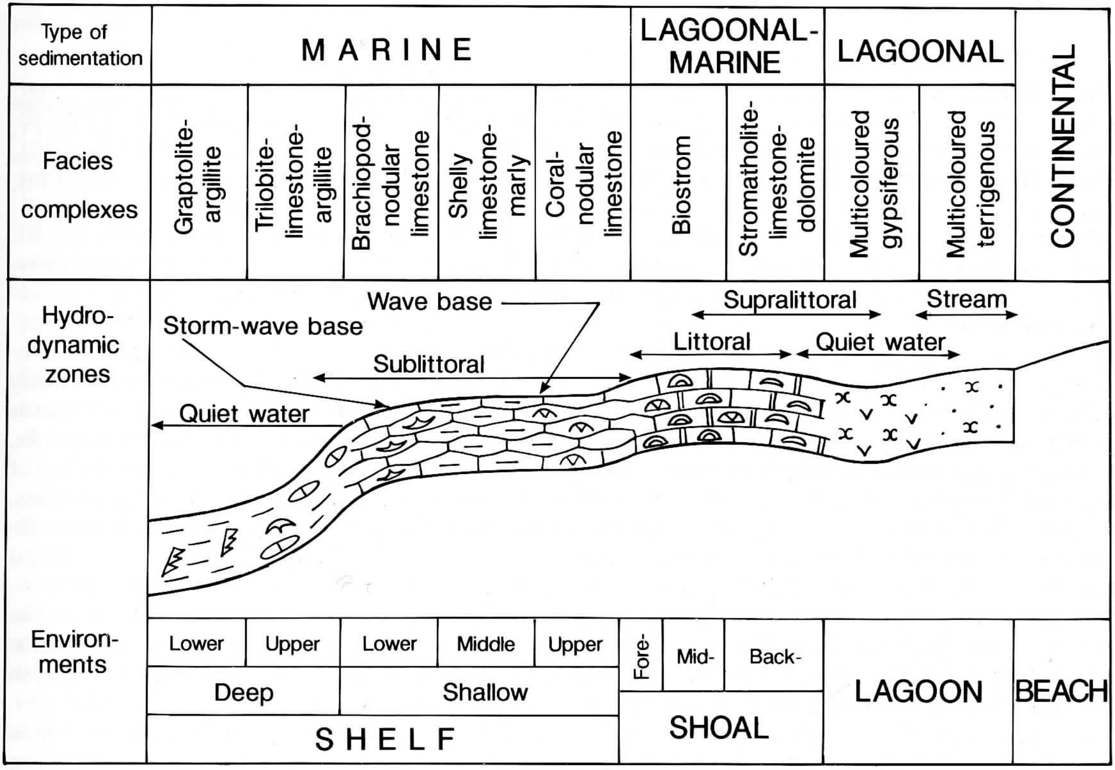
The cross-section though the carbonate platform margin in the Polar Urals indicates the presence of a typical reef-rimmed shelf (cf. Wilson 1974), which was situated on the ocean-facing passive continental margin open to equatorial trade currents. In this respect, the carbonate platform of the western Urals differs essentially from the other larger Silurian carbonate platforms, which lay further to the continental interior and were sheltered from the trade currents.

Siberian epicontinental sea

The Siberian sea was one of the most extensive basins of carbonate sedimentation in the world after the North American cratonic region. According to recent reconstructions (e.g. Scotese 1986), this sea was located at lower to moderate latitudes of the Northern Hemisphere (20°–35°). It represented a typical epicontinental basin, having comparatively restricted connection with an open ocean. The carbonate facies and sedimentary environments of the Siberian sea have been studied thoroughly by a team of specialists led by Tesakov and Predtechenskiy (e.g. 1979, 1985, 1986).

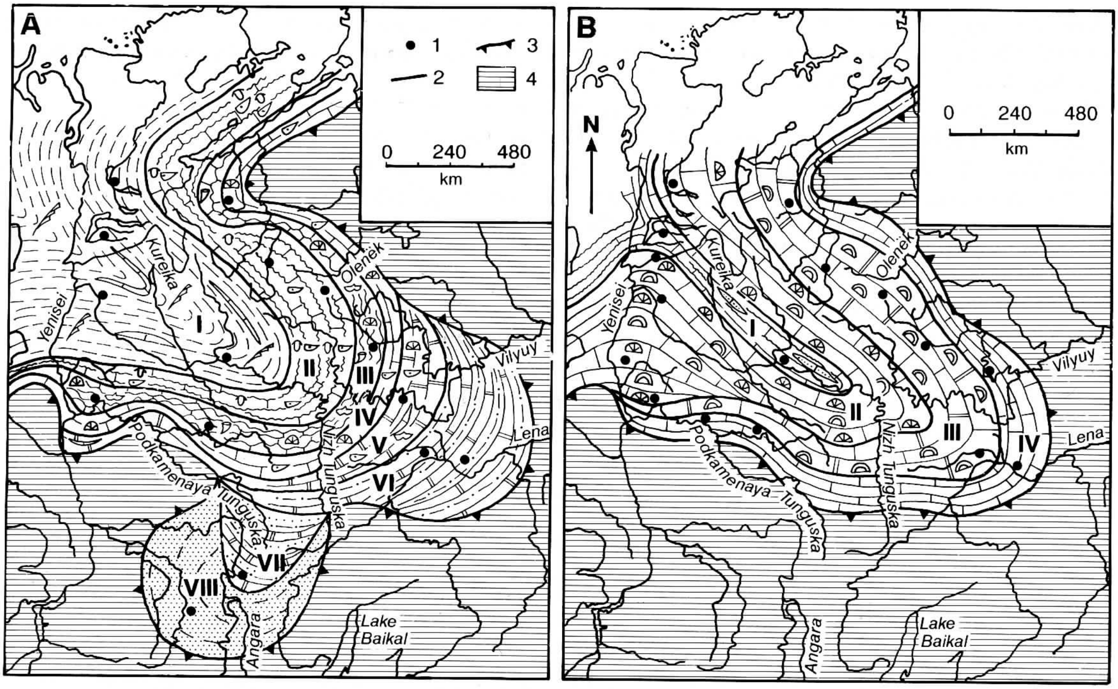
The Silurian Siberian sea extended for 1500 km into the platform, being mostly surrounded by flat land (Text-fig. 8). Only the north-western areas were open to the ocean, with the 'mouth' of the seaway being some 1000 km wide. The transition area from the sea to the ocean is referred to by Tesakov *et al.* (1985) as the Hatanga–Norilsk pericraton.

TESAKOV, PREDTECHENSKY et al., 1979



TESAKOV, PREDTECHENSKY, KHROMYCH et al., 1986

TEXT-FIG. 7. Facies model for the Siberian epicontinental sea.



TEXT-FIG. 8. Facies belts of the Siberian epicontinental sea. *A*, early Llandovery; B, early Wenlock; (after Tesakov 1981). 1 = studied localities; 2 = facies belt limits; 3 = limits of the basin; 4 = continent. Description of the facies belts.

A: Deep shelf; I, argillites and marls with graptolites, orthocones in limestone interlayers; II, micritic limestones with trilobites and ostracodes. Shallow shelf; III, nodular limestones with corals and brachiopods; IV, limestones with ostracodes and tabulates. Shoal; V, dolomites and limestones with ostracodes, brachiopods and corals. Lagoons and restricted shelf; VI, siltstones and dolomites with rare corals and brachiopods; VII, dolomites, siltstones and sandstones; VIII, siltstones and sandstones.

B: Shallow shelf; I, biomicritic limestones; II, limestones with corals and stromatoporoids. Shoal; III, dolomites and limestones dominated by stromatoporoids, locally occurring corals and stromatolites. Restricted shelf; IV, limestones with rare ostracodes and corals.

On the basis of palaeoclimatic data, the Siberian sea was located in the warm, arid belt. Aridity increased to the south-east, farther away from the ocean (i.e. the climate became more arid towards higher latitudes). This is evidenced by the appearance of gypsum, fluorite, celestine, etc. in the rocks, and also by the presence of oolitic limestones and hydromica. In the early Silurian, the salinity of sea water is assumed to have been mostly normal marine, but becoming higher in late Silurian times, especially in the south. Mostly terrigenous sedimentation took place at the southern and south-western margins of the basin near the Altai-Sayan fold zone. These areas were later transformed into land environments.

Terrigenous sedimentation was also dominant in the pericratonic areas, represented in the geological record by argillites with rare carbonate lenses and interbeds. The extensive sector of the sea lying between the pericratonic and nearshore belts can be treated as a carbonate platform, in which the different facies belts were subparallel to the coastline.

Tesakov *et al.* (1979) have compiled a facies model for the Siberian basin, supplemented by us with data from the same authors (1986) on the environments (Text-fig. 7). The spatial distribution of the facies is shown in Text-figures 8*A* and 8*B*. According to this model, four main groups of environments are distinguished – deep shelf, shallow shelf, shoal, and lagoon. The full set of environments and their distribution in distinct belts was characteristic for the Llandovery, whilst from the beginning of the Wenlock only shoal and restricted marine environments prevailed across the whole of the sedimentary basin.

In deep shelf environments, represented by graptolite–argillite and trilobite–limestone–argillite complexes, carbonates occur sporadically as lenses and interbeds, increasing in number with shallowing of the sea. At the beginning of the Silurian there were some interbeds of black bituminous limestones abounding in nautiloids (Tesakov *et al.* 1985). The close relationship of these limestones with graptolitic rocks allows them to be interpreted as pelagic. The deep shelf environments in the sense of Tesakov and his colleagues clearly correspond to the shelf margin and basin environments of the Baltic Silurian facies model.

Shallow shelf sediments are represented mostly by various nodular limestones (packstones, wackestones) with very rich benthic faunas. Based on differences in bottom topography, water depth, hydrodynamics, hydrochemistry etc., three belts and a number of local varieties can be distinguished within the shallow shelf. Lower shallow shelf deposits are represented by a brachiopod-dominated nodular limestone complex, in which argillaceous limestones are predominant. Bioturbation is extensive. The occurrence of tempestite interlayers reflects deposition above storm wave base. Ostracodes and brachiopods are dominant members of the faunal communities.

The middle shallow shelf is characterized by shelly limestones and a marlstone complex with a highly variable rock composition; the marls alternate with skeletal and coquinoid limestones. Brachiopod banks, crinoidal limestones, and argillaceous nodular limestones with trace fossils are present. The formation of this complex was associated with flat elevations of the sea floor in the middle of the shallow shelf, mostly inhabited by diverse coral or brachiopod biotas, but, more rarely also by gastropod dominated communities. In places there were flat-lying biostromes.

A coral–nodular limestone complex with a predominance of coarse, nodular, coral-rich limestones and containing abundant skeletal particles including crinoids and various other groups has been considered as a typical facies of the upper shallow shelf. It contains marl interbeds and brachiopod banks. Corals were the dominant fauna, especially large tabulates and numerous rugosans, but no true organic build-ups have been recorded. Compared with the previous belt, these rocks are considerably less argillaceous, with the sediments more winnowed; they are interpreted as having accumulated at wave base.

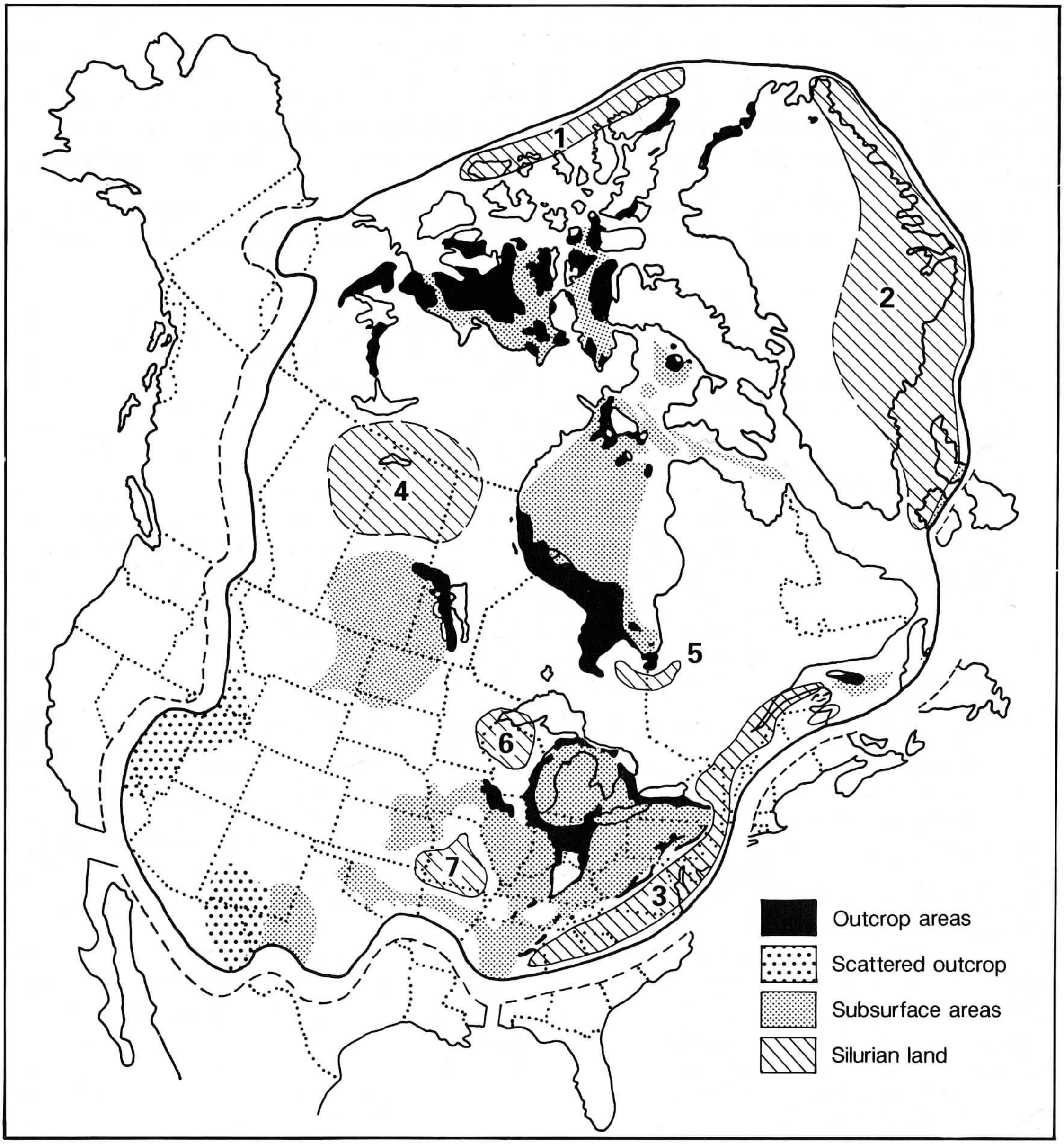
The following two facies complexes are associated with a shoal belt located in a high energy environment (above wave base), with very variable sea floor topography and diverse sedimentary conditions. Widespread features included stromatoporoid and coral biostromes, nodular skeletal packstones and grainstones, pelletal limestones with oncolites, and stromatolites interbedded with argillaceous dolomites that contain mud cracks, hardgrounds, and conglomeratic interlayers. Locally there may have been interbiostromal or back-biostromal semi-restricted areas of higher water salinity. This is true particularly of the so-called back-shoal area, where laminated and bun-shaped stromatolites are widely distributed in algal, oolitic and nodular limestones and dolomites. The final complex represents a transition to hypersaline lagoonal sediments, containing gypsum and other sulphide minerals.

A pattern of evolution of communities can be observed in the shoal belt. In the late Llandovery, corals were dominant, followed by stromatoporoids in the Wenlock (particularly abundant stromatoporoid-biostromes), and then by ostracodes in the Ludlow. From the end of Llandovery times, practically the whole area of the Siberian basin was covered with shoal belt sediments, and thus by then the region had become a very shallow warm sea with an abundant fauna. In the Ludlow, further regression and increased aridity led to an increase in water salinity and impoverishment of communities. The Přídolí is represented only by red, gypsiferous, terrigenous and dolomitic rocks devoid of fossils.

General regression was accompanied by continuous oscillations of sea level, but after drastic lowering in the Telychian these oscillations were restricted to shoal belt depth intervals. Such a long-term persistence of an extremely shallow sea seems to have been one of the characteristic features of the Siberian basin, creating conditions for the formation of a highly variable facies mosaic. The lack of a clear facies zonality and well-developed cyclicity of sequences gives evidence of epicontinental platform-type sedimentation.

North American epicontinental sea

The North American platform was the largest Silurian area of carbonate sedimentation forming a

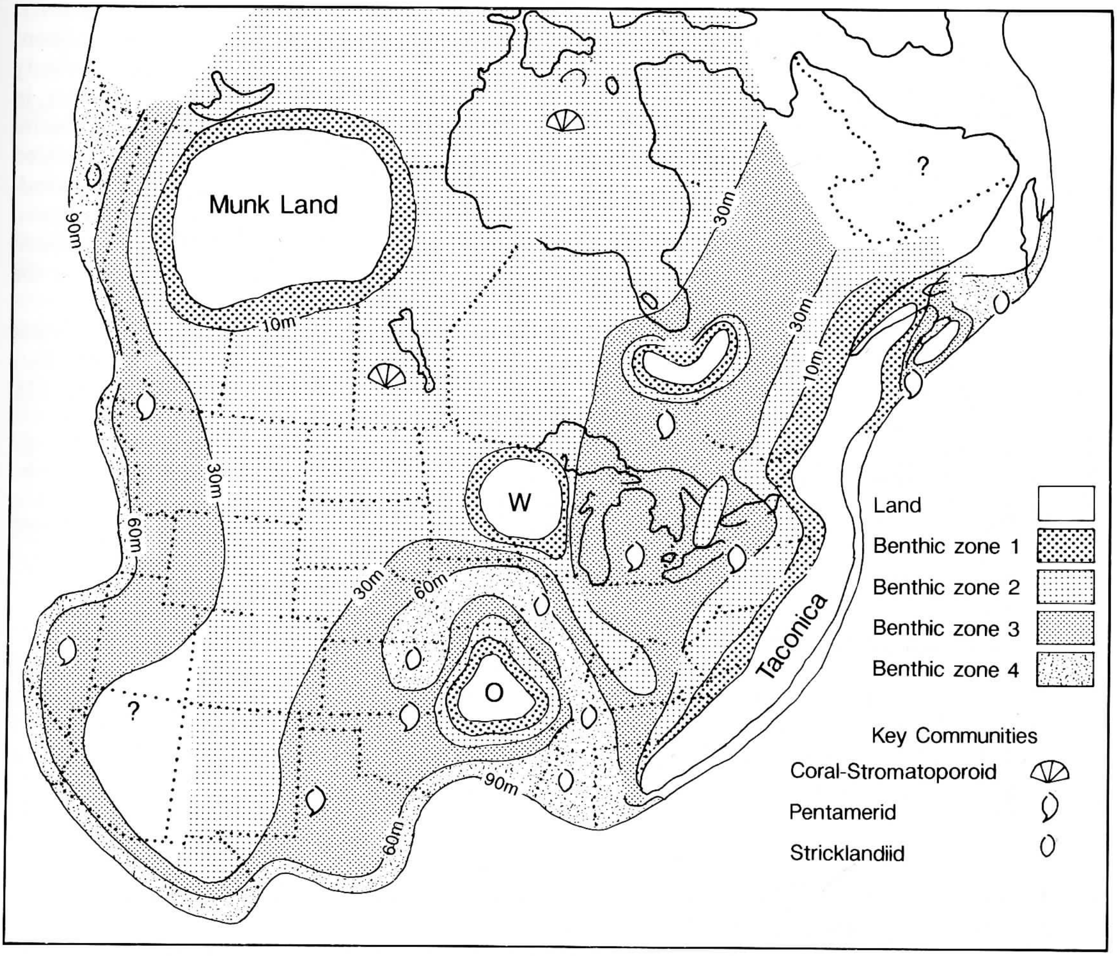


TEXT-FIG. 9. The North American craton in the early Silurian. Land areas are 1, Pearya; 2, Eocaledonia; 3, Taconica; 4, Munk Land; 5, Fraserdale Land; 6, Wisconsin Dome; and 7, Ozark Dome. Areas added to the continent in post-Silurian time are detached, with their boundaries marked by dashed lines. (After Johnson 1987.)

single sedimentary basin, i.e. it was a shallow sea covering practically the whole craton (e.g. see Berry and Boucot 1970; Johnson 1987), although the present preserved distribution of Silurian rocks does not allow this view to be asserted unambiguously. The platform extended for *c.* 6000 km from north to south, and was located between latitudes 30° N and S (Scotese 1986), thus having optimally favourable conditions for carbonate accumulation.

A schematic map compiled by Johnson (1987) shows the margins of the North American craton, the limits of the supposed land areas, outcrops, and subsurface areas of Silurian rocks (see text-fig. 9). In addition to small, isolated land areas, two local intracratonic depressions (Michigan and Illinois basins) have been distinguished. Along the eastern and north-eastern margins of the platform, land barriers (Taconica, Eocaledonia, and Pearya) separated the shallow epicratonic seas from the ocean. At the southern and western margins there were no barriers but direct connection with the ocean. Thus during the early Silurian, more or less normal marine conditions prevailed throughout the platform seas, but in the late Silurian extensive evaporite basins (Michigan, Ellesmere Island) were formed.

Berry and Boucot (1970) have distinguished two main belts of carbonate rocks: an internal dolomite suite; and an external limestone suite. The limestones are surrounded in turn by belts of



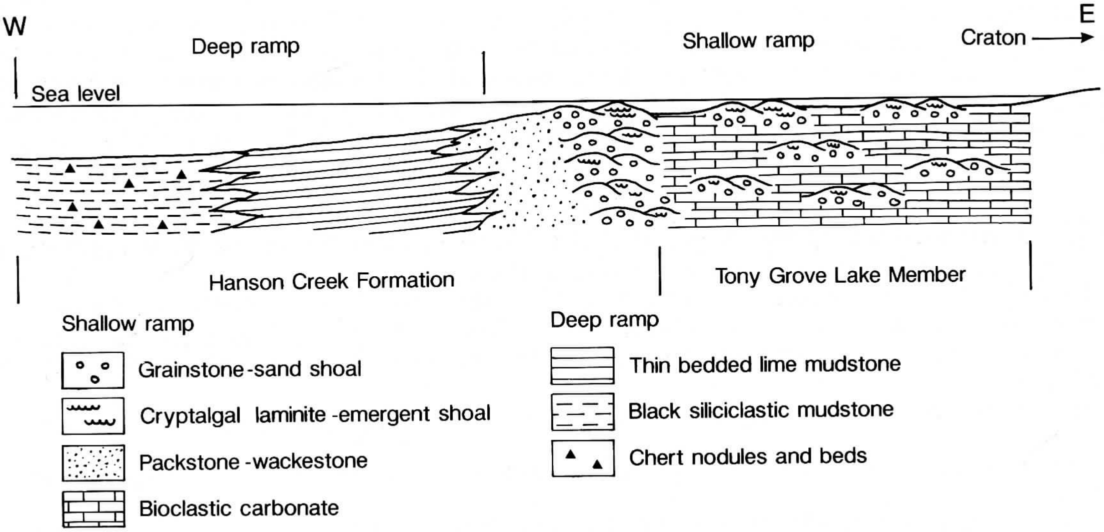
TEXT-FIG. 10. Bathymetric map of the North American craton during the early Telychian maximum sea level stand. (From Johnson 1987.)

terrigenous rocks, including sandstones, siltstones and shales (mudstones) containing mostly graptolites, although in places there are also shelly fossils in the vicinity of the marginal land areas. Berry and Boucot (1970), as well as other American authors, interpret the dolomites of the central part of the platform mostly as secondary, epigenetic dolomites as they have yielded the same fossils as the limestones. Lithologically the rocks of the limestone suite are somewhat more argillaceous than the dolomites.

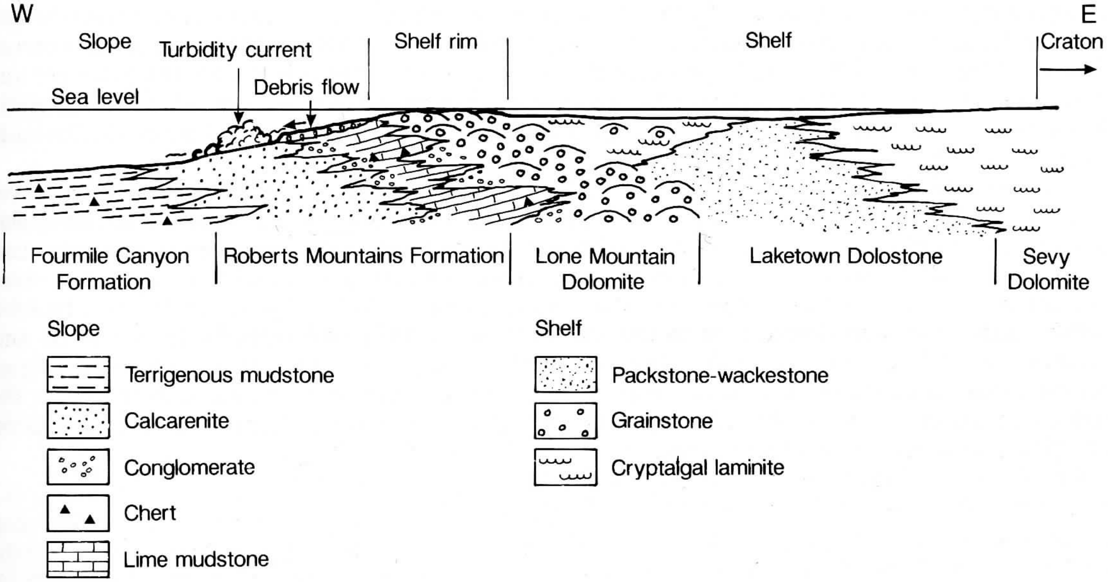
A more detailed picture of sea floor topography and distributional patterns of the main facies can be obtained from the bathymetric maps compiled by Johnson (1987) on the basis of the occurrence of fossil communities. A map of the early Telychian sea level maximum (Text-fig. 10) shows that a fairly considerable part of the platform was covered by extremely shallow sea, with depths not exceeding 30 m (within the limits of benthic assemblage zones 1 to 3 of Boucot 1975). Within such depths, local rises and depressions in the sea floor topography had remarkable effects on the accumulation of carbonates, leading to high variability in sediment types (mosaic sedimentation, as on the present Bahama banks). At the same time, one should note an apparent tendency of depth-related communities to be aligned subparallel to the coastline of the supposed islands, craton margins, and intracratonic depressions.

One of the most characteristic features of Silurian carbonate sediments on the North American platform is their clear cyclicity, and at the same time their significant spatial (lateral) homogeneity. Johnson (1980), in analysing recurrent benthic communities in the early Silurian of the midcontinent (Iowa, Illinois), stressed a depth-related nature of the cyclicity, i.e. he explained such a community pattern in terms of cyclic fluctuations in sea level over a broad and very flat sea bottom. Later, in dealing with the formation of cyclic carbonates of the Interlake Group of the Williston basin, Johnson and Leschinsky (1986) reached the conclusion that in addition to the depth-related cyclicity, there could have been an alternative type of cyclicity caused by the interaction of wind-generated waves, tides, and sea-bottom topography as in Recent carbonate bank environments. This last type of sedimentation was common for the shallowest parts of the huge, integrated platform sea. Thus a combination of platform to bank type sedimentation was characteristic for the North American Silurian epicontinental sea.

A transition from the epeiric-sea carbonate platform to a deeper basin has been studied in Nevada by Hurst *et al.* (1985), who described an early Silurian carbonate ramp extending from tidal flats to the basin and the occurrence of a variably wide shoal belt at the basin margin (Text-figs 11, 12).



TEXT-FIG. 11. Schematic facies model for the early to mid-late Llandovery carbonate ramp in Nevada. Most of the shallow-ramp facies are now secondary dolomites. (From Hurst *et al.* 1985.)



TEXT-FIG. 12. Schematic facies model for the latest Llandovery to Ludlow rimmed shelf in Nevada. Most of the shelf facies are now secondary dolomites. (From Hurst *et al.* 1985.)

In the late Llandovery this ramp subsided considerably, then rose again and remained stable up to the Ludlow as a typical rimmed shelf. The shelf/slope boundary is characterized by the presence of grainstones of the shoal belt; on the slope there are turbidites. Shoreward of the shoal belt various dolomitic rocks were distributed, containing stromatolites and other fossils.

It should be noted that this interpretation has not been accepted fully, but nevertheless, we consider it useful to demonstrate some aspects of facies patterns around the marginal area of the North American craton open to the ocean. It is also interesting to trace the evolution of a ramp-like margin into a rimmed shelf. Bearing in mind such characteristic features as the wide distribution of dolomites, the relatively restricted connection with oceans, and the extreme shallowness of the sea over wide areas, we can note that there was much in common in patterns of carbonate deposition in the North American and Siberian epicontinental seas, which formed a characteristic type of carbonate depositional environment not exactly comparable with those of modern settings.

CONCLUDING REMARKS

In discussing the genesis, palaeogeographical distribution, and facies patterns of Silurian carbonate rocks it is generally possible to use many aspects of modern analogues (e.g. Milliman 1974; Lees 1975; Scholle *et al.*1983) and also to employ general theories of carbonate platform sedimentation worked out over the past few decades (Wilson 1975; Tucker 1985; Read 1975). In general terms, the formation of Silurian carbonates took place in more or less similar depositional settings to those of today.

The most characteristic features of Silurian carbonate sedimentation appear to be as follows:

1. A wide distribution of shallow marine carbonates with, in contrast, only a limited distribution of pelagic facies.
2. The considerable role of dolomites within Silurian carbonate rocks.
3. A great variety of depositional environments for shallow marine carbonates, including epicontinental platform type sedimentation, which has no direct modern analogues.

There are two general reasons for the above-mentioned characteristics: (*a*) most of the continents and shelf seas were situated in the warm equatorial climate belt; (*b*) the topography of the Silurian continents was mainly flat, and consequently the amount of clastic influx into shallow seas was relatively limited. Only in the second half of the Silurian times did this influx increase considerably, when the overall regression of cratonic seas caused a drastic diminution of the areas of carbonate deposition.

A striking feature for all types of Silurian carbonate platform environments that we have summarized above, i.e. for epicratonic, semirestricted and pericratonic seas, was an unusually flat sea bottom, sloping only very gently towards the cratonic margins. As a consequence, those seas had a very wide tidal flat/lagoonal or semirestricted shelf area in which dolomitic sediments were prevalent, containing a typical assemblage of fossil organisms such as algae, ostracodes, lingulid brachiopods, eurypterids, and vertebrates. Also typical was the wide distribution of shoal and shallow shelf environments, favouring the flourishing of corals, stromatoporoids, algae, pelmatozoans and other frame-building organisms. Intense reef-building started therefore in the middle Silurian times in many regions (e.g. Baltic, Welsh Borderland, Michigan and Illinois basins, Tuva, etc.), and true barrier reefs developed in the late Silurian (e.g. Western Urals).

Acknowledgements. We are grateful to M. G. Bassett who invited us to write this paper and helped with language correction and in many other ways. L. Lippert, Mrs D. G. Evans and Mrs L. Norton drafted the figures. We are indebted to our colleagues who are involved with us in compiling a Baltic Silurian palaeogeographical atlas on which our facies maps here are based (full acknowledgement is made in Bassett *et al.* 1989). We thank also N. N. Predtechenskiy and M. O. Kovalevskaya for providing some literature, and A. Noor for linguistic help.

REFERENCES

AHR, W. M. 1973. The carbonate ramp: an alternative to the shelf model. *Transactions of the Gulf Coast Association of Geological Societies*, **23**, 221–225.

BASSETT, M. G., KALJO, D. and TELLER, L. 1989. The Baltic region. 158–170. *In* HOLLAND, C. H. and BASSETT, M. G. (eds.). *A global standard for the Silurian system*. National Museum of Wales, Geological Series, No. 9, Cardiff. 325 pp.

BERGER, W. H. and WINTERER, E. L. 1974. Plate stratigraphy and the fluctuating carbonate line. *In* HSÜ, K. J. and JENKYNS, H. C. (eds.) Pelagic sediments: on land and under the sea. *Special Publications of the International Association of Sedimentologists*, **1**, 11–48.

BERRY, W. B. N. and BOUCOT, A. J. 1970. Correlation of the North American Silurian rocks. *Special Papers of the Geological Society of America*, **102**, 1–289.

—— and WILDE, P. 1978. Progressive ventilation of the oceans – an explanation for the distribution of the Lower Paleozoic black shales. *American Journal of Science*, **278**, 257–275.

—— —— 1983. Evolutionary and geologic consequences of organic carbon fixing in the primitive anoxic ocean. *Geology*, **11**, 141–145.

BEZBORODOVA, I. V. 1988. Fatsial'nye tipy dolomitov razlichnogo vozrasta [Facies types of dolomites of different ages]. 35–57. *In* TIMOFEEV, P. P. and KUZNETSOV, V. G. (eds.). *Evolyutsiya karbonatonakopleniya v istorii zemli*. Nauka, Moskva.

CARANNATE, G., ESTEBAN, M., MILLIMAN, J. D. and SIMONE, L. 1988. Carbonate lithofacies as paleolatitude indicators: problems and limitations. *Sedimentary Geology*, **60**, 333–346.

DEGENS, E. D. and STOFFERS, P. 1976. Stratified waters as a key to the past. *Nature, London*, **263**, 22–27.

DOYLE, L. J. and ROBERTS, H. H. (eds.). 1988. *Carbonate-clastic transitions*. Developments in Sedimentology, no. **42**, 1–304.

EINASTO, R. 1986. Osnovnye stadii razvitiya i fatsial'nye modeli siluriyskogo kraevogo basseina Baltiki [Main stages of development and facies models of the East Baltic Silurian pericontinental basin]. 37–54. *In* KALJO, D. and KLAAMANN, E. (eds.). *Teoriya i opyt ekostratigrafii* [Theory and practice of ecostratigraphy]. Valgus, Tallinn.

FLÜGEL, E. 1979. *Microfacies analysis of limestones*. Springer-Verlag, Berlin, 633 pp.

FRIEDMAN, G. M. and SANDERS, I. H. 1967. Origin and occurrence of dolomites . *In* CHILINGAR, G. V., BISSEL, H. J. and FAIRBRIDGE, R. W. (eds.). Carbonate rocks. *Developments in Sedimentology*, **9A** 215–245.

HECKEL, P. H. and WITZKE, B. J. 1979. Devonian world palaeogeography determined from distribution of carbonates and related lithic palaeoclimatic indicators. *In* HOUSE, M. R., SCRUTTON, C. T. and BASSETT, M. G. (eds.). The Devonian System. *Special Papers in Palaeontology*, **23**, 99–123.

HURST, J. M., SHEEHAN, P. M. and PANDOLFI, J. M. 1985. Silurian carbonate shelf and slope evolution in Nevada: history of faulting, drowning and progradation. *Geology*, **13**, 185–188.

JAEGER, H. 1976. Das Silur und Unterdevon vom thüringischen Typ in Sardinien und seine regionalgeologische Bedeutung. *Nova Acta Leopoldina, Abhandlungen der Deutschen Akademie der Naturforscher Leopoldina*, Neue Folge, **45**, No. 224, 263–299.

JOHNSON, M. E. 1980. Paleoecological structure in Early Silurian platform seas of the North American midcontinent. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **30**, 191–216.

—— 1987. Extent and bathymetry of North American platform seas in the early Silurian. *Palaeoceanography*, **2**, 185–211.

—— and LESCINSKY, H. L. 1986. Depositional dynamics of cyclic carbonates from the Interlake Basin. *Palaios*, **1**, 111–121.

KALJO, D. (ed.). 1970. *Silur Estonii* [*The Silurian of Estonia*]. Valgus, Tallinn, 343 pp.

KONYUKHOV, A. I. 1988. Evolyutsiya karbonatonakopleniya na materikovykh okraynakh v mezozoe i kaynozoe [Evolution of carbonate accumulation on the continental margins in the Mesozoic and Cenozoic]. 72–95. *In* TIMOFEEV, P. P. and KUZNETSOV, V. G. (eds.). *Evolyutsiya karbonatonakopleniya v istorii zemli*. Nauka, Moskva.

KORINEVSKIY, V. G. 1988. Vazhneyshiy epizod tektonicheskoy istorii Yuzhnogo Urala [Most significant episode of tectonical history of South Urals]. *Geotektonika*, **2**, 37–51.

LEES, A. 1975. Possible influence of salinity and temperature on modern shelf carbonate sedimentation. *Marine Geology*, **19**, 159–198.

—— and BULLER, A. T. 1972. Modern temperate-water and warm-water shelf carbonate sediments contrasted. *Marine Geology*, **13**, 67–73.

MCKERROW, W. S. and ZIEGLER, A. M. 1972. Paleozoic oceans. *Nature Physical Science*, **240**, 92–94.

MILLIMAN, J. D. 1974. *Marine carbonates*. Springer-Verlag, Berlin, Heidelberg and New York, 375 pp.

NELSON, C. S. 1988. An introductory perspective on non-tropical shelf carbonates. *Sedimentary Geology*, **60**, 3–12.

NESTOR, H. and EINASTO, R. 1977. Fatsial'no-sedimentologicheskaya model' Paleobaltiyskogo siluriyskogo perikontinental'nogo basseina [Facies-sedimentological model of the Paleobaltic Silurian pericontinental basin]. 89–121. *In* KALJO, D. (ed.). *Fatsii i fauna silura Pribaltiki*. Valgus, Tallinn.

—— —— 1982. Application of shelf and slope concepts to the Silurian Baltic basin. 17–23. *In* KALJO, D. and KLAAMANN, E. (eds.). *Ecostratigraphy of the East Baltic Silurian*. Valgus, Tallinn.

PATRUNOV, D. K. 1987. Uroven' karbonatnoy kompensatsii kak predel'naya glubina karbonatonakopleniya [Carbonate compensation level as depth limit for carbonate sedimentation]. 111–122. *In Stratigrafiya i formirovanie okeanicheskoy kotloviny Atlantiki*. Leningrad.

PUTSHKOV, V. N. 1979. *Batial'nye kompleksy passivnykh okrain geosinklinalnykh oblastey* [*Bathyal complexes of passive margins of geosynclinal regions*]. Nauka, Moskva, 260 pp.

READ, J. F. 1982. Carbonate platforms of passive (extensional) continental margins: types, characteristics and evolution. *Tectonophysics*, **81**, 195–212.

—— 1985. Carbonate platform facies models. *Bulletin of the American Association of Petroleum Geologists*, **69**, 1–21.

RONOV, A. B., KHAIN, V. E. and SESLAVINSKIY, K. B. 1984. *Atlas litologo-paleogeograficheskikh kart mira. Pozdniy dokembriy i paleozoy kontinentov* [*Atlas of world lithological-palaeogeographical maps. Late Precambrian and Paleozoic of continents*]. Nedra. Leningrad.

RYAN, W. B. and CITA, M. B. 1977. Ignorance concerning episodes of ocean-wide stagnation. *In* Influence of abyssal circulation on sedimentary accumulations in space and time. *Marine Geology*, **23**, 197–215.

SCHLAGER, W. and GINSBURG, R. N. 1981. Bahaman carbonate platforms – the deep and the past. *Marine Geology*, **44**, 1–25.

SCHOLLE, P. A., ARTHUR, M. A., EKDALE, A. A. 1983. Pelagic environment. *In* SCHOLLE, P. A., BEBOUT, D. G. and MOORE, C. H. (eds.). Carbonate depositional environments. *Memoir of the American Association of Petroleum Geologists*, **33**, 620–692.

—— BEBOUT, D. G. and MOORE, C. H. (eds.). 1983. Carbonate depositional environments. Ibid. **33**, 1–708.

SCOTESE, C. R. 1986. Phanerozoic reconstructions: a new look at the assembly of Asia. *Technical Report. Texas Institute of Geophysics*, **66**, 1–54.

SHISHKIN, M. A. 1986. Stratigraficheskaya model' fatsii dlya siluriyskikh i nizhne-srednedevonskikh otlozheniy zapadnogo sklona Polyarnogo Urala [Stratigraphic facies model of the Silurian, Lower and Middle

Devonian of the western slope of the Polar Urals]. 186–192. *In* KALJO, D. L. and KLAAMANN, E. R. (eds.). *Teoriya i opyt ekostratigrafii*. Valgus, Tallinn.

—— 1987. Stratigraficheskaya model' fatsii siluriyskikh-srednedevonskikh otlozhenii zapadnogo sklona Pripolyarnogo Urala i prognoz nekotorykh vidov poleznykh iskopaemykh [Stratigraphical facies model of Silurian –, Middle Devonian deposits of the western slope of the Urals and prognosis of some kinds of mineral resources]. *In* Stratigrafiya i paleogeografiya fanerozoya evropeiskogo severo-vostoka SSSR. *Trudy X geologicheskoy konferentsii Komi ASSR, Syktyvkar*, 28–32.

SHUISKIY, V. P. 1983. *Verhnesiluriyskiy i nizhnedevonskiy rifovye kompleksy zapadnogo sklona Urala. Voprosy ekosistemnogo analiza* [*Upper-Silurian and Lower-Devonian reef complexes of the western slope of the Urals. Problems of ecosystem analyses.*] Preprint. Uralskiy nauchnyi centr AN SSSR, Sverdlovsk, 83 pp.

SIMONE, L. and CARANNANTE, G. 1988. The fate of foramol ['temperate-type'] carbonate platforms. *Sedimentary Geology*, **60**, 347–354.

TESAKOV, Y. I. 1981. Razvitie ekosistem drevnikh platformennykh sedimentatsionnykh basseinov. [Evolution of the ecosystems of the ancient platform sedimentary basins]. 186–199. *In Problemy evolutsii geologicheskikh protsessov*. Nauka, Novosibirsk.

—— PREDTECHENSKIY, N. N. *et al.* 1979. *Silur Sibirskoy platformy. Novye regionalnye i mestnye stratigraficheskie podrazdelenia* [*Silurian of the Siberian platform. New regional and local stratigraphical units*]. Nauka, Novosibirsk, 96 pp.

—— —— BERGER, A. Y. *et al.* 1985. *Opornyi razrez reki Moiero silura Sibirskoi platformy* [*Key section of the Moiero River, Silurian of the Siberian platform*]. Nauka, Novosibirsk, 176 pp.

—— —— KHROMYCH, V. G. *et al.* 1986. *Fauna i flora Zapolarya Sibirskoiy platformy* [*Fauna and flora of the polar areas of the Siberian platform*]. Nauka, Novosibirsk, 216 pp.

TOMCZYK, H. and TOMCZYKOWA, E. 1979. The development of the Prototethys Ocean and its influence on the differentiation of Paleozoic deposits in Poland. *Bulletin de l'Académie Polonaise des Sciences. Série de Sciences de la Terre*, **26**, 103–118.

TUCKER, M. E. 1974. Sedimentology of Palaeozoic pelagic limestones: the Devonian Griotte (southern France) and Cephalopodenkalk (Germany). *In* HSÜ, K. J. and JENKYNS, J. C. (eds.). Pelagic sediments on land and under the sea. *Special Publications of the International Association of Sedimentologists*, **1**, 71–92.

—— 1985. Shallow-marine carbonate facies and facies models. *Special Publications of the Geological Society of London*, **18**, 147–169.

VOINOVSKIY-KRUEGER, K. G. 1947. Dva kompleksa paleozoya na zapadnom sklone Polyarnogo Urala. [Two Palaeozoic complexes on the western slope of the Polar Urals]. *Sovetskaya Geologiya*, **6**, 27–44.

WILSON, J. L. 1974. Characteristics of carbonate platform margins. *Bulletin of the American Association of Petroleum Geologists*, **58**, 810–824.

—— 1975. *Carbonate facies in geologic history*. Springer-Verlag, Berlin, Heidelberg and New York, 471 pp.

DIMITRI KALJO

HELDUR NESTOR

REIN EINASTO

Institute of Geology
Estonian Academy of Sciences
Estonia pst. 7, Tallinn 200001
USSR