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Cyclicity of Shallow-Water Carbonate Sediments in Different Climatic Zones

V. G. Kuznetsov

Institute of Oil and Gas Problems, Russian Academy of Sciences, ul. Gubkina 3, Moscow, 117701 Russia
e-mail: vgkuz@yandex.ru

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Abstract—Based on the study of several different-age shallow-water carbonate sediments from different regions, it is established that cyclothems formed in basins of arid and humid climatic zones differ in their composition and structure. It is shown that the influence of climate was indirect. The climate governed salinity (particularly, in extremely shallow-water settings of initial and terminal stages of the formation of cyclothems) and, thus, stimulated changes in the biota. The biota, in turn, controlled the composition of carbonate material and mechanisms of its sedimentation.

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FORMULATION OF THE PROBLEM

The cyclic structure is in fact a universal feature of all sedimentary (including carbonate) sequences. Repeated changes in basin depth are the main cause of the cyclicity of subaqueous formations. Such changes may be related to different processes: eustasy, vertical tectonic movements, transgressions and regressions, sedimentation rates, their intricate combinations, and others. These phenomena, in turn, may be regional or global and caused by both terrestrial and extraterrestrial processes. Moreover, the latter factor is rather frequently used to explain cyclicity of different orders (Malinovskii and Florenskii, 1963; Naidin, 1989, 1990; Schwartzager and Fischer, 1983; Fischer and Bottjer, 1991; and others).

In general, an elementary sedimentary cyclothem of shallow-water settings begins and terminates with extremely shallow-water (frequently, littoral) sediments, which are separated by sediments of deeper facies. Boundaries of cyclothems are frequently, but not always, marked by hiatuses that record periods of subaerial exposition. Such cyclothems are traditionally termed as transgressive–regressive rhythms, although it is now clear that deepening of a basin may not be related to transgression (i.e., expansion of the basin area) and, vice versa, shoaling is not always related to regression. Therefore, use of terms “transgressive” and “regressive” in this paper is a tribute to tradition, and they actually bear structural rather than genetic sense.

The study of carbonate complexes in several regions revealed that the composition and, what is more important, the structure of shallow-water cyclothems formed in basins of arid and humid climatic zones are different. The careful analysis of publications devoted to such cyclothems in rocks of different regions and ages shows that the differences have universal rather than local character (owing to the limited number of examined sections). The present communication is an attempt to examine causes responsible for these differences. In so doing, original classification of rocks and terminology are retained, wherever possible. In some cases, we also used terms most widespread in the Russian literature, mainly in line with terminology accepted in (*Sistematika…*, 1998), although this approach is not always possible. For example, the term “calcarenite” designates just limestone with sand-size dimension of grains size. However, it is unclear whether these grains represent fossils, their fragments, oolites, clots, or true calcareous sandstones.

CARBONATE CYCLOTHEMS OF ARID ZONES

In terms of the composition, structure, and physicogeographic and geochemical sedimentation settings, carbonate cyclothems of the Vendian–Lower Cambrian carbonate–saliferous formation are best studied. The structure, composition, and deposition environments of cyclothems have been investigated for several typical carbonate complexes, such as the Uspun, Kudulakh, Yuryakh, and Usol’e (Osa Horizon) formations (Bezborodova et al., 1982; Kuznetsov, 1992, 1999, 2003; Kuznetsov and Kurtse, 1985; Kuznetsov and Suchy, 1990, 1992; Kuznetsov et al., 1988, 2000).

The carbonate members show a distinct cyclic pattern with the three-member structure of cyclothems (Fig. 1). Their basal member (element) is composed of clayey dolomites, dolomitic marls, and calcareous and dolomitic mudstones.

The mudstones are dark gray to black, thin- and irregularly bedded rocks with a significant admixture of carbonate material leading to the formation of dolomitic and other varieties of marls. The clayey material

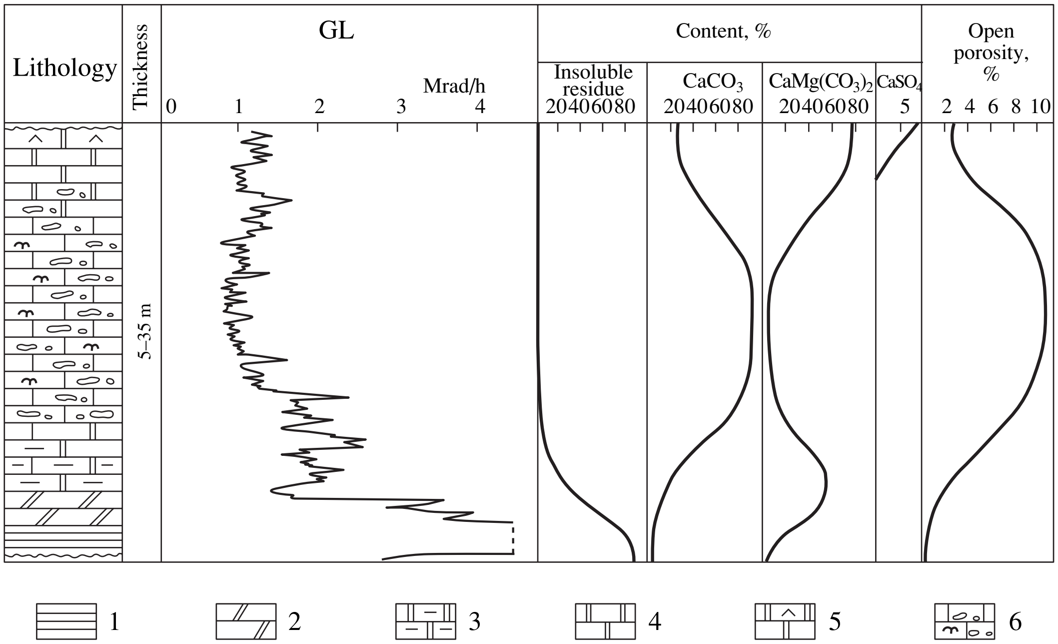

Fig. 1. Schematic structure of cyclothems in Lower Cambrian sections of the Siberian Platform. (1) Mudstone, (2) dolomitic marl; (3) clayey dolomite; (4) dolomite; (5) dolomite with anhydrite inclusions; (6) cyanobacterial limestone. (GL) gamma log.

is represented by smectites, hydromicas, and the subordinate palygorskite and sepiolite.

The dominant structural type of rocks is represented by micro-grained (less commonly, fine-grained) dolomites that form relatively sustained beds. Locally, one can see isolated small (0.2–0.5 mm) rounded peloids, which occasionally make up thin interlayers. The rocks are usually characterized by massive structures, while thin horizontal and cross bedding are subordinate. Desiccation cracks and structures resembling tidal channels are also recorded. Anhydride is present as individual acicular crystals, plates, or rounded nodules from several millimeters to 2–3 cm or more in size. Algal (cyanobacterial) dolomites are second in terms of abundance. Thin sections demonstrate intricate algal structures (filaments and fibers), which produce an irregular fibrous lamination. The algal dolomites enclose various intraclasts (subrounded fragments of micritic dolomite) with a thick black shell or entirely black color (black pebbles). Flat-pebbled conglomerates, as well as dissolution and collapse breccia, make up isolated interbeds.

The middle members of cyclothems have a simpler structure. They are usually composed of limestones and redolomitized organogenic varieties, which virtually lack the clayey admixture. The limestones are mainly composed of diverse (rounded and frequently equigranular) tissue elements of cyanobacterial origin, such as oncolites, clots, lumps, and various peloids. In slightly altered rocks, the cement is composed of primary fibrous material, which envelopes the grains. The later cement in interstices is composed of medium- to coarse-crystalline materials. Rocks in the middle members of cyclothems demonstrate wide development of recrystallization and dolomitization (at least, two generations).

The upper members of cyclothems are composed of relatively variable in textural–structural characteristics and genesis dolomites virtually lacking the clayey admixture. These are primarily represented by micro- to fine-grained uniform massive dolomites with thin regular and subordinate cross bedding. Algal dolomites consisting of fibrous enveloping Cyanophyceae remnants are also widespread. Stromatolitic dolomites with peculiar columnar outgrowths and corresponding growth bedding are remarkable. These rocks contain anhydrite crystals, nodules, and nests, which become abundant and locally make up a continuous bed of nodular anhydrites (up to 1–2 m thick) at the top of cyclothems. Changes in the porosity of rocks are consistent with rock type variations in the section. The average porosity of rocks varies from 1.5–2.5% in the lower member of cyclothems to 11–12% in the medium member, and ~2% in the upper member. Maximal values are 7.0–7.5, 21, and 4–5%, respectively.

The thickness of cyclothems varies from approximately 5 to 30–35 m. Their boundaries are frequently marked by hiatuses, which are visible even in drill cores.

The composition and textural–structural characteristics of rocks imply that the lower member of cyclothems formed in extremely shallow-water, intertidal and, partly, supratidal settings usually with low-energy hydrodynamics. This is evident from the high clay content, primarily microgranular texture of sediments, numerous desiccation cracks, and tidal scours with cross-bedded structures of the flow. Flooding phases are marked by the development of enveloping algae, while draining periods are reflected in the formation of desiccation cracks and peeling of platy fragments, which serve as material for flat-pebbled conglomerates and black pebbles.

The middle member of cyclothems formed in a sea basin with relatively normal salinity, which was close to the average oceanic one, and high-energy hydrodynamics. This is indicated by the substantially calcareous composition of sediments, the occurrence of not creeping but rolled along the bottom forms of algal structures (usually rounded and relatively well-sorted oncolites and catagraphites), and the low content of micritic material, particularly in central parts of cyclothems. The basin was relatively shallow with the bottom located at least within the photic zone. This is evident from the universal presence of algal remains, although the total water volume was sufficient to provide high-energy hydrodynamics.

The upper member of cyclothems is again typical of intertidal and supratidal sabkha environments. However, they are characterized by the following distinctions relative to the beginning of the sedimentation cycle: (i) the influx of clayey material was negligible, as is evident from the accumulation of pure dolomitic sediments; (ii) columnar stromatolites developed here can be attributed to the upper intertidal zone and lower supratidal zone (based on analogy with their present-day and some past counterparts); and (iii) the higher content of sulfates, which make up beds in some places, reflects higher salinity of the basin at terminal stages of the sedimentation cycle. The anhydrite beds probably represent sediments of residual lagoons (lakes) that appeared in the supratidal zone during regression and sealevel fall.

Let us consider several examples demonstrating the composition and structure of cyclothems in other Paleozoic sections.

The Upper Ordovician Yagshor, Khoreiver, Zapadnyi Tebuk, Muker, and Salyukta formations of the Timan–Pechora region formed in basins with substantially elevated salinity (Zhemchugova et al., 2001).

The summary cyclothem of the Salyukta Formation (uppermost Ordovician) of the Khoreiver Depression is also characterized by the three-member structure. The lower member includes bioturbated microgranular (“silty and bioclastic–silty”, according to Zhemchugova et al.) dolomites with admixture of organogenic detritus, which are replaced upsection by silty ostracod and granular dolomites. The section is crowned by “microlaminated sedimentary” dolomites with abundant fenestrae.

This type of structure is also typical of cyclothems in the Malaya Tavrota Horizon (Ashgillian) in the Subpolar Urals. According to (Zhemchugova et al., 2001), the “idealized” structure of the cyclothem is as follows: silty clayey dolomite–bioclastic silty dolomite with bryozoans, crinoids, stromatoporids, brachiopods, and fucoids (in silty varieties)–silty dolomite with stromatolite structures–thin-laminated algal laminae with desiccation cracks. It should be noted that the occurrence of diverse fauna (including the marine stenohaline echinoderms) in the central member of cyclothems suggests average oceanic salinity in the basin of that time and secondary origin of relevant dolomites.

Cyclothems in the coeval Muker Formation (Khoreiver Depression) are basically similar, although their composition is slightly different. The basal part of cyclothems is composed of bioclastic silty dolomites with bryozoan remains, whereas the middle member is composed of thin-bedded *algal laminites* (italicization by V.K.). The section is crowned by bedded and nodular anhydrites (Zhemchugova et al., 2001).

According to (Peterson and Hait, 1972), cyclothems of the Carboniferous De Moin Formation in the Paradox basin (the Rocky Mountains, United States) consists of five members (from the base to top): (1) dark gray dolomitic clays and clayey dolomites enriched in organic matter; (2) light gray to gray calcareous dolomites with rare fossils; (3) algal limestones with fusulinids, brachiopods, ostracods, smaller foraminifers, and coral remains; (4) clotted limestones with numerous diverse foraminifers, clots of microgranular (probably, algal) carbonate, and oncolites; and (5) anhydrites.

This sedimentary succession characterizes changes in bathymetry and salinity of the sedimentation basin. Intertidal and subtidal sediments of the basin with slightly elevated salinity at the initial stage graded into shallow-water facies with the average oceanic salinity (this is evident from the occurrence of marine algae and stenohaline and other faunas) and sediments deposited in the high-salinity basin. Like in other similar situations, limestones in the middle member are characterized by relatively high porosity, while rocks from its basal and upper members are compact.

Cyclothems in Lower Cretaceous sections of southern Florida have a remarkable structure (Winston, 1972). Figure 2 illustrates its typical structure based on the data from many drill cores. The cyclothem usually includes three members. The lower and upper members are generally similar. The lower member includes the following units (from the bottom to top): microcrystalline dolomites with anhydrite crystals and nodules (Fig. 2, bed 1); gray clayey micritic limestones; light chalklike limestones with foraminifers (beds 2 and 3). Rocks of this member are relatively compact and virtually impermeable. The middle member is composed of detrital, organogenic detrital, oolitic, and foraminiferal limestones characterized by commercial reservoir properties (beds 4–6). In the upper member, the rock group is similar to that in the lower member, but the succession is reversed (beds 7–9). The cyclothem is crowned by an anhydrite bed.

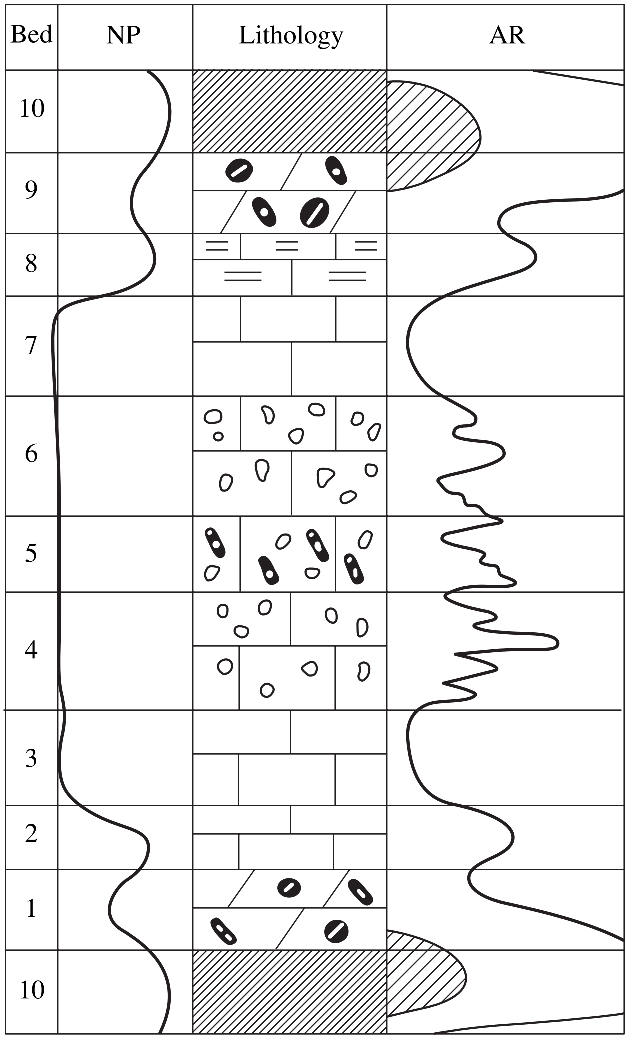

Fig. 2. Structure of cyclothems in Lower Cretaceous sections of southern Florida (Winston, 1972). Lithology: (1, 9) Microcrystalline dolomites with anhydrite crystals and nodules, rare interstices; (2, 8) gray clayey micritic limestones; (3, 7) micritic limestones and microgranular calcarenites with miliolids and chalklike porosity; (4, 6) calcarenite, detrital, oolitic, pelletal, and foraminiferal limestones with interstitial and cavernous porosity; (5) calcarenite limestones with interstitial and cavern porosity; (10) bedded anhydrites. Beds 4–6 are characterized by effective porosity; beds 3 and 7 are usually impermeable for oil; beds 1, 2, and 8–10 are impermeable oil-capping rocks. Logs of (NP) natural polarization and (AR) apparent resistance.

The situation is similar in reefal facies. For example, Upper Silurian reefs of the Guelph Formation (Michigan basin, United States) have a three-member structure. The basal member is composed of marine microgranular limestones and dolomites with echinoderm and bryozoan remains (mud mound facies). The middle part consists of coral–stromatoporoid carbonates deposited in high-energy hydrodynamic settings (reef core facies). The upper member is composed of subtidal and supratidal (almost pure dolomitic) laminites with parallel and slightly wavy bedding (Coniglio et al., 2004).

CARBONATE CYCLOTHEMS IN HUMID ZONES

The Afonino Horizon of the Givetian Stage (Devonian) represents cyclic carbonate sediments of the humid climatic zone. These sediments have been studied in the Zaikino deposit located in the southwestern Orenburg region (Kuznetsov and Chemodanov, 1996). The carbonate sequence is a member of the terrigenous–carbonate autochthonous (according to N.S. Shatsky) platformal formation that accumulated in a shallow-water epicontinental sea basin. The Afonino history of this area was marked by one of the largest Givetian transgressions.

Elementary cyclothems (from 2 to 18 m thick) are generally characterized by the two-member structure (Fig. 3). The basal member is composed of compact (slightly clayey in some places) microgranular and pelletal limestones with a low content of shelly detritus. The upper part consists of granular and subordinate biohermal coral–stromatoporoid limestones with remains of brachiopods, crinoids, ostracods, algae, and other organisms. Organic remains constitute no less than 40–60 vol % of granular rocks. Limestones are irregularly dolomitized in some places. The stylolitic surface is developed in the entire section.

Rocks of the lower member are compact (porosity up to 2–4%), whereas rocks of the upper member are substantially more porous: the porosity coefficient ranges from 4.5 to 20% with two modal intervals of 9–10 and 13–15%.

The composition of sediments and organic remains therein indicate their deposition in a shallow-water sea basin with average oceanic salinity and periodic high-frequency fluctuations of sealevel. At initial stages of the rapid sealevel rise, microgranular calcareous sediments with relatively rare detritus and pellets accumulated in intertidal zones under conditions of low-energy hydrodynamics. The further sealevel rise fostered the development of normal marine environments with more intense hydrodynamics, which stimulated the accumulation of granular varieties with abundant and diverse detritus.

Cyclothems of Devonian perilittoral and subtidal (i.e., extremely shallow-water) carbonate sediments (dolomites) of southern China include three members (Chen et al., 2001). The basal part, which corresponds to the initial phase of transgression, is composed of thin (horizontal and gentle) sinuous-bedded laminites. However, they are absent in some cyclothems. The cyclothems are largely composed of variegated bioturbated microgranular limestones that contain different amounts of shelly detritus (mudstones and wackstones), which are replaced upsection by granular limestones (packstones and wackstones) with pellets, ostra-

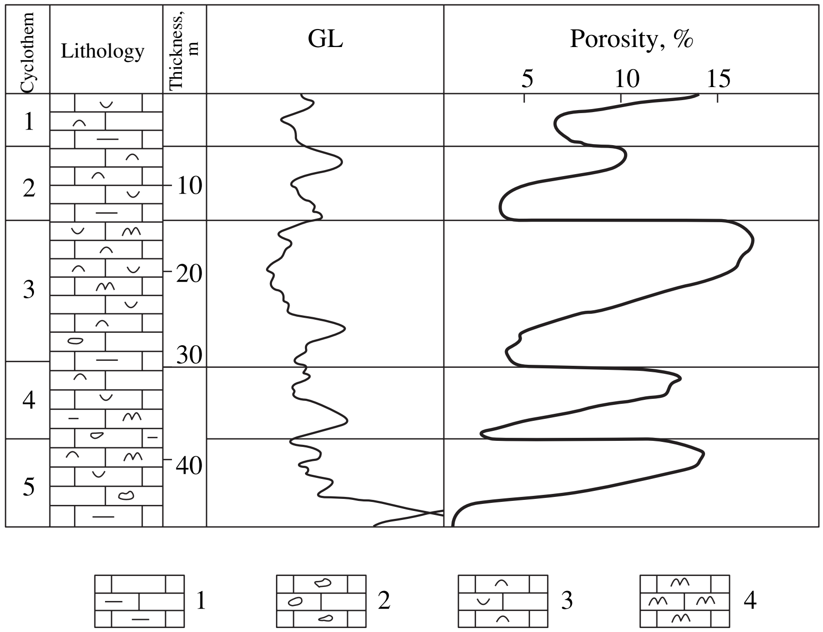

Fig. 3. Cyclicity of the carbonate member D-V-2 (Givetian) in the Zaikovo oil field (Volga–Ural region). (1–4) Limestones: (1) microgranular, locally clayey, (2) pelletal, (3) organogenic-detrital, (4) biohermal. (GL) gamma log.

cods and branching stromatoporoids. The top of cyclothems is again composed of microgranular laminites with signs of intense surface leaching and karstification. It should be noted that shoaling in this case was not accompanied by changes in the mineral composition of carbonate sediments.

Tournaisian sediments of the Volga–Urals region represent the most comprehensively studied carbonate complexes of the humid zone. These rocks have been studied in the Orenburg region (our data), Tatarstan (Postnikova et al., 1982; Kazakova, 1985), and other areas. It should be noted that chracteristics of cyclothems appear to be identical, although the study objects, tasks, and methodical approaches are different.

Cyclothems in lower Tournaisian sections of the South Tatar Arch have been studied in detail (Kazakova, 1985). The complete cyclothem consists of four closely interrelated members (Fig. 4). The basal member is composed of microgranular and pelitomorphic limestones enriched in clays (up to 10–15%). Tissue elements (clots, lumps, and fine detritus) constitute up to 20 vol %. The rocks are largely characterized by horizontal thin-bedded structure. They are relatively compact with porosity coefficient usually not exceeding 4%.

These rocks are replaced upsection by clotted foraminiferal limestones with tissue elements constituting up to 30–50%. They are mostly represented by clots (up to ~0.1 mm) with obscure contours, differently granulated foraminiferal tests, as well as rare ostracod, bivalve, and brachiopod remains. The limestones are characterized by discontinuous microlaminated structures owing to the presence of very thin clayey laminae. The rocks are usually marked by low porosity, although the porosity coefficient is sometimes as high as 14%.

The third member is composed of clotted-detrital limestones with the content of tissue elements and their size increasing up to 50–80% and 1–1.5 mm, respectively. They are represented by clots of microgranular carbonate, sludge, and debris of algae and various faunal fossils. The average content of clayey material is up to ~1%. The rocks are characterized by clotted-spotty and subordinate discontinuous microlaminated structures.

The fourth member is composed of clotted-detrital limestones with tissue elements (0.5–1.5 mm) constituting approximately 80 vol %. They are represented by presumably algal clots and remains of corals, foraminifers, echinoderms, brachiopods, bivalves, and Cyanophiceae algae. The limestones usually contain a small amount of pellicular and interstitial cement. Rocks of the third and fourth members are characterized by the highest porosity (up to 17–18%). The thickness of cyclothems ranges from 3–11 to 20–50 m. Their upper boundaries are usually marked by hiatuses.

In general, the cyclothems are characterized by the two-member structure. The lower member is composed of compact microgranular slightly clayey limestones. The upper member includes granular limestones with tissue elements represented by various faunal remains, clots, and lumps.

A similar two-member structure and succession of limestones has also been established in Tournaisian sections of the Orenburg region (Kuznetsov, 1992) and eastern slope of the South Tatar Arch (Postnikova et al., 1982). Their reservoir and other physical properties

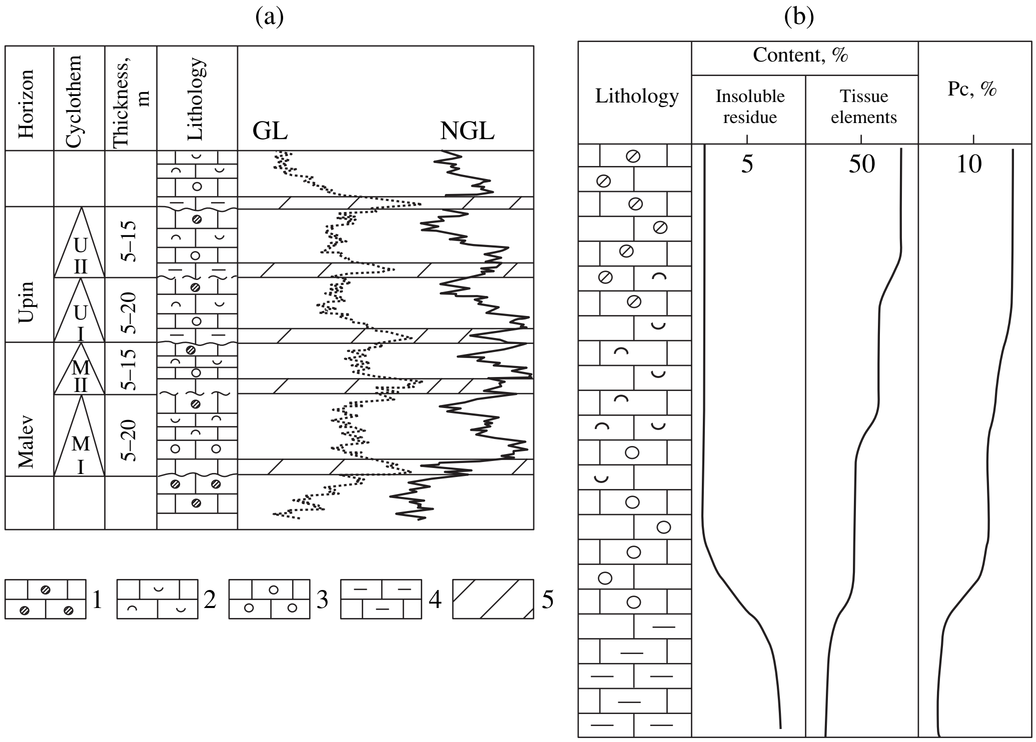

Fig. 4. Cyclicity in Tournaisian sections of the Volga–Ural region. Modified after (Kazakova, 1985). (a) Cyclicity in the Malev and Upin horizons; (b) schematic section of the typical cyclothem. (1–5) Limestones: (1) lumpy-detrital, (2) clotted-detrital, (3) foraminiferal-clotted, (4) microgranular with admixture of clayey material, (5) reference horizons.
(GM) Gamma log; (NGL) neutron gamma log.

also show similar changes. For example, average porosity of rocks of the three-member Zavolzhsk Horizon increases from ~1.5% in the lower cyclothem to 10% in the upper cyclothem (the content of insoluble clayey residue amounts to 7 and 1–5%, respectively). In the two-member Cherepet Horizon, the content of insoluble residue in the lower cyclothem amounts to 10%, while porosity is as low as 6%. In the upper cyclothem, the porosity increases to 7.0–8.5%, while the content of clayey admixture is decreased.

Mukhametshin (1982) obtained interesting data on the distribution of reservoir properties in several Tournaisian sections on the western slope of the South Tatar Arch. Based on estimates of the distribution of permeable (effective) interbeds in borehole sections, he showed that their content increases from insignificant values in the basal part of cyclothems to appreciable values in the middle member and maximal values in the uppermost member.

Properties of the studied rocks and diversity of organic remains therein imply that Tournaisian sediments accumulated in the photic zone of a shallow basin with normal oceanic salinity. Sediments began to accumulate in a low-energy (littoral) hydrodynamic setting with the influx of a small quantity of clayey material and then continued in shallow marine environments with relatively high-energy hydrodynamics.

The composition and structure of several Mesozoic cyclothems in shallow-water carbonate sections are described in a special issue dedicated to intertidal deposits (*Tidal Deposits,* 1975).

Carbonate cyclothems in Upper Triassic sections of the Northern Calcareous Alps, well known as Lofer cyclothems (Fischer, 1975), are characterized by the following typical composition and structure (Fig. 5). The eroded and karstified surface is overlain by specific rocks, ~0.5 m thick on the average, known as loferites ("element B," according to Fischer). They represent gray and beige microgranular dolomitic calcilutites (thin-bedded gently undulating algal mats with abundant fenestrae, desiccation cracks, and basal conglomerates in some places). This element (member) also contains pink and brown microgranular limestones (calcilutites) and dolomites (dololutites) with rare foraminifers, ostracods, and small bivalves. Specific features of these rocks point to relatively calm intertidal environments.

The cyclothem is largely composed of ~5-m-thick massive granular limestones (calcarenites) of the subtidal facies. They enclose diverse remains of marine organisms: dominant bivalves (megalodonts and others), dasicladacean and codiacean algae, corals, brachiopods, foraminifers, gastropods, echinoderms, and bryozoans ("element C," according to Fischer). The biota

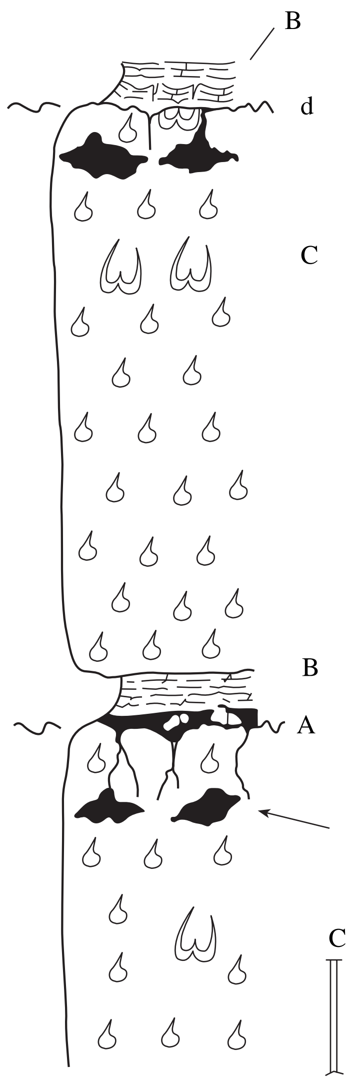

Fig. 5. Structure of the Lofer cyclothem. Upper Triassic, Northern Alps (Fischer, 1975). (A, B, C) Elements of cyclothems; (d) unconformity and weathered zone. Bar is 1 m.

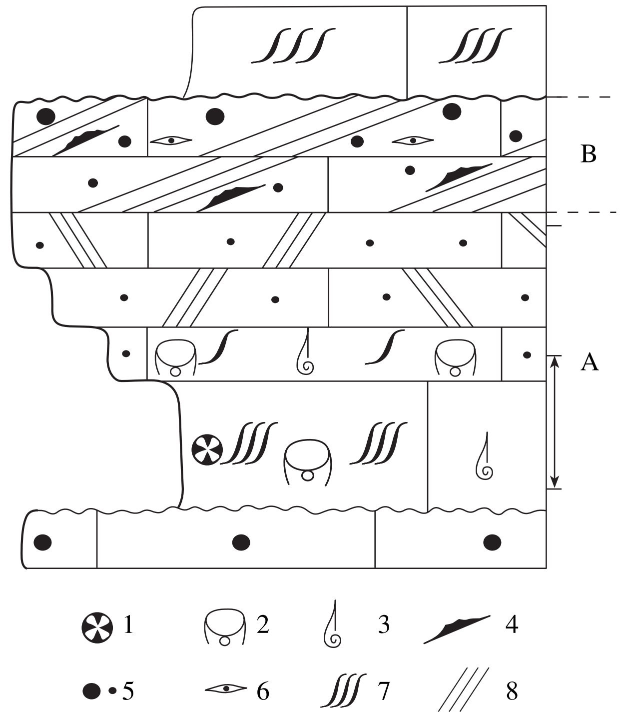

Fig. 6. Schematic structure of cyclothem in the Bathonian section, Burgundy, France (Purser, 1975). (1) Corals: (2) oncolites; (3) microfossil debris; (4) microcaverns; (5) pelletoids (circle size corresponds to the relative size of members); (6) stromatactis; (7) bioturbation; (8) cross bedding. (A) Subtidal zone; (B) intertidal and supratidal zone. Bar is 1 m.

composition unambiguously indicates shallow marine environments with normal salinity and high-energy hydrodynamics. The uppermost member of these limestones ("element A," according to Fischer) with signs of intense karstification is composed of variegated (red and green) microgranular limestones with calcareous intraclasts, numerous desiccation cracks, and caverns filled with clayey material enclosing calcareous pebbles. Fischer believed that these clays represent altered soil deposited on the drained and leached carbonate rocks of "element C."

Structurally similar cyclothems are developed in Bathonian "granular limestones" in the Burgundy Province, France (Purser, 1975). Cyclothems (3–4 m thick, up to 12 m in some places) begin with microgranular uniform limestones (wackstones and mudstones) frequently with large (2–5 cm) oncoids and other algal structures and fragments of solitary corals and mollusks (Fig. 6). The limestones are partly dolomitized and frequently bioturbated in some places. They rapidly grade upsection into granular varieties (peloid calcarenites and calcirudites) with grain size increasing upward the section. The upper interval (1–2 m) of the section is composed of cross-bedded peloid calcarenites and oncoid-bearing calcilutites with stromatactis typical of intertidal and supratidal settings. These caverns (2–20 mm high and 5–20 cm long) are nearly parallel to bedding surfaces and filled with fibrous cement, which frequently include geopetal structures and microstalactites that mark desiccation periods. Like in Devonian cyclothems of China mentioned above, shoaling in this region is not marked by any cardinal changes in the mineral composition of rocks.

Similar cyclicity patterns have been established in reefal buildups. For example, lower members of cyclothems in the Late Devonian Verkhshomash reef in the Permian Urals region are composed of compact low-permeable algal limestones. The upper members consist of granular oolitic, peloid, and biodetrital limestones with high primary porosity (Vilesov and Voevodkin, 2005).

Cyclothems in Serpukhovian reefs of the Donbas region also show similar patterns. The basal member is composed of relatively compact low-clayey limestones. The upper member consists of pure biohermal and granular varieties. Active karstification of the uppermost part of cyclothems during the draining of reefs promoted their high cavern porosity (Kuznetsov, 1980; Kuznetsov et al., 1978).

CARBONATE CYCLOTHEMS OF SEMIARID ZONES

Cyclothems in basins of semiarid zones obviously occupy an intermediate position between their counterparts in arid and humid regions. Although this assumption is generally valid, compositions and structures of cyclothems actually depend on their facies type. The Bashkirian sections of the northern Solikamsk Depression in the Uralian foredeep are typical in this respect (Vilesov, 2004).

The Voznesensk, Prikamsk, Cheremshansk, and Melekes horizons of the Ozernoe deposit enclose several asymmetric cyclothems. The basal member is usually composed of organogenic-detrital limestones (calcareous sandstones and gravelstones) with a thickness of 5–15 cm (occasionally, up to 30 cm). They rest upon an uneven hummocky surface of underlying rocks with erosion signs. The composition and structure of overlying members slightly vary in different facies zones. Vilesov identified here two (tidal and carbonate sandstone) zones, which actually characterize the typical shallow marine settings. He divided cyclothems of tidal zones into the initial, transgressive, and regressive members. The lower and middle members (total thickness ~1 m) are composed of gray to dark gray clayey medium-bedded limestones with undulating bedding surfaces and local secondary dolomitization. The limestones are represented by the organogenic-detrital (bioclastic, according to Vilesov), peloid, polydetrital-algal, and polydetrital-foraminiferal varieties with microgranular to fine-grained calcite cement. Organic remains are represented by algae, foraminifers, brachiopods, ostracods, gastropods, and echinoderms. The upper member (0.9–2.0 m) is composed of light gray and gray, frequently spotty (pinkish, yellowish, and so on), inequigranular medium-bedded dolomites with undulating bedding surfaces and irregular distribution of the clayey material and sulfates.

The transgressive member of cyclothems in the carbonate sandstone zone consists of gray to dark gray, thin- to medium-bedded (locally, microlaminated), limestones with different contents of the clayey material and numerous stylolitic surfaces. The limestones are characterized by microgranular and algal textures with abundant foraminifers, thin-shelled brachiopods, bryozoans, and crinoids. The thickness varies from 0.15 to 1.5 m (usually, not more than 1.0 m). Limestones of the upper (regressive, according to Vilesov) member are gray to light gray, medium- to thick-bedded algal, foraminiferal-algal, polydetrital, bioclastic, ooidal, and oolitic rocks with fine- to medium-grained crystalline matrix. It is notable that the upper member includes layers of compact stromatolite-type limestones. The upper member has a total thickness of 0.7–3.3 m.

In both cases, the lower member formed in relatively low-energy hydrodynamic settings, which is evident from the fine-grained composition of sediments with microgranular and fine-grained cement and relatively thin bedding. The upper member accumulated under relatively high-energy hydrodynamics, which promoted the formation of granular textures, coarser cement, and thicker but less regular beds. Shoaling fostered the replacement of limestones by dolomites (with sulfates in some places) in intertidal settings and by stromatolitic varieties in shallow marine settings.

Maksimovich (1982) presented a more general description of similar cyclothems (without subdivision into facies zones) in Bashkirian sections. The lower member (the onset of transgression) is composed of mudstones, clayey limestones, and calcareous conglomerates and breccia (products of the erosion of underlying rocks). The middle member (maximum transgression) primarily consists of foraminiferal-algal limestones. The upper (regressive) member is dominated by micrognanular, stromatolitic, and subordinate detrital limestones. In general, organogenic-detrital limestones from the middle member have the best reservoir properties. Porosity is significantly lower in clay-rich limestones of the basal member and in microganular limestones of the upper member.

Representative data on the distribution of reservoir properties in Bashkirian sections are reported in (Suleimanov et al., 1983). They studied the distribution of permeable interbeds in 340 boreholes at four deposits in the South Tatar Arch and Melekes Depression. In contrast to the Tournaisian sections described above, where permeable interbeds are distributed asymmetrically with maximum confined to uppermost parts of cyclothems, their distribution in Bashkirian sections is symmetrical with the peak confined to central parts of cyclothems and minimums localized in their basal and uppermost parts.

One more example of cyclothems of the semiarid zone is provided by the upper section of the Caradocian Malaya Makarikha Formation in the Khoreiver Depression of the Timan–Pechora petroliferous basin (Zhemchugova et al., 2001). Judging from lithology and fauna, sediments of this formation accumulated during the humid-to-arid transitional period. In general, the formation is composed of silty (microgranular) and silty-bioclastic limestones, which frequently contain secondary dolomite and diverse marine fauna (brachiopods, bryozoans, and crinoids). The faunal diversity and occurrence of stenohaline forms, such as echinoderms, unambiguously point to normal oceanic salinity of the sedimentation basin.

The basal member is composed of silty and clayey limestones with secondary dolomite and fucoids (Fig. 7, nos. 1, 2, 7). They are replaced upsection by

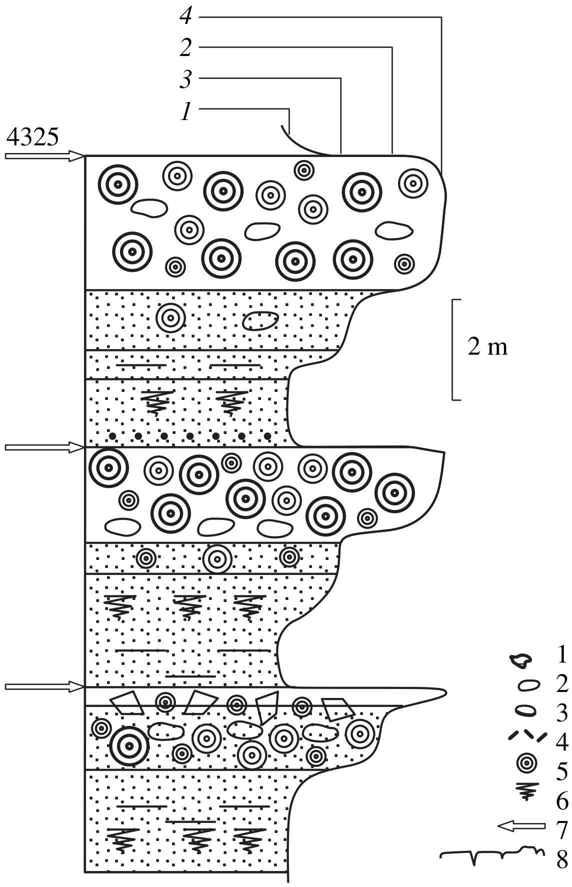

Fig. 7. Structure of elementary cyclothems in the upper part of the Malaya Makarikha Formation. Modified after (Zhemchugova et al., 2001). Limestones: (*1*) silty, (*2*) granular-silty, (*3*) silty-granular, (*4*) granular (litho- and bioclastic). Depth in borehole 12. (1) Intraclasts; (2) lithoclasts; (3) rounded bioclasts; (4) peloids; (5) oolites; (6) bioturbation; (7) erosional surface; (8) boundaries of cyclothems.

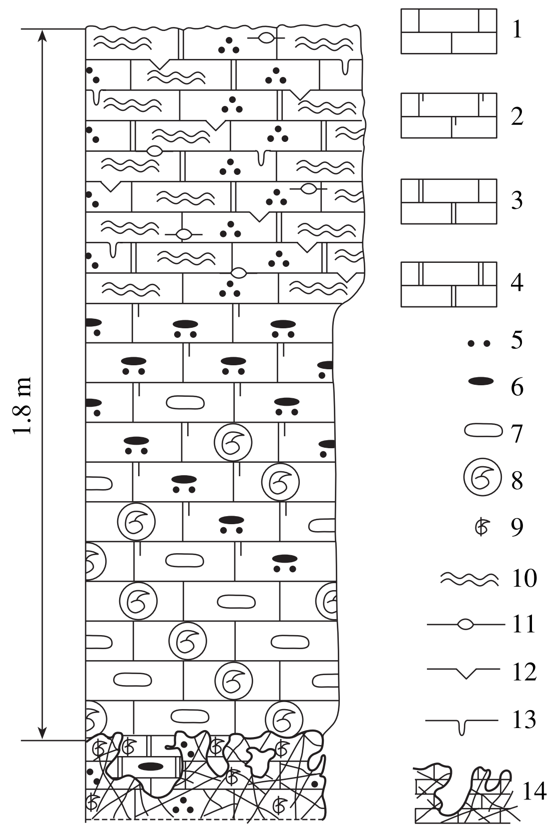

Fig. 8. Structure of the Tithonian cyclothem in the Balta section of Northern Caucasus. (1) Limestone; (2) dolomitic limestone; (3) calcareous dolomite; (4) dolomite; (5) clots and small lumps; (6) lumps and nodules; (7) pellets; (8) large rounded detritus; (9) small detritus; (10) stromatolites; (11) fenestrae; (12) desiccation cracks; (13) traces of bioturbation; (14) microkarst.

silty-bioclastic, locally dolomitized limestones (Fig. 7, 4, 6). The diverse granular material is represented by oolites, peloids, bioclasts, and rounded fragments of silty, oolitic, and algal limestones. Some cyclothems contain dolomite–anhydrite interbeds at the top.

Thus, silty sediments of calm marine settings gave way to granular shallow-water facies deposited in relatively high-energy environments. The biota composition implies normal oceanic salinity of the basin. In case of shoaling, dolomitic–anhydritic sediments accumulated in semiarid climatic environments.

Cyclothems in Mesozoic carbonate sequences of the semiarid zone are represented by Tithonian sediments of the Callovian–Valanginian carbonate formation (North Caucasus) deposited on the northern shelf of the Tethys (Kuznetsov et al., 1992; Kuznetsov, 1999, 2003).

Figure 8 illustrates the structure of a typical cyclothem. Its base is composed of light gray coarse-grained inequigranular dolomitic limestone (5–15 cm thick), which rests upon the eroded surface. The peloid-detrital limestone contains intraclasts. Peloids (0.5–1.5 mm across) composed of cryptocrystalline calcite are dominant. Detrital material is represented by almost unidentifiable fragments with occasional recognizable foraminiferal tests. The peloid-detrital groundmass encloses small intraclasts (sometimes, up to 10 mm across) of clotted limestone from the underlying bed. The rocks are variably dolomitized. Dolomite (up to 40%) is represented by different-size crystals and characterized by the fine-grained (medium-grained in some places) texture.

The overlying bed is composed of brownish gray limestone (1.0–1.1 m) with graded stratification. The lower part of this bed includes peloid-detrital limestone with tissue elements (~0.5–3.0 mm, 80–90%. Peloids are mainly algal products. However, some of them can be coprolites. The rock encloses isolated algal fragments with a capricious “lacy” structure.

Detrital material is largely represented by fragments of brachiopod shells and subordinate crinoids and bryozoans. The fragments are usually well rounded. Like peloids, they have a thin micritic rim related to granulation. Organogenic clasts are generally larger (0.5–3.0 mm) than peloids. The peloids and organogenic detritus are cemented by the fine-grained crustification-interstitial calcite (15–20 vol %).

The upper part of the bed is composed of dolomitic limestone with obscure clotted-lumpy texture. The cryptocrystalline clots (~0.05 mm) and lumps (0.1–0.5 mm or more in some cases) constitute approximately 80 vol %. They are closely packed and poorly distinguishable. The microcrystalline cement is up to 5%.

The uppermost bed of brownish gray calcareous dolomite is characterized by obscure thin-laminated slightly undulating stromatolite-type structure and local fine dissemination of calcite crystals (structure of the bird's-eye type). Desiccation cracks and vertical fucoids are also present. The rocks are characterized by thin-laminated structure with irregular (sometimes, lenticular) laminae, 0.3–1.5 mm thick, with indistinct boundaries. The bed thickness is 0.7 m.

The character of changes in rocks shows that the studied section represents an upward shoaling succession, which is typical of carbonate sequences. The onset of transgression is marked by the formation of basal detrital limestones accumulated on the eroded surface. The subsequent transgression promoted the formation of a shallow sea with normal salinity. This is evident from findings of algal remains and diverse fauna (stenohaline forms and others). The relatively high-energy environments were responsible for the crushing of organic remains and the rounded appearance of their fragments. The successive upsection diminution of tissue elements, the replacement of peloid-detrital limestones by stromatolitic dolomites, and the development of desiccation cracks and bird's-eye structures indicate calmer hydrodynamic settings due to general shoaling of the basin up to the point of its complete draining. In other words, the upper part of the succession is represented by intertidal and subtidal sediments.

Bykov et al. (1972) described eight similar cyclothems in upper Callovian–Oxfordian carbonate sequences of eastern Turkmenistan.

The lower part of each cyclothem is largely composed of clayey pelitomorphic (virtually compact and impermeable) limestones, whereas the upper part consists of granular (organogenic-detrital, oolitic, and clotted-lumpy) limestones with a high porosity (20–24%). The clayey admixture is virtually absent.

Although the carbonate sequence described above is a constituent of the Upper Jurassic carbonate–saliferous formation, these sediments accumulated in a shallow sea basin with normal or nearly normal salinity, which is evident from the diverse composition of marine organisms. Sulfates and salts began to accumulate only in the Kimmeridgian–Tithonian, when the arid climate was really established.

COMPARATIVE ANALYSIS OF THE STRUCTURE AND COMPOSITION OF CYCLOTHEMS IN DIFFERENT CLIMATIC ZONES

Even the limited number of examples described above clearly demonstrates that shallow-water carbonate sections are always characterized by the cyclic structure. Moreover, the composition and structure of cyclothems are different in humid and arid climatic zones.

The first most remarkable and, at first sight, readily explainable difference consists in the composition of cyclothems. They are dominated by sandstones in humid zones and dolomites in arid zones.

The second difference lies in the structure of cyclothems. In carbonate sequences of arid zones, cyclothems have the three-member structure: their basal member is composed fine-grained, frequently clayey dolomites and dolomitic marls; the central (middle) member consists of granular organogenic-detrital limestones with irregular dolomitization in some places; and the upper member is again composed of microgranular microbial dolomites, (including stromatolitic varieties). Cyclothems of humid zones have a simpler (two-member) structure: microgranular limestones (with different contents of clays) in the lower part of the section and granular limestones usually with diverse organic remains in the upper part.

In both cases, boundaries of cyclothems are relatively sharp, sometimes with erosion signs. The upper surface of cyclothems in humid zones frequently bears traces of karstification and leaching.

These features of cyclothems are also responsible for different physical properties (porosity and others) of rocks. In arid zones, the highest porosity is typical of central parts of cyclothems. In cyclothems of humid zones, such properties are characteristic of their middle and, particularly, upper parts, where primary pores are accompanied by leaching caverns.

It would by too naive and simple to assume that sea-level fluctuations, which ultimately determine the formation of cyclothems, have different trends in arid and humid zones, and such trends are responsible for different structures of the cyclothems. These trends were most likely similar. Walter (1891) noted that it is more correct to speak about changes in the distance between the seafloor and surface. According to the modern terminology of sequence stratigraphy, this process is referred as change in the accommodation space as a volume that provides the sediment accumulation potential and serves as a function of sealevel fluctuations and subsidence (Jervey, 1988).

Thus, the general trend of the process in basins of different climatic zones was uniform: sealevel rise after hiatus (and, frequently, draining)—establishment of marine environment with moderate depths and normal salinity—shoaling (and, frequently, draining). However, although climatic fluctuations were basically similar, changes in the chemistry of waters in the course of climatic fluctuations provoked different modes of sedimentation.

In other words, the beginning of the cycle in both cases is marked by accumulation of intertidal and subtidal fine-grained sediments with the elevated content of clay material in sea basins with similar depths and hydrodynamic environments. However, salinity of waters in the humid zone was close to the average oceanic one (this is confirmed by the limited number of findings of marine fossils) and limestones were deposited. In contrast, salinity of waters in the arid zone was high due to intense evaporation, resulting in the disappearance of suppression of the euryhaline fauna. This ecological niche was occupied by cyanobacterial communities, which extracted dissolved carbon dioxide from water. The consequent increase in pH stimulated the precipitation of magnesian compounds and the ultimate formation of dolomites (Kuznetsov, 2003, 2005).

The further transgression (i.e., sealevel rise in general) led to the establishment of shallow or moderately deep settings with high-energy hydrodynamics. Owing to a significant volume of water, the basin retained its normal salinity even under arid conditions. These periods were marked by accumulations of biomorphic and granular calcareous sediments (including detrital varieties).

The subsequent sealevel fall and shoaling of the basin at terminal stages of cycles had different consequences in various climatic zones. Moreover, the shoaling could result from both external (tectonic uplift, sealevel fall, and others) and internal causes. High sedimentation rates of carbonate, particularly biogenic, material result in rapid overcompensation and, correspondingly, lesser distance between the seafloor and surface.

By the way, the last phenomenon can explain the apparent contradiction between rapid subsidence (and, as a consequence, rapid transgression), on the one hand, and slow regression, on the other. Negative and positive sealevel fluctuations occur with similar velocities, but the basin deepens more rapidly at the initial stage of transgression, the more so if the influx of clayey material is very intense, the biogenic system of carbonate material extraction is lacking, and the carbonate accumulation cannot compensate the sealevel rise. Thus, the illusory effect of rapid subsidence is created. The above-mentioned overcompensation and progressive shoaling, which is unrelated to tectonic uplifting and regression, become possible only after the formation of a stable biotic community and the commencement of intense extraction of carbonates from seawater and their precipitation .

However, shoaling in the humid climatic zone was not accompanied any principle changes in salinity. Biogenic and granular limestones continued to accumulate. Consequently, fine-grained intertidal sediments of the terminal stage are represented by calcareous (not dolomitic) laminites and stromatolites. The stromatolites were often destroyed during exhumation and karstification, which were rather intense under conditions of humid climate and abundant atmospheric precipitation, resulting in the two-member structure of cyclothems.

In arid climatic zones, shoaling fostered the increase in water salinity, the consequent disappearance of the stenohaline fauna and associated organogenic and organogenic-detrital sediments, and the predominance of cyanobacterial (microbial, in general) communities. These processes stipulated the precipitation of magnesian compounds and the ultimate formation of dolomites with stromatolites and other microbial forms (including the bird's-eye structures). Draining under conditions of low humidity was unfavorable for the dissolution of rocks and leaching in upper members of cyclothems.

The structure and composition of cyclothems in semiarid zones are consistent with this model. In coastal zones (tidal facies of Bashkirian sequences in the Solikamsk Depression) with sealevel fluctuations and drastic changes in water volume, depth variations changed the water salinity and, as a consequence, the composition of sediments up to the point of the appearance of sulfates. In shallow-water zones, where sealevel fall only resulted in partial shoaling rather than draining, salinity remained virtually unchanged and limestones continued to accumulate, although highly organized organisms were suppressed and purely biogenic limestones were actively replaced by their stromatolitic varieties.

In other words, the external factor (climate) is superimposed on similar (in essence) sealevel fluctuations and governs internal parameters of the basin (salinity).The latter factor, in turn, influences the character of biota, eventually resulting in different compositions and structures of carbonate sequences.

Naturally, there are some deviations from this general model. Cyclothems of the same climatic zone can differ from each other in certain specific (not principle) parameters. For example, the thickness of cyclothems and their individual members are governed by variations in the rate (and amplitude) of subsidence and eustatic sealevel fluctuation, sedimentation rate, and so on.

Reduction of distance between the seafloor and surface not necessarily results in the complete draining, deposition of intertidal and subtidal sediments, and formation of hiatuses at the upper surfaces boundary of cyclothems. In this case, salinity does not increase (or increases insignificantly) even in arid climates. Therefore, accumulation of relatively thick microbial dolomites (the more so, sulfates) is impossible.

Some changes in the character of carbonate sedimentation are probably related to the evolution of biosphere and sedimentary process in general. For example, biogenic granular varieties in Cambrian cyclothems are composed of different algal (cyanobacterial) clots, calcibionts, and oncolites, whereas the biogenic component is largely represented by remains of skeletal organisms since the Middle Paleozoic.

CONCLUSIONS

The study of the composition and structure of carbonate cyclothems formed in shallow sea basins shows that they are different in arid and humid climatic zones.

Cyclothems of arid regions are characterized by the dolomitic composition and the three-member structure. Their lower member is composed of intertidal and subtidal facies of the initial transgression stage (microgranular dolomites with different contents of clays). The middle member consists of shallow-water granular limestones, which frequently underwent secondary dolomitization and contains diverse organic remains. The upper part includes microgranular (usually, microbial) intertidal and supratidal dolomites of the regressive stage, frequently with sulfates in the form of nests, inclusions, occasional lenses, and beds.

The two-member cyclothems of humid regions are composed of limestones. Their basal member is composed of clayey microgranular limestones, whereas the upper part consists of granular limestones with diverse organic remains. The uppermost layers bear numerous caverns related to karstification during continental hiatuses at the terminal stage of cycles.

Differences in the composition and structure of cyclothems are governed by the influence of climate on hydrochemical parameters of the basin and, in turn, its biota. The latter factor plays a crucial role in the sedimentation of carbonates and their composition. Increase in water salinity suppressed the biota (in particular, its stenohaline forms) in intertidal and subtidal settings of arid regions. Thus, the ecological niche was occupied by microbial communities, which extracted the dissolved carbon dioxide from water. The consequent increase in alkalinity led to the predominant precipitation of magnesian compounds.

Salinity of intertidal and subtidal settings in humid regions remained virtually unchanged. Faunal communities were also retained (some changes in them were caused by variations in hydrodynamics of environment rather than salinity). Moreover, the uppermost parts of cyclothems were frequently eroded by surface waters as a result of draining at the terminal stage of cycles.

Thus, climatic changes had an indirect impact on the composition and structure of cyclothems in shallow-water carbonate sequences. This impact was realized through changes in basin salinity, which influenced the biota and, in turn, modes and mechanisms of the sedimentation of carbonates and their composition.

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