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Duration of the Lateral Paragenetic Reef–Evaporite System Formation

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Abstract—Duration of the functioning of elements of the lateral paragenetic reef–evaporite systems in Cambrian and Late Jurassic has been calculated. Discrepancy between total durations of the vertical growth of barrier reefs and evaporite formation varies by a factor of 3–50. Neither barrier reefs were growing up nor salt was deposited in halogenic basins for enormous time spans. Specific features of the reef–evaporite system should be taken into account in the estimation of ore potential (in particular, presence of sulfides of Pb, Zn, and other metals) in barrier-reef massifs.

INTRODUCTION

The factual material on halogenic rock associations and reef complexes from different lithotectonic zones covering a wide stratigraphic range from Cambrian to Quaternary undoubtedly indicates their lateral conjugation. At the same time, opinions on genetic relationships between reefs and evaporites and their synchronization are substantially different, and the reef–evaporite system remains poorly studied in many respects.

According to the classic concept, Phanerozoic salt deposition was proceeding during epochs of arid climate in halogenic basins with a very limited connection with open sea (continental halogenesis is beyond the scope of this paper). The biohermal bridge playing the role of bar between water reservoirs is most favorable for evaporation (Sedletskii *et al.*, 1977). The formation of reef bars and halogenic sequences should display a certain temporal correlation.

According to (Sedletskii *et al.*, 1977, p. 8), halogenic sequences replace the reef complex “within a narrow zone including transitional members of the reef core–salt facies series.” The bioherm formation is considered an important factor providing necessary conditions for halogenesis at any stage of its evolution. The seafloor submergence promotes a fast vertical growth of reef complex, whereas the substrate emergence displaces the bioherms to the hydrodynamic activity zone where they are destroyed. According to (Sedletskii *et al.*, 1977, p. 9), “specific mechanism of bioherm formation provides a compensation character of the process with respect to tectonic factors. Consequently, this leads to the stabilization of hydrodynamic regime in the halogenic sedimentation basin controlled by the reef formation.” Thus, the biohermal bar between the open sea and halogenic basin automatically regulates the seawater inflow into the basin. This was shown for all morphological and tectonic types of halogenic basins related to oceanic water in arid climate (Strakhov, 1962). Sedletskii *et al.* (1977) did not study in detail the dynamics of conjugated reef and salt formation.

The lateral conjugation of halogenic and reef complexes is accepted by some advocates of the endogenic origin of saliferous sequences. The facies conjugation of both complexes “is traced throughout the entire series of marine environments and is lacking beyond this series” (Belenitskaya *et al.*, 1990, p. 279). However, considering spatiotemporal relationships between these complexes in compliance with ideas advanced by Grachevskii *et al.* (1969), Belenitskaya *et al.* assumed that these complexes are mostly asynchronous formations within an inferred common sedimentation basin and the stages of reef growth and halogenesis alternated” (Belenitskaya *et al.*, 1990, pp. 218–282). Reefogenic and halogenic rocks are confined to the lower and upper member, respectively, of a common sedimentation cycle. The temporal coincidence of halogenesis and reef formation was noted for the Siberian Basin in Cambrian–Early Ordovician,[1] and the Ciscaucasus Basin in Late Jurassic. However, “the synchronization of halogenesis and reef formation requires an additional substantiation” (Belenitskaya *et al.*, 1990, p. 282).

According to Kuznetsov (1972, 1978), relationships between salts and reefs depend on the saliferous sequence type (affiliation of the reefs to the bar facies was not mentioned). The homogeneous monocyclic saliferous sequence is younger than reefs. In the case of thick reefs and polycyclic evolution of the basin and deposition of polycyclic saliferous sequences, the relationship between reefs and host rocks becomes more complex. “Reefs may be formed during the deposition of carbonate or clayey–carbonate sediments at basin

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[1] In geological literature this basin is commonly named as the East Siberian Basin, and its age is accepted as Early–Middle Cambrian (Vysotskii *et al.*, 1988 among others).

margins or some local elevations. Periodic rises of salinity spread over the whole water reservoir, provoke salt deposition, and lead to short-term intervals in the reef growth that resumes at the next stage of carbonate sedimentation. As a result, the reef displays hiatuses corresponding to periods of salt accumulation in the adjacent depressions" (Kuznetsov, 1978, p. 236). According to this author, the polycyclic saliferous sequence can completely or partly correlate with reefs.

One should emphasized two important points in these notions. First, Kuznetsov called attention to signs of hiatuses within the reef massif. Periodic intervals in the reef evolution may also be recorded by anhydrite layers. "In these cases, carbonate reef rocks were not synchronously formed with evaporites in the inter-reef space; however, the reef massif, on the whole, is stratigraphically coeval with evaporites" (Kuznetsov, 1978, pp. 236–237). Second, the author explains the interval in reef formation by salting of the basinal water rather than interruption in the reef growth when its crest reaches a minimal depth and remains at that level for rather a long time.

In the case of exogenic halogenesis, we admit the crucial role of barrier reefs as regulators of seawater delivery to the halogenic basin. Taking into account possible environments and reef formation rate, as well as structural features of halogenic sequences and salt deposition rate, one should note that the reef formation and salt deposition as temporally interrelated processes can hardly be realized. This work attempts to determine and compare the formation duration of each element of the lateral paragenetic reef–evaporite system as exemplified by the East Siberian and Ciscaucasus halogenic basins. Some general aspects of the reef growth and salt deposition are given below.

FORMATION CONDITIONS AND SPECIFIC FEATURES OF THE REEF GROWTH

Modern reef-builders (corals, algae, and other autotrophic lime-releasing organisms) develop in seawater of normal salinity (annual mean temperature +20°C) with a small amount of suspended particles and plentitude of nutrients. Water desalting or salting and high suspension content are unfavorable for corals. Reefs can develop on any substrate and in any part of the sea (ocean), if the depth does not exceed 20–40 m. The depth of 5–10 m is most favorable for the bloom of reef-forming corals and hydroids. The tectonic factor is commonly regarded as critical for the long-term growth of reefs.

According to (Nalivkin, 1955), the rate of modern reef-builder growth varies from 0.7–0.8 to 20 cm/yr (2.5 cm/yr, on the average). The composition of reef-builders changed with time in the Phanerozoic (Kuznetsov, 1983, 2000). Therefore, conditions of their habitat could differ from the present-day ones. The rate of carbonate material recovery and reef growth also could be different.

The localization of reef at a depth favorable for its development (growth) is controlled by tectonic movements. According to (Kuznetsov, 1978), it is also governed by eustatic oscillations in the sedimentation basin. These factors are crucial for the determination of vertical growth rate of reef massifs. The principal relationships between tectonic motions and reef formation are reduced to the following variants (Nalivkin, 1955; Zadorozhnaya *et al.,* 1982, Baikov, 2002).

The reef substrate gradually subsides with a rate equal to the reef-builder growth rate. This is the most suitable variant providing the fast vertical growth of reef massif.

The reef substrate gradually subsides, but the subsidence rate is less than the reef-builder growth rate. The vertical reef growth proceeds slowly, because the potential of reef-builders is not completely realized and the reef massif expands in the lateral direction. A partial erosion of vertical framework is possible. Zadorozhnaya (1975) believes that mainly lenticular reef bodies elongated in the horizontal direction are formed in this case (horizontal dimension is larger than the vertical one).

The reef substrate experiences complex multifold oscillations (alternation of submergence with a rate optimal for reef-builder growth and interruptions in movement). Periods of the maximal possible vertical growth of framework give way to its lateral expansion and even partial erosion of reef massif. Such pulses result in the formation of fir-shaped reefs typical of many massifs with well-studied morphology. Currently, one cannot discriminate between the duration of vertical growth and the total duration of reef formation.

The reef substrate submerges with a rate higher than the compensating growth of reef-builders. In this case, the framework-forming organisms should die when the reef crest subsides to a depth greater than 45 m.

The reef substrate steadily emerges. The reef massif turns out to be in the wave agitation zone and gradually decreases in thickness.

The commonly accepted influence of tectonic movements on reef-forming organisms does not principally differ from the influence of eustatic oscillations. In general, reefs should be regarded as formations with continuous-discontinuous evolution.

In order to estimate the growth rate of such reefs, we have to consider the reef thickness and total growth time, which includes the times of vertical and lateral growth, the duration of possible erosion, and the negative influence of eustatic oscillations. It is impossible to separately assess these time spans for modern and ancient reefs. Therefore, when calculating the growth rate of a specific reef within a certain stratigraphic range, we are forced to accept its geological age as the growth time and thus underestimate the calculated growth rate with respect to the actual value. In fact, dividing the reef thickness by its geological age, we estimate the reef formation rate that takes into account all nuances of its development rather than the reef growth rate.

We calculated the formation rate for atolls and barrier reefs of various ages (Baikov, 2002).

The formation rates for Devonian, Paleogene–Quaternary, Neogene and Quaternary atolls vary from 25 to 106 B[2] (Nalivkin, 1955); the growth rate of the Paracel Atoll is estimated at 3 mm/yr. Approximately the same formation rates are typical of Silurian, Devonian, Permian, Triassic, and Jurassic barrier reefs (18–110 B). If the Great Barrier Reef was formed over the recent 20000 yr (Kuznetsov, 1978), its formation rate is 7.5 mm/yr. Based on these calculations, we can draw the following conclusions that provide insights into the time necessary for the formation of lateral paragenetic reef–evaporite systems.

The ability of biohermal body to grow with an enormous rate (up to 20 cm/yr), only comparable with the deposition of chemogenic sulfates and chlorides of Na, K, and Mg (up to 10 cm/yr), is not actually realized even in the Quaternary. The most reliable estimates (3 mm/yr) pertain to the reef growth rate at Paracel Island. This estimate indicates that despite various types, ages, and thicknesses of reef edifices, the total time required for the formation of reefs as a result of their continuous vertical growth accounts for 5.5% of the total time of reef formation, i.e., geological age.

The thickness of reefs does not grow for more than 90% of the formation time. One can suppose that the reefs grow in the lateral direction and undergo partial erosion during this enormous time span that surely included many intervals. It is also likely that the reef-builders died off and their vital activity subsequently resumed in favorable ecological environments.

DURATION OF SALT DEPOSITION AND EVOLUTION OF HALOGENIC BASINS

Study of the Kimmeridgian–Tithonian sulfate–halogenic Gaurdak Formation in the Central Asian halogenic basin (East Turkmenian Subbasin) and Kungurian halogenic formation in the Upper Kama Basin showed a great discrepancy between the formation time of halogenic sequences estimated from geological data (17 and 9.9 Ma, respectively) and from calculations taking into account the thickness of annual anhydrite and halite layers (Baikov and Sedletskii, 2001). Therefore, we suppose that two temporal parameters should be recognized in the study of halogenic basins and related reef complexes: total duration of the halogenic basin existence (Kimmeridgian–Tithonian in the East Turkmenian Subbasin) and the total duration of salt deposition recorded in sediments and section (a few hundred thousand years in the East Turkmenian Subbasin). Similar temporal discrepancies are typical of other halogenic basins; however, they have not attracted the attention of researchers as yet.

This fact can only be explained by numerous hidden hiatuses in the hemogenic salt precipitation owing to several factors, e.g., desalting of brine and virtually complete conservation of the halogenic basin (its volume remains almost constant, and chemogenic sediments of the annual cycle do not precipitate at all). The development of barrier reefs with all attributes of their growth is considered the most important factor providing the stabilization of water volume in the basin. It looks possible that the long-term (millions of years) existence of the halogenic basin was related to periodic variations from extraarid to semiarid climate. At a certain balance between the inflow of marine and river waters and atmospheric precipitates, on the one hand, and evaporation, on the other hand, the basin could be conserved. In particular, when the inflow and evaporation are equalized, the system does not reach the chloride stage and ceases at the $CaSO_4$ precipitation level (Kopnin, 1977). The onset of halite precipitation requires a disturbance of water balance in the basin; i.e., the evaporation must exceed the inflow of low-saline marine water. If evaporation in semiarid climate is very low, the basin can exist at any (carbonate, sulfate, or halite) stage much longer than the calculated time without appreciable precipitation of the respective components.

Thus, dividing the total thickness of carbonate, anhydrite, and chloride salt rocks by the thickness of annual layers typical of Phanerozoic halogenic sequences, we can very roughly estimate the time of sedimentation. Assuming that sedimentation was continuous, only the lower limit of sedimentation period is determined in this case.

Numerous periods of desalting of halogenic basins, e.g., the East Siberian Basin, distinctly recorded by carbonate precipitation after the deposition of readily soluble salts, undoubtedly indicate an abrupt subsidence of the barrier reef area. The reef massif cannot compensate the substrate subsidence for some time. Therefore, the reef bar does not practically control seawater inflow into the halogenic basin.

The duration of evaporite and barrier reef formation in the East Siberian and Ciscaucasus halogenic basins is discussed below.

THE EAST SIBERIAN BASIN

The Cambrian East Siberian K-bearing basin is an example of halogenic basins with reliably established long-term evolution history and lateral reef–evaporite system. The basin is filled with polycyclic saliferous sequence (terminology according to Grachevskii and Kuznetsov).

The basin is situated within the Siberian Platform covering a vast territory (more than 2 million km^2). The geology and salt potential of the basin are considered in

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[2] Bubnoff units = 1 mm/ka.

many publications (Zharkov, 1974; Britan *et al.*, 1977; Vysotskii *et al.*, 1988; and others).

The East Siberian Basin has an almost triangular shape (in plan view) with the southern vertex localized near Irkutsk. Based on the basement morphology, the basin includes the Angara–Lena, Sayan–Yenisei, and Tungusska syneclises coupled with the Baikit and Nepa–Botuoba anteclises. The Angara-Lena and Murbai–Chastin troughs, as well as the Nyui–Dzherba and Berezov basins, extend along the eastern zone of the East Siberian Basin. The Kan–Tasseev, Velma and other smaller basins and the Bakhta–Kondroma Trough are situated near the western zone. The Ilga Basin is localized in the southern East Siberian Basin known as the Irkutsk Amphitheater. The Nepa–Botuoba Anteclise hosts the Surinda–Gazha Trough with economic resources of potash salts.

The East Siberian Basin was formed in the Cambrian as a giant negative platform structure. The total thickness of halogenic sequences and other sediments exceeds 3600 m. The saliferous section is characterized by a multifold intercalation of rock salt layers (thickness 5–30 m, occasionally up to 50–400 m) with sulfate and carbonate rock layers and members that are traced over vast territories within the basin. The total thickness of rock salt is more than 2500 m.

Britan *et al.* (1977) recognized 17 salt units (from S_1 to S_{16}) and 16 carbonate reference horizons, or members (from R_{I} to R_{XVI}) in the Lower–Middle Cambrian section. Their stratigraphic position with respect to the known formations is shown in the table.

The saliferous portion of the section begins with the terrigenous–carbonate–salt sequence (Mot Formation) consisting of three subformations and pertaining to the Lower Cambrian or Vendian Irkutsk Horizon (Khomentovskii, 1976). The lower Mot Subformation is composed of partly red-colored sandstones, siltstones, and shales up to 200 m thick. The middle and upper Mot subformations consist of dolomites, sandstones, siltstones with anhydrite interlayers and locally developed rock salt layers (units S_{16}, 370 m; S_{15}, 425 m). The overlying carbonate–halogenic complex is subdivided into the Usol'e, Bel'sk, Bulai, Angara, and Litvintsevo formations. Middle and Upper Cambrian suprasalt rocks (Maya Horizon and Ilga Formation) consists of red-colored siltstones, sandstones, and clayey limestones with occasional anhydrite in the lower part of the section.

The Usol'e Formation comprises five salt and four reference carbonate members (table). The thickness of salt members varies from 8 to 75 m and abruptly increases to 1000–1200 m in depressions. The rock salt contains carbonate, carbonate–sulfate, and halopelitic interlayers. The reference members, 40–50 m thick, commonly consist of dolomites and anhydrites.

The overlying Bel'sk Formation is largely composed of intercalating dolomites and limestones with trilobite remains, 240–520 m in the total thickness. The sporadically traced rock salt members (S_9, S_8, and S_{7a}) have a total thickness of 50–200 m.

The Bulai Formation (95-150 m) mainly consists of dolomites with local sandstone, siltstone, and limestone interlayers containing abundant fossils. Anhydrite and anhydrite–dolomite interlayers occur in the lower part of the section.

The Angara Formation is characterized by the most complex structure and facies variability. It includes five salt members (S_6–S_2) and four carbonate members (R_{VI}–$\mathrm{R}_{\mathrm{III}}$) with a total thickness of 300–650 m. Each rock salt member varies in thickness from a few tens meters to 150 m (occasionally, 250–300 m). Areas of members S_4, S_3, and S_2 consecutively decrease in comparison with the lower members. Saturation of the section with salt varies from 12 to 58%. The Angara Formation hosts member S_6 (300 m) with the economic potash salt in the Surinda–Gazha Trough (Nepa potash deposit).

The saliferous section is completed with the Litvintsevo Formation containing two carbonate members (R_{II} and R_{I}) and salt member S_1, more than 220 m in total thickness. The rock salt S_1 (up to 100 m) occurs in the central Irkutsk Amphitheater and Tungusska Syneclise.

The overlying suprasalt red-colored siltstones, sandstones, and clayey limestones (occasionally with anhydrite in the lower part) reach 1000 m in thickness and pertain to the Middle–Upper Cambrian Maya Stage.

Thus, the East Siberian halogenic basin existed for no less than 42.7 Ma and was characterized by abrupt variations of water salinity. Zharkov (1974) recognized here five cycles of halogenic sedimentation of the first order (Irkutsk, Usol'e, Bel'sk, Angara, and Litvintsevo). Each cycle is subdivided into cycles of the lower order corresponding to the particular salt members and layers. Water in the basin experienced periodic salting up to the point of sylvite and carnallite precipitation. Numerous desalting events of different durations are recorded by variable-thickness anhydrite, dolomite, and limestone layers. During some periods, the water salinity fell to the normal level, as indicated by trilobite remains and other fossils in limestones.

Periodicity of salting and subsequent desalting of the basinal water can be explained in terms of its paleogeography. This basin was an inland water reservoir. In the north, northeast, and east, it was bordered by a relatively narrow (100–150 km) and extended (~2000 km) zone of archeocyathean–algae reefs of the barrier type up to 1800 m thick (Britan *et al.*, 1977; Savitskii and Astashkin, 1978; Chechel and Mashovich, 1983). They are reliably known to grow during the Usol'e, Bel'sk, Angara, and Litvintsevo times and are inferred to exist during the middle–late Mot time and Maya Age. The reef system spatially coincides with a clearly expressed flexure where the layers dip at angles up to 30° NE. In general, the localization of reefs was controlled by NW faults in the basement. An open sea with normal water salinity extended northeast of the barrier zone. It is likely that when the reef growth could not compensate

Stratigraphic subdivision of Cambrian saliferous rocks in the Siberian Platform (Britan *et al.*, 1977)

System	Series	Stage, horizon	Reference horizon (R) and salt member (S)	Formation
Cambrian	Upper			Kondrat’evo (Ilga)
	Middle	Maya		Upper Lena
		Amga (Zeledeevo)	R_{I}	Litvintsevo
			S_1	
	Lower	Naman	R_{II}	
		Chara	S_2	Angara
			R_{III}	
			S_3	
			R_{IV}	
			S_4	
			R_{V}	
			S_5	
			R_{VI}	
			S_6	
		Olekma	R_{VII}	Bulai
		Uritskii	S_7	
		Tolbachan	$S_{7\mathrm{a}}$	Bel’sk
			R_{VIII}	
			S_8	
			R_{IX}	
		El’gyai	S_9	
			R_{X}	
		Usol’e	S_{10}	Usol’e
			R_{XI}	
			S_{11}	
			R_{XII}	
			S_{12}	
			R_{XIII}	
			S_{13}	
			R_{XIV}	
			S_{14}	
		Irkutsk	R_{XV}	Mot (upper and middle subformations)
			S_{15}	Ostrovnaya
			R_{XVI}	
			S_{16}	

for the substrate subsidence, the seawater freely entered the basin, resulting in the deposition of dolomites or limestones with trilobites. As soon as the reef barrier abruptly interrupted connection of the basin with open sea, the water salinity rapidly increased, resulting in the precipitation of calcium sulfate, halite, sylvite, and carnallite.

Let us consider the dynamics and relative time of reef–evaporite interaction in more detail.

The origination of reef barrier in the large fault zone and biohermal bar therein resulted in separation of the East Siberian during the in Irkutsk time. The vertical reef growth evidently surpassed the substrate subsidence. As soon as the barrier crest turned out to be at a depth characterized by deficiency in seawater inflow relative to evaporation during the arid climate, water salinity in the basin gradually started to increase. The intense vertical growth of barrier reefs should be changed into their lateral expansion if substrate motions were insignificant. The supply of seawater into the halogenic basin attained a minimum during halite precipitation (member S_{16}). This implies that the reefs turned out to be at a depth least possible for their vital activity and their partial destruction cannot be ruled out.

The subsequent desalting of water in the basin reached the conditions of carbonate precipitation (member R_{XVI}). The inflow of a large volume of seawater can be explained by an abrupt subsidence of substrate underlying the barrier reef system. During a certain time span, the rate of negative tectonic motions was much higher than the compensation ability of reef-builders. Due to the deceleration or even cessation of subsidence, the crest of intensively growing reef again reached a depth insufficient for maintenance of the previous balance of inflow and evaporation. The water salinity increased and halite started to precipitate (member S_{15}). Because the substrate subsided with a minimum rate, the vertical reef growth gave way to its expansion in the lateral direction, and the reef crest could be partly eroded.

The subsequent fast desalting resulted in the deposition of calcareous ooze (member R_{XV} in the upper part of the Irkutsk Horizon). This implies that the seawater again poured into the basin and diluted the brine owing to the fast uncompensated subsidence of the barrier reef. As a result, the seawater salinity approached the normal level.

The multifold cyclic repetition of interrelated events, similar to those described for the Irkutsk time, took place in the barrier reef and halogenic basin during the Usol'e, Bel'sk, Bulai, Angara, and Upper Lena ages. Carbonate members (R_{XIV}–R_{I}) were formed in the East Siberian Basin contemporaneously with the intense subsidence of barrier reefs and their intense vertical growth. When the reef crest reached a certain depth, the readily soluble salts started to precipitate (members S_{14}–S_1). However, the vertical growth of reefs did not cease for some time.

At the final stages of salt precipitation, reefs largely expanded in the lateral direction and could partly be destroyed.

Thus, two stages can be recognized in the evolution of barrier reefs bordering the halogenic basin. The first stage corresponds to the biogenic and (or) chemogenic deposition of carbonates within the basin. The second stage corresponds to the precipitation of calcium sulfate and readily soluble salts.

In the late Middle Cambrian (Maya Age) and Late Cambrian, the barrier reef ceased to function as a depth-compensating mechanism and regulator of seawater supply from the feeding basin, and the lateral paragenetic reef–evaporite system was disturbed. As a result, the East Siberian halogenic basin disappeared.

Let us calculate the timing of rock salt deposition and inferred vertical growth of reefs for the lateral paragenetic reef–evaporite system of the East Siberian Basin. As mentioned above, the total thickness of rock salt units is more than 2500 m, and the thickness of barrier reefs is about 1800 m. If the halite precipitation rate is 4–8 cm/yr, the time needed for the sequence formation should be 2500 m : 8 cm = 31250 yr or 2500 : 4 cm = 62500 yr. If the vertical growth rate is assumed to be 3 mm/yr, the increment of 1800 m requires 1800 m : 3 mm = 600000 yr. If the vertical growth time accounts for 2–5% (3.5%, on the average) of their formation time falling on Early–Middle Cambrian Aldan and Amga ages, equal to ~42.7 Ma (Afanas'ev, 1987), the vertical reef growth lasted for 42.7 Ma : (100 × 3.5) = 1494500 yr. This estimate should be much greater if the Irkutsk Horizon is referred to the Vendian.

The substantial discrepancy (by a factor of 10–50) between total times of evaporite formation and vertical reef growth is interpreted as follows.

The calculation does not take into account the calcium sulfate precipitation time, which is several times longer than the halite precipitation. The account of this factor markedly decreases the above discrepancy. The vertical growth duration of ~1.4 Ma corresponds to the coeval deposition of carbonate members of the East Siberian Basin. During a long time span of ~41.2 Ma, the reefs did not grow, because they were situated below the depth suitable for reef-builders or in the wave agitation zone and partly eroded.

THE CISCAUCASUS HALOGENIC BASIN

The Late Jurassic (Kimmeridgian–Tithonian) Ciscaucasus halogenic basin developed in a narrow pericratonic trough in the southern Scythian Plate. The carbonate–sulfate rocks and salts in this basin cover an area of ~50000 km^2. Salt rocks fill the East Kuban and Terek–Kuma depressions divided by the Elbrus–Stavropol Uplift. Since the depressions are sufficiently isolated, they the may be recognized as Western Ciscaucasus and Eastern Ciscaucasus Subbasins (Baikov *et al.*, 1987).

The East Kuban Basin is oriented in the northwestern direction at an acute angle to the strike of the Caucasus Foldbelt. In the northeast, it borders along the Nevinnomyssk Fault on the Stavropol Uplift. The sublatitudinal Cherkessk Fault serves as a boundary with the North Caucasus marginal massif in the south. The western boundary with the West Kuban Trough extends along the Lagonak Terrace of the Sochi–Belorechenskaya anti-Caucasus fault zone and further along the Kanev–Berezan Arch, where the Upper Jurassic rocks pinch out, merging with a similar zone of the Stavropol Uplift that was formed along the Nevinnomyssk Fault. In the southeast, the basin extends toward the Mineral'nye Vody Salient belonging to the Elbrus–Stavropol transverse uplift. The general contour of the Western Ciscaucasus Subbasin is clearly delineated since the Oxfordian as a shallow-water shelf (Boiko *et al.*, 1977).

The thick halogenic sequence, identified as the Kuznetsov Formation (Sapunova and Chernenko, 1982), was formed in the Western Ciscaucasus Subbasin. It is subdivided into four members corresponding to large sedimentation rhythms. The lower halite member I is up to 1100 m thick. The transitional zone between underlying Oxfordian–Kimmeridgian limestones and member I is composed of intercalating anhydrites and limestones (up to 120 m) with rock salt interlayers. The upper halite unit contains anhydrite layers varying from 1 to 25 m in thickness. Member II consists of anhydrites and carbonate rocks reaching 110–220 m in thickness. The sulfate–halite member III (up to 320 m) contains 54 rock salt layers, 0.05–11.3 m thick, and 50 anhydrite layers, 0.05–6.4 m thick. Clay interlayers (up to 2.0 m) are also noticed. Member IV is made up of anhydrites, clays, and rock salt, up to 120 m in the total thickness. The most intense subsidence of the Western Ciscaucasus Subbasin occurred along the Koshehabl–Yaroslavskaya–Shedok line. The thickness of halogenic sequence in the Yaroslavskaya area reaches 1800 m (65–70% of rock salt and 20–25% of anhydrite). The most subsided part of the Western Ciscaucasus Subbasin is a K-bearing structure that hosts up to three potash salt layers 5–16 m thick (Derevyagin and Sedletskii, 1977; Derevyagin, 1981).

The overlying rocks of the Laba Formation are composed of alluvial–lacustrine varicolored clays with sandstone interlayers. The section starts with a transitional member, up to 120 m thick, with anhydrite interlayers and rock salt pockets. The maximal subsidence zone (thickness up to 1200 m) is retained. The Laba Formation completely pinches out at the basin walls.

The Laba rocks are overlain with indications of erosion by Berriasian oolitic, sandy, and organogenic detrital limestones reaching 40–50 m in thickness.

Thus, the Western Ciscaucasus halogenic Subbasin existed for no less than 1 Ma. Like the East Siberian halogenic basin, the Western Subbasin was characterized by significant fluctuations of water salinity. Periodic salting and subsequent desalting of water in this subbasin are not so clearly expressed as in the East Siberian Basin and can also be explained from its specific paleogeography.

The Kimmeridgian–Tithonian Western Ciscaucasus Subbasin was an inland reservoir separated from the open sea by a system of large barrier reefs and connected with sea only in the south and southwest. The best-studied barrier reefs in the southwestern part of the subbasin make up a nearly meridional belt of outcrops extending from Mounts Fisht and Oshten toward the Nagoi-Chuk Range and further along the Lagonak Range. The reefs are related to the Tsitsin and Kurdzhip faults that are elements of the anti-Caucasus Sochi–Belorechenskaya Fault (Khain and Lomize, 1961; Sedletskii *et al.*, 1977; Boiko *et al.*, 1977; Boiko, 2001). The coral and algal limestones, up to 900 m thick, are predominant rocks. Their age is determined as Oxfordian–Tithonian (*Geologiya SSSR*, 1968) or Oxfordian–lower Tithonian (Khain and Lomize, 1961).

According to Sedletskii *et al.* (1977), the barrier reefs already served as a bridge between the open sea and shelf zone of the East Kuban Basin in the Oxfordian. Khain estimated their thickness in Oxfordian at approximately 250 m (*Geologiya SSSR*, 1968). The thick Oxfordian–Kimmeridgian limestone sequence indicates that seawater was freely delivered to the basin at that time. Hence, the reef-forming organisms, which existed at the first stage of reef evolution, had no time to compensate for the substrate subsidence and the reef crest was situated at a considerable depth for all that time.

In the early Tithonian, the reef crest was localized at the shallowest depth, so that the seawater inflow became less than the evaporation. As a result, $CaSO_4$ and NaCl began to precipitate from concentrated brines. One can suggest that the vertical growth either rapidly and completely compensated for the insignificant substrate subsidence or ceased to grow and started to expand in the lateral direction by the onset of halite precipitation, i.e., at the second stage of barrier reef evolution. If the substrate was almost immobile or growing up, the upper section of the reef was eroded.

The Western Ciscaucasus Subbasin was repeatedly desalted during the Tithonian (at least, up to the $CaSO_4$ precipitation stage). Consequently, the brine concentration increased in three cases up to so high levels that even potash salts could precipitate. The barrier reefs insignificantly submerged due to the substrate subsidence, because thicker, and were partly eroded after displacement into the zone of high hydrodynamic activity. This cycle was repeated for many times.

Further events in the Tithonian led to filling of the halogenic basin with continental varicolored terrigemous sediments of the Laba Formation (up to 1200 m). This implies that the reefs emerged above the sea level like a dam and completely separated the East Kuban Basin, which continued to subside, from the feeding marine basin. The reefs were partly destroyed, but the section eroded by the Berriasian time is unknown.

Thus, by the early Laba time, the barrier reef ceased to function in a regime necessary for the existence of halogenic basin. The lateral reef–evaporite system was disturbed, and the Western Ciscaucasus Subbasin dried up.

Let us calculate durations of the continuous rock salt deposition and probable vertical growth of reefs as elements of a lateral paragenetic system of the Western Ciscaucasus Subbasin. The thickness of the saliferous Kuznetsov Formation is 1800 m, including ~360 m of anhydrites and 1300 m of rock salt. The thickness of barrier reefs is approximately 900 m, including 250 m of the Oxfordian section (*Geologiya SSSR*, 1968) and 650 m of the Kimmeridgian–Tithonian section. If the halite precipitation rate is 4–8 cm/yr, the precipitation of 1300 m of rock salt requires 1300 m : 4 cm = 32500 yr or 1300 m : 8 cm = 16 250 yr. If the reef growth rate is 3 mm/yr, the time of their continuous (i.e., total) vertical growth is 900 m : 3 mm = 300000 yr including 83000 yr falling on the Oxfordian and 117000 yr falling, on the Kimmeridgian and Tithonian. It should be noted once again that the upper age limit of the vertical reef growth remains ambiguous. Based on the high deposition rate and probable hiatuses in $CaSO_4$ and NaCl precipitation, we previously supposed that the precipitation of 1800 m of anhydrite (gypsum) and halite required no more than 1 Ma (Baikov, 2002). The vertical reef growth in the Tithonian was limited by this value. If the average duration of vertical reef growth accounted for 3.5% of the formation time, i.e., geological age (in this case, Oxfordian + Kimmeridgian ages + 1 Ma = 5.6 + 6.6 + 1.0 = 13.2 Ma), the vertical growth took place during 13.2 Ma : (100 × 3.5) = 452000 yr, including 7.6 Ma : (1200 × 3.5) = 266000 yr in the Kimmeridgian (partly, Tithonian).

Thus, as in the East Siberian Basin, a discrepancy by a factor of 3–15 is revealed between the total time of evaporite formation (17500 –35000 yr) and the total time of vertical reef growth in the Kimmeridgian and Tithonian (117000 or 266000). The discrepancy is smaller if the Tithonian portion of the reef is subtracted and the $CaSO_4$ precipitation time is taken into account. In any case, as in the East Siberian Basin, reefs of the Western Ciscaucasus Subbasin did not grow during approximately 7.3 Ma of the Kimmeridge and partly Tithonian time, the subbasin was situated either below a depth suitable for the vital activity of reef-builders life or in the wave agitation zone.

METALLOGENY OF THE REEF–EVAPORITE SYSTEM

According to Boiko (1997, 1998, 2001), bioherm formation is favorable for the mobilization of ore matter. As exemplified by the Ciscaucasus halogenic basin (North Caucasus Basin, after Boiko), two sources of ore matter can be inferred for the paragenetic reef–evaporite system.

First, chalcophile elements of denudation areas were accumulated in Oxfordian and Kimmeridgian carbonate rocks and subsequently mobilized by brines of evaporite basins. Under conditions of large-scale supply of phytoplankton, sulfide ores of Pb, Zn, and other elements precipitated on a geochemical barrier behind the reef at the boundary of the normal seawater and near-bottom metal-rich brines. In particular, oil shales enriched in ore matter were found in sediments of back-reef zone in the Greater and Lesser Laba interfluve, as well as along the Ardon, Urukh, and other rivers in the Eastern Ciscaucasus Basin (Boiko, 2001). In the East Siberian Basin, the Ketemene lead occurrence at the mouth of the Lesser Ketemene River, a left tributary of the Lena River (Davydov, 2002), likely belongs to the same type. Back-reef facies of this region include dolomites and limestones of the Ketemene Formation. The ore matter likely underwent a secondary redistribution, because the ore occurrence is localized in the zone of epigenetic dolomitization and recrystallization. The are-bearing rock is composed of coarse-crystalline cavernous dolomite that crossuts the bedding of host carbonate rocks.

Second, the dissolved, colloidal, or suspended ore matter of the feeding marine basin was mobilized. An appreciable amount of chalcophile elements was absorbed by plankton. Compensation currents directed toward the halogenic basin delivered an enormous mass of plankton into the barrier reef zone. Reef-builders assimilated the ore matter mobilized by plankton.

According to the concept of metalliferous reef systems worked out by Davydov (2002), the mineralized solutions delivered from the deep crust along tectonic faults serve as a source of ore matter. Lead–zinc ore deposits formed during the sedimentary–diagenetic, diagenetic, and epigenetic stages. The diagenetic stage, when the buried chloride brines saturated with metals migrate from unlithified sediments to the lithified carbonate reservoir rocks, is important for reef systems. Ore mineralization in reefs is formed due to the spillover of mud brines from the adjacent depressions into reefs and changes of compaction and permeability at contacts of different structural–genetic types of sediments.

Massifs of reef-forming organisms, which consolidated during the growth, are evidently most favorable for ore deposition. The reef massifs have high primary and secondary porosity created during their displacement to the high hydrodynamic activity zone or emergence above the sea level.

Davydov suggested that lead and zinc compounds precipitate in carbonate sediments of the depression zone. The mud accumulation rate is much less than the reef growth rate. Therefore, metalliferous brines may only enter the coeval reefs during the first (carbonate) stage of barrier reef formation. As the reef grows, synchronous development of these processes should be completely upset during the second stage. Carbonate sedimments of the back-reef zone should come in contact with older section of the reef massif, because the coeval reefs will be localized at much higher levels.

In the case of polycyclic evolution of basins (not only halogenic!), the metalliferous carbonate sediment may be deposited at the hypsometric level corresponding to the zone of eroded cavernous reefs. This zone may be younger than the sediments if they come into contact along a fault, which governs the subsidence of reef substrate, or older if the sediment adjoin the cavernous zone.

The secondary porosity is of great importance at the epigenetic stage of ore formation when the dispersed ore matter undergoes redistribution and regeneration (Davydov, 2002).

Forecasting of cavernous units and wave agitation zones in reefs of the second stage may result in the discovery of orebodies localized at various hypsometric and stratigraphic levels of reef systems, especially orebodies evolving for a long time.

CONCLUSIONS

(1) The East Siberian halogenic basin with barrier reefs, up to 1800 m thick, and rock salt sequence reaching 2500 m in thickness existed in the Early–Middle Cambrian for 42.7 Ma. Duration of the functioning of particular elements of the lateral paragenetic reef–evaporite system is as follows.

If the rate of vertical reef growth was 3 mm/yr, the total time of vertical growth (without regard for hiatuses) was 600000 yr. If the vertical growth accounted for 3.5% of the time of reef evolution (i.e., geological age), the vertical growth lasted for 1494500 yr (without regard for the possible growth of reefs in the late Vendian).

The total time of halite precipitation (i.e., without regard for desalting periods) is 31250–62500 yr at the precipitation rate of 4–8 cm/yr.

Thus, discrepancy between the total times of vertical reef growth and evaporite formation varies by a factor of 10–50 (without considering the time of $CaSO_4$ precipitation). Reefs did not grow and salts were not deposited during a prolonged time span of approximately 41.2 Ma.

In the Tithonian Western Ciscaucasus Subbasin, which existed for approximately 1 Ma, barrier reefs are 900 m thick, while the rock salt sequence is 1300 m thick. The vertical growth of reefs lasted for 117000–266 000 yr, and the total time of halite precipitation was 266250–325000 yr. Discrepancy between the total times of vertical reef growth and evaporite formation varies by a factor of 3–15 (without regard for the time of $CaSO_4$ precipitation). This discrepancy is significant, but much smaller than for the East Siberian Basin. Reefs did not grow and salts were not deposited for approximately 7.3 Ma.

(2) Although the studied halogenic basins are separated by a time interval of 369 Ma, no principal differences in origin and functioning of the Early–Middle Cambrian and Late Jurassic lateral paragenetic reef–evaporite systems have been established.

(3) Despite the prolonged existence of barrier reefs (millions and tens of million years), the lateral paragenetic reef–evaporite system only functioned during tens of thousand years. At the late stage of halite and K–Mg-salt precipitation, the vertical growth of reefs should cease if the substrate did not undergo slow subsidence compensated by reef-builders.

(4) Four (carbonate, sulfate, halite, and potash–magnesian) stages are recognized in the evolution of halogenic evaporite basins. We recognize two stages in the evolution of barrier reefs bordering the halogenic basin.

At the first stage corresponding to carbonate sedimentation within the basin, reefs and carbonate sediments are incompletely coeval only when the reefs are confined to the initial stage of carbonate precipitation at critical depths. In this environment, the chemogenic carbonate material precipitates for a certain time under conditions that rule out the coeval growth of reefs. In the East Siberian Basin, substrate subsidence in the barrier reef zone might be so intense that the basinal brine was diluted up to the point of normal salinity after salt deposition, as indicated by the presence of trilobite remains and other fossils.

At the second stage corresponding to the precipitation of sulfates and readily soluble salts, the formation of the lateral reef–evaporite system was a natural continuation of the first stage of barrier reef evolution. Their vertical growth continued or ceased depending on substrate motions relative to its preceding position. Therefore, the vertical growth reef is coeval with sulfate sediments and a part of halogenic rocks. We believe that the lateral expansion of reefs could take place only during the precipitation of potash–magnesian salts when seawater inflow into the halogenic basin practically ceased. Since the reef crest was situated at a shallow depth, it could partially destroyed.

Numerous oscillations of substrate in the barrier reef zone against the background of general tectonic movements complicate the continuous-discontinuous character of the evolution of large reef systems. To date, it is impossible to estimate the duration of particular oscillations. However, it is evident that they significantly control the duration of vertical reef growth.

(5) Barrier reef system in the East Siberian Basin extends over a long distance (approximately 2000 km) along a large fault governing their evolution. Therefore, one can hardly expect completely synchronous motions (in sign and rate) of the substrate along the entire zone. Regardless of the general subsidence trend, some segments of the zone moving with a lower velocity could be left behind or stabilized somewhat earlier, relative to other segments. In other words, the reefs could exist at a certain moment at different depths along the barrier zone strikes (at present, reconstruction of this process is impossible). However, the resultant cyclic activity of reefs regulated the seawater supply to the East Siberian Basin and governed the deposition of carbonates or sulfate and chloride sediments.

(6) Taking into account the specific character of lateral reef–evaporite system evolution, we suggest that in the presence of barrier reefs as regulators of seawater delivery to a basin, the latter becomes potentially halogenic not from the onset of $CaSO_4$ (or especially halite) precipitation. Under conditions of arid climate, the halogenic scenario of basin with an exogenic source of salt starts to evolve when the reef crest approaches the minimal depth. Chemogenic carbonate sediments could be deposited in the basin before this event. Now the inflow–evaporation balance is disturbed and the basin water can gradually be salted. Under favorable conditions, the geologic potential of halogenic basins is completely realized up to the point of precipitation of potash–magnesian salts.

(7) Specific features of the lateral reef–evaporite system evolution should be taken into account for estimating the potential of barrier reefs for mineral resources (particularly, sulfides of Pb, Zn, and other metals).

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