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GEOLOGY

The Late Visean–Serpukhovian Stage of Reef Formation in Russia and Adjacent Countries

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Reef building started in the Late Archean–Proterozoic as relatively simple calyptrae and, later, as biostromes and bioherms. This process became widespread in the Phanerozoic in the form of reefs (*sensu stricto*) and other organogenic structures. It was established long ago that this process is characterized by a certain cyclic mode in which periods of large-scale and intense reef development alternate with epochs of strong deceleration [2, 3, 5–9]. Most researchers recognize, with certain variations, the Early–Middle Cambrian, Silurian–Frasnian, Permian, Middle–Late Triassic, Late Jurassic, and Oligocene–Quaternary maximums in reef formation.

Many researchers believe that the Famennian–Middle Carboniferous interval lacks shallow-water wave-resistant reefs and is dominated by Walsorth mud knolls on calm-water slopes, probably as a result of the relatively insignificant distribution of Early Carboniferous reefs. This is evident from the limited number of publications dedicated to the Visean–Serpukhovian reefs. For instance, only 5–7% of publications are related to the Visean–Serpukhovian structures and the remainder is devoted to Visean reefs in the most detailed world bibliography of Lower Carboniferous reefs compiled by Flügel and Flügel-Kahler [6].

Despite their relatively limited development, upper Visean–Serpukhovian (locally, probably lower Bashkirian) reefs are known and have sometimes been described in detail in several areas of Russia and other countries. In other words, one can outline an additional reef formation maximum. This has been partially mentioned in [1, 2, 4]. The present communication is devoted to a more detailed description of the upper Visean–Serpukhovian reefs, their types, tectonic and paleogeographic position, and relevant specific biota.

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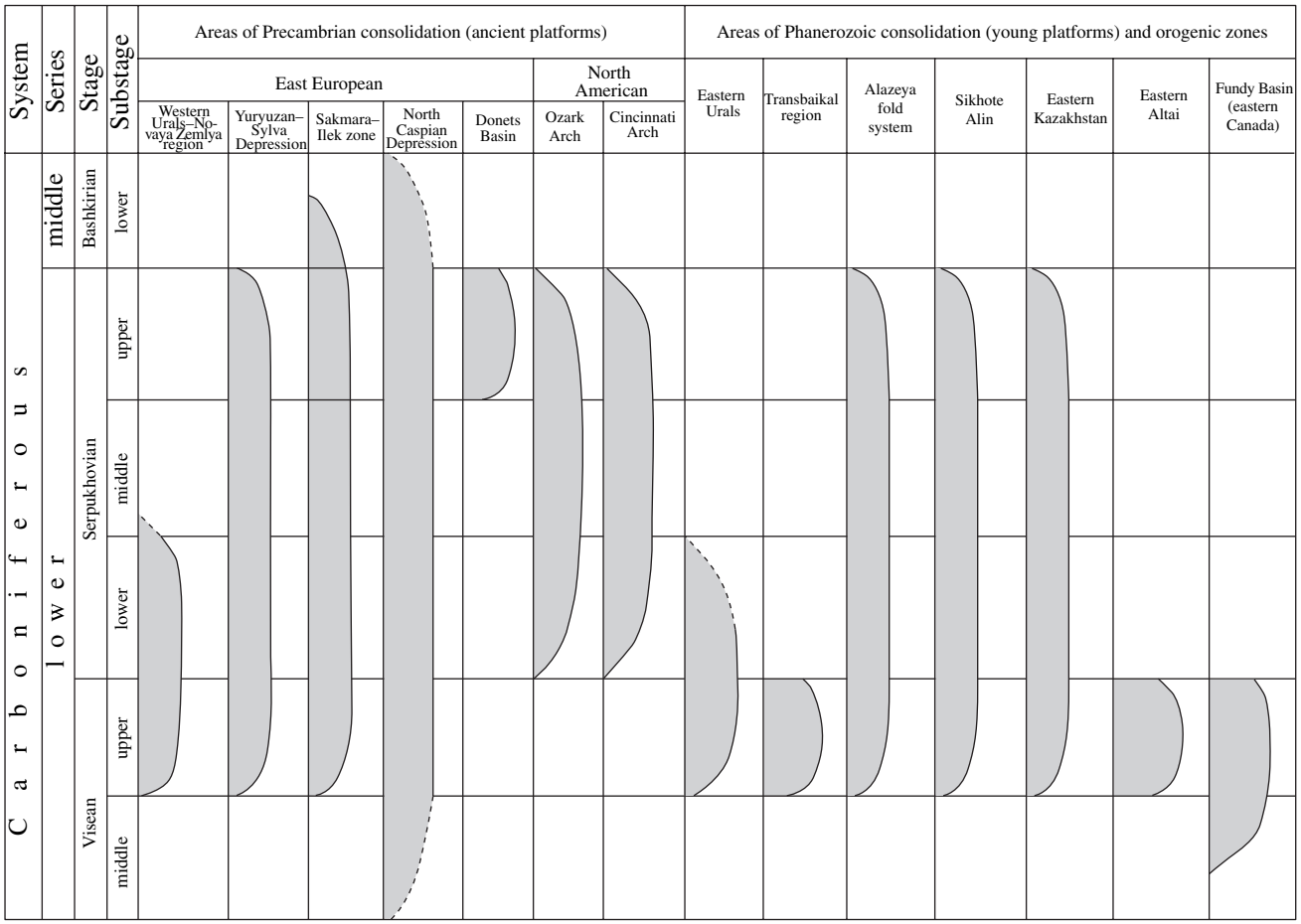
In the former Soviet Union, the late Visean–Serpukhovian organogenic structures are developed in the East European Platform (including its eastern and southeastern periphery), Kazakhstan, central Asia, and the Russian Northeast and Far East. Beyond Eurasia, reefs of the time interval being considered have been recorded in the North American continent, Western Europe, and eastern Australia. The figure demonstrates the schematic geographic and stratigraphic distribution of these reefs. The reefs of the West Uralian–Novaya Zemlya region are referred to the East European Platform, because they formed on the continental margin of Euramerica, whereas reefs of the eastern Urals developed as island-arc structures of the Uralian paleocean.

We are aware that the presented review of Visean–Serpukhovian reef distribution is far from complete. Nevertheless, we can conclude that this period can be considered an autonomous and specific reef formation stage.

The duration of the Visean–Serpukhovian stage is slightly variable in different regions and, probably, corresponds to the middle Visean–early Bashkirian interval with maximum development of reefs in the late Visean–Serpukhovian. The early–middle Visean and Bashkirian reefs are either doubtful (i.e., they are carbonate rather than reefal structures, as has been established, for example, in Tengiz) or they are only locally developed.

Thus, the Tournaisian–early Visean frameless mud knolls were rapidly replaced by the late Visean–Serpukhovian reef-forming structures. The interval between the Serpukhovian and the Permian (or Late Carboniferous–Permian) reef formation epochs probably corresponded to the Middle Carboniferous–initial Late Carboniferous (?).

This period was marked by the formation of various organogenic structures, such as biostromes, bioherms, and reefs (*s. s.*), i.e., large structures with well-developed reefal facies and detrital aprons, which indicate their formation above the wave base. Reefs occur in carbonate and terrigenous (or terrigenous–volcanogenic) formations indicating the high reef-building potential of the relevant biota, which was able to form



Stratigraphic and geographic distribution of Visean–Serpukhovian reefs.

reefs both in the most favorable carbonate sedimentation settings and in unfavorable environments of terrigenous and volcanogenic sediment accumulation.

The organogenic structures of this period are highly variable. They include asymmetric reef systems, such as coastal reefs (late Visean (?)–early Serpukhovian Zlokazov reefs of the southern Urals, Serpukhovian reefs of the Donets Basin and, partly, the Fundy Basin of Canada), barrier and marginal reefs fringing deep-sea basins (late Visean–Serpukhovian reefs of the Novaya Zemlya–western Urals region, reefs of the North Caspian Basin and eastern Kazakhstan, middle–late Visean reefs of Great Britain and Belgium), thick isolated intrabasin reefs (Tengiz and other reefs of the North Caspian Basin), and relatively small structures of shelf areas, such as Okaian reefs of the Buzuluk Depression; reefs of the eastern Transbaikal region; bioherms of the Bluefield Formation (western Virginia), Pennington Formation (Alabama), Lion Creek Formation (Queensland, eastern Australia); and others.

The tectonic positions of reefs and the geodynamic regimes of their formation are also variable. Most of the known structures are connected with ancient platforms and their fringing, although such confinement is likely explained by different degrees of the study of structural zones rather than their real distribution. In the East European Platform, reefs are developed along its northeastern (in ancient coordinates) margin in the transition zone between the Uralian paleocean and North Caspian microocean, while reefs of Belgium and Great Britain formed on the margins of their southern continental shelf facing the paleo-Tethys, i.e., on passive margins of the Euramerican continent. Reefs of Wrangel Island and the Chukchi Sea coast associated with carbonate and terrigenous–carbonate formations are also related to the Euramerican shelf, because they formed on its passive margin at the junction of the Uralian paleocean and Panthalassa. In the North American Platform, reefs are developed on the slopes of large intraplatform uplifts (arches).

The large aulacogen of the Greater Donbas and Dnieper–Donets Basin was another structure related to the ancient reef-hosting platform.

Many reefs fringed passive and active margins of microcontinents, e.g., the reefs of the Alazeya zone in the Verkhoyansk–Kolyma fold system, which was separated from the Siberian Platform and represented a microcontinent in the Early Carboniferous, and the

reefs of the Gissar zone confined to the western margins of the Tajik microcontinent and formed in the southern part of the paleo-Tethys (the Gissar paleocean) located between the Tajik and Kara Kum–Tarim microcontinents.

Several reefs located in the eastern Urals, eastern Kazakhstan, Sikhote Alin, and other regions developed on active margins and associated volcanic island-arcs.

The process of reef formation was also typical of young platforms during their initial consolidation stages, i.e., immediately after folding (e.g., reefs of the eastern Transbaikal region and Fundy Bay of eastern Canada).

The Visean–Serpukhovian reefs formed in different geodynamic settings, such as spreading in passive margins, subduction in active margins (volcanic island-arcs and others), and post-orogenic, rift, and stable intraplate environments.

The Visean–Serpukhovian reefs were characterized by a specific reef-building biota, which included diverse algae, bryozoans, corals, foraminifers, crinoids, brachiopods, gastropods, bivalves, ostracodes, goniatites, and subordinate calcareous sponges and stromatoporoids. Special studies show that the main reef-building role belonged to bryozoans and algae.

Bryozoans mainly accumulated and, to some extent, stabilized the material, while algae cemented it. Bryozoan diversity was high and dominated by Fenestelida. Corals dwelling on reefs were usually scarce and had negligible frame-building significance.

The high diversity of Cyanophiceae (cyanobacteria), Chlorophyceae and, to a lesser extent, Rhodophyceae algae is remarkable. The Cyanophiceae are represented by *Girvanella, Ortonella, Bevocastria, Garvudia, Rectangulina*, and others. The Chlorophyceae are present as *Fasciella, Camea, Pseudocamea, Paleoberesella*, Dasicladaceae, Siphonaceae, and subordinate phylloid algae. In addition, algae produced abundant carbonates and created geochemical environments favoring precipitation of carbonate material; i.e., they accumulated and, which is important, cemented the carbonate material.

Thus, the Visean–Serpukhovian reefs are characterized by the specific composition and high diversity of reef-building organisms. They occupy a transitional position between the monotonous biocoenosis of Tournaisian–early Visean mud knolls and the substantially more diverse community of Late Carboniferous–Permian reefs, where Hydrozoa (*Paleoaplesina*), Sphinctozoa, and Foraminifera, in addition to algae and bryozoans, played a significant role.

Conclusions. The late Visean–Serpukhovian corresponds to an autonomous reef formation stage separated by a short interval from the previous formation stage of the Famennian–Tournaisian mud knolls and by a longer interval from the formation stage of the Late Carboniferous–Permian reefs. It is marked by development of different organogenic structures, ranging from simple biostromes and bioherms to thick intricately differentiated reefs.

The main reef-building organisms were algae and bryozoans, with subordinate crinoids and foraminifers. Thus, the biocoenosis of these reefs is transitional from the impoverished community of the Famennian–Tournaisian mud knolls to the more diverse and taxonomically renovated assemblage of Late Carboniferous–Permian reef-building organisms. Reefs of this stage formed on various tectonic and paleotectonic structures, such as stable cratons, passive and active margins of continents and microcontinents, island-arc shelves, and young platforms. They developed in spreading and subduction environments of passive and active continental margins, respectively.

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